

Performance comparison of a group of thermal conductivity enhancement methodology in phase change material for thermal storage application



Carlos R. Abujas^{a, **}, Aleix Jové^a, Cristina Prieto^{a, *}, Manuel Gallas^a, Luisa F. Cabeza^b

^a Abengoa Research, C/ Energía Solar n° 1, Palmas Altas, 41014, Sevilla, Spain

^b GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, c/ Pere de Cabrera s/n, 25001, Lleida, Spain

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ABSTRACT

Phase change materials (PCM) are able to store thermal energy when becoming liquids and to release it when freezing. Recently the use of PCM materials for thermal energy storage (TES) at high temperature for Concentrated Solar Power (CSP) technology has been widely studied. One of the main investigated problems is the improvement of their low thermal conductivity. This paper looks at the current state of research in the particular field of thermal conductivity enhancement (TCE) mechanisms of PCM to be used as TES. This work considers a numerical approach to evaluate the performance of a group of TCE solutions composed by particular configurations of two of the principal TCE systems found on the literature: finned pipes and conductive foams. The cases are compared against a single PCM case, used as reference. Three different grades of graphite foams have been studied, presenting a charge time 100 times lower than the reference case for the same capacity. For fins two materials are analyzed: carbon steel and aluminum. The charge times of fin cases are from 3 to 15 times faster, depending on the amount and type of material employed. The internal mechanisms are analyzed to understand the results and locate possible improvement.

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1. Introduction

1.1. Thermal energy storage (TES)

Low-carbon economy policies are every year more strict and demanding. By 2050 the low-carbon economy roadmap presented by the EU intends to reduce emissions to 80% below 1990 levels, which implies progressive cuts of 25%, 40% and 60% in 2020, 2030 and 2040 respectively [1]. The main actors in this reduction are the power and the industrial sectors. As the energy demand is expected to increase in the incoming years, the pressure to reach a renewable energy driven power system increases as well [2–4].

In response to this request the number several Concentrated Solar Power plants (CSP) have been built, like PS10 and PS20 in Spain or more recently Khi Solar One in South Africa. These commercial plants are based on Direct Steam Generation (DSG) where

the boiler of conventional Rankine cycles is replaced with a solar receiver. CSP is unique among renewable energy generation sources because it can easily be coupled with thermal energy storage (TES) making it highly dispatchable [5–9]. Although the mentioned plants have installed TES based on steam accumulators, currently it is not feasible to manage the large capacities required for long time operation using this storage technology. As more hours of production and a better coupling of the demand curve add valuable capabilities to this technology, lots of efforts have been made over the last decades to achieve an efficient large scale thermal storage for high temperature processes.

Among the options analyzed, latent heat based systems have emerged as great potential storage systems [10,11]. This technology relies on the energy contained in a material changing its phase, capable of concentrating high energy ratios on narrow temperature ranges. Thanks to these effects ultra-compact units can store big amounts of energy, which can be absorbed or released at an almost constant temperature. The latent-latent heat transference allows a better matching in the boiler, maximizing the exergy efficiency in the evaporator as the temperature difference can be maintained constant, with the consequent benefit to the entire power plant.

* Corresponding author.

** Corresponding author.

E-mail address: cristina.prieto@abengoa.com (C. Prieto).

Nomenclature

A_{fin}	area occupied by the fins
A_{PCM}	area occupied by the PCM
A_{tot}	total area occupied by the system
f	volume fraction occupied by fins
D_{PCM}	diameter of the PCM region
D_{pipe}	external diameter of the process pipe
ϵ	accessible porosity of the foam
ρ	material density
H	material energy per unit mass
k	material thermal conductivity
T	temperature
h	sensible energy stored per unit mass
h_{ref}	reference energy level per unit mass
c_p	material specific heat
β	volume liquid fraction of the PCM
L	latent heat of the PCM
$T_{solidus}$	solidus temperature of PCM
$T_{liquidus}$	liquidus temperature of PCM

1.2. Phase change material (PCM) selection

The most common studied phase change transformations [12–15,35] have been the solid-liquid and liquid-gas, although some other transformation are under investigation, such as solid-solid for the development of structural materials capable of storing energy. However, the latter transformation stores small energy quantities compared with the formers and its phase transition temperature is not generally suitable for the industrial application here considered. Liquid-gas transformation has, as a general rule, the highest energy density, but this attractive property is linked with the important drawback of a high volume variation, that makes it difficult to store the gas phase in conventional containers. In contrast, solid-liquid transformation has still a high energy conversion and relatively small volume variation, making it suitable to solve the demanding storage requirements.

Related to the DSG technology, working steam pressures between 100 and 150 bar have been reported as the most interesting conditions for the power block operation [16]. For an optimum TES the PCM melting point has to be close to the boiling temperature of the steam, between 310 °C and 342 °C for the pressures here considered. It is important to consider that, for the discharge process, the boiling temperature has to be reduced below the PCM melting point with the correspondent impact on the power block.

The chosen PCM media must present other properties as high energy density and chemical stability. Of course, reduced cost, high conductivity and safety issues such as low corrosion, non-toxicity and non-flammability are properties desired for the optimal storage material. None of the materials tested fulfills completely the list of requirements here exposed. Organic materials are discarded by their low operation temperature. Within the inorganic materials, pure metals and alloys have great conductivity but in general the energy density found does not pay off the high costs of the material. In contrast, inorganic salts have shown a good ratio of energy density and material cost, but they have generally low thermal conductivity, making difficult to design a proper heat transference system.

NaNO_3 presents a suitable melting temperature, reduced cost and great thermal stability with the extra that it is a very well-known and studied salt as heat transfer fluid for the CSP molten

salt tower technology. With the aid of the correct TCE system the material could offer a feasible solution for CSP Industry. For these reasons it will be the storage media employed for this analysis.

1.3. Thermal conductivity enhancement systems

As already seen, further developments are required to successfully implementing the PCM on a commercial storage units. Within the group of inorganic salts the main research efforts have been focused in the development of thermal conductivity enhancement systems (TCE).

One first option to reach this goal is to increase the transfer area between both mediums (storage and heat transfer fluid medium). This possibility has been specifically and deeply analyzed for the design of PCM cascade [17], where the storage unit is composed by different encapsulated PCM materials stages with sequentially increasing melting points. The encapsulation of the PCM can achieve this purpose, allowing a direct contact with the process fluid. However during the process some energy density is lost due to the shell thickness and the requirement of an interior empty space for the volume expansion management. Shell material must be carefully selected [18] to handle the operation conditions, either from the chemical degradation, mechanical stresses and high pressures and temperatures.

A second option is to extend the surface area using fins attached to the process pipe. This solution is commonly employed in the industry as a mechanism for improving the heat transference on heat exchangers; the transient nature of the PCM exchange implies additional challenges to achieve an optimal design. The shape and position of the fin is crucial to achieve good heat transference. Most of the studies are focused on simple geometries, being longitudinal straight fins [19,20,21] and circular fins [22] the most studied geometries. Some studies had shown a better performance from longitudinal fins [23] rather than circular. In the work proposed by Doerte et al. [24] a complex longitudinal fin pattern is suggested for increasing the heat transfer ratio.

A third option to increase the heat transference is to mix the PCM with a high conductivity carrier material. Due to its high thermal conductivity, graphite foams with high porosity have been employed to improve the heat transference of PCM [25,26]. This composite material has to be infiltrated with the PCM to ensure a proper distribution in the foam structure. The infiltration must maximize the amount of filled PCM, ensuring the evacuation of the contained gas.

An alternative proposed methodology was the use particles of expanded natural graphite (ENG) mixed with the PCM to improve the system conductivity [27]. This solution pretends to mix the ENG particles with the PCM in liquid or solid state, ensuring the resultant composite is compact enough to maintain the properties, avoiding PCM leakage in the container element.

Besides the extensive amount of literature material published on different TCE systems for PCM, consistent comparative between these systems are scarce on the literature. The work developed in this paper is intended to partially cover this lack of comprehensive analysis, providing a general comparative between two of the most popular TCE, longitudinal fins and graphite foams, and their improvement over a single PCM system.

1.4. Objectives and scope

The aim of this work is to find the optimal TCE system for a given TES configuration. The scope of the analysis is not only to find which system shown the better performance but to find which specific configuration works better within the cases analyzed. The study will be focused in two TCE systems, longitudinal fins and

graphite foams, over a PCM storage unit composed by NaNO₃. The cases considered different amount of TCE material as well as different quality grades to evaluate the impact of these parameters. The charging time will be employed as the main predictor of the performance of the embodiment, using a non-improved PCM reference case as a baseline. Internal temperature distribution and thermal flow will be presented and discussed in order to better understand the improvement observed on the charging time and locating possible points to further optimization.

This work is structured in five parts: First, the methodology of the study is exposed and the relevant cases defined, detailing the sizing approach to ensure the comparability of the results obtained. Next, the model is described including details of the internal equations and boundaries condition considered. The result of the appliance of this model to the cases previously defined is exposed and discussed in the Result section. All the results here presented are focused on the thermal performance of the embodiments, but some additional consideration must be taken into account when choosing the appropriate TCE system for any specific application. In the Discussion section some of these factors are introduced and general rule recommendations are given. Finally, the conclusions obtained from the analysis of the results here obtained are exposed, highlighting the strengths of the systems and the points to address to improve the technology feasibility.

2. Method

2.1. System description

This work considers a numerical approach to evaluate the performance of a group of TCE solutions. The cases selected are composed by particular configurations of two of the principal TCE systems found on the literature, finned pipes and conductive foams. These solutions will be applied on a system composed by a vertical pipe surrounded by the storage material and the TCE considered. The chosen PCM is NaNO₃, which is a popular material on thermal energy storage applications due the compatibility of its melting points with a wide range of industrial processes, as well as its competitive cost and good storage properties. The internal pipe selected, inside of which the process fluid flows, has a diameter of 63 mm and 3 mm thickness (see Fig. 1). This diameter is the result of the design of a commercial heat exchanger made by Abengoa Engineering, used in the feasibility study of a DSG commercial plant. The most important properties of the materials used are presented in Table 1.

To ensure a fair comparative between all the cases, they have been sized to provide the same thermal capacity and to operate on the same conditions. This sizing procedure is specific for each kind of TCE system, and will be further explained in their subsequent sections, but the general approach is to keep the amount of PCM (A_{PCM}) constant for all the cases. Therefore, on the sizing process, the energy stored in the TCE medium and tube has not be taken into account, as it will be much lower than the energy stored in the PCM itself. The procedure here explained is intended to ensure that the variation on the results can only be caused by the interaction of the PCM with the TCE system, allowing the comparison of the effects of each one.

2.2. Finned pipe

This solution considers longitudinal fins fused to the vertical process pipe. The fin pattern considered is based on prior studies [24], focused on increasing the heat transfer to the storage medium (Fig. 1). Despite other previous works employs simple longitudinal fins [28], it has been pointed that this configuration could

misrepresent the potential of fins as TCE media. Besides being more complex than other options, it has been proven that this specific fin pattern is more efficient in the transmission of heat than simple fin configurations. Therefore, the chosen option is considered more interesting for comparing against other TCE systems.

Aluminum and carbon steel are chosen as fin materials, the former for its high conductivity properties as an optimal solution from the thermal points of view, the latter for its widespread application as heat exchanger material and as desirable option from the cost perspective. It is easy to forecast that aluminum will have better performance than steel, but the inclusion of the latter is useful for two purposes: first, it allows to estimate the behavior of steel fins, which can be itself useful for applications with mid heat transfer requirements, and second, it provides a result with low conductivity to determine the influence of such parameter on the fin pattern design.

In order to fully explore the capabilities of the fins, the fraction of the TCE material has been included as a case parameter, varying from 5% to 20% of the total volume of the system. The range chosen for these fins will provide information for the proper TCE amount for realistic application having a maximum limit to avoid excessive penalty on the energy density of the PCM. The minimum limit has been set to the smallest amount of TCE that is expected to obtain a noticeable improvement on the thermal performance.

With this, the effect of the amount of TCE can be analyzed in two conductivity scenarios, providing useful information about the effect of this factor on the total heat transference.

For ensuring a comparable thermal capacity on all systems the geometries must be adapted on each case. The methodology followed for adapting the geometry is focused in find a specific and constant PCM area (A_{PCM}) and keeping the pattern shape of the fins. The parameters used for this adaptation are shown in the Fig. 1.

First, the PCM diameter (D_{PCM}) is set to the correspondent to the reference amount of PCM plus the area occupied by the fins (A_{fins}) on each case, according to Equation (2). The area occupied by the fins is obtained using the fraction of TCE characteristic of the case (f).

$$A_{fin} = \frac{f}{1+f} A_{PCM} \quad (1)$$

$$A_{tot} = A_{PCM} + A_{fin} = \frac{\pi}{4} (D_{PCM}^2 - D_{pipe}^2) \quad (2)$$

Second, the fins are stretched to maintain the separation between the end of each fin and the outer surface (d). Lastly, fin thickness is modified to match the required fin area. This last step is made numerically, using the geometry model of the heat exchanger. The thickness of the fins is recursively modified until the required area is achieved. A limit of 0.1 mm of precision in this thickness is considered, as a higher precision have little sense from a manufacturing point of view.

Notice that in this process both the pipe diameter (D_{pipe}) and the pipe thickness are kept constant.

2.3. Conductive foam

This solution involves a composite material with a complex structure of storage medium regions surrounded by a conductivity matrix. This matrix can be made of different materials, typically carbon, graphite or metals. For the present work graphite foams are chosen as the most promising material for this solution, being able to reach the highest conductivities.

The mean size of the PCM regions on the composite is, in general, too small to be simulated individually on a macro scale

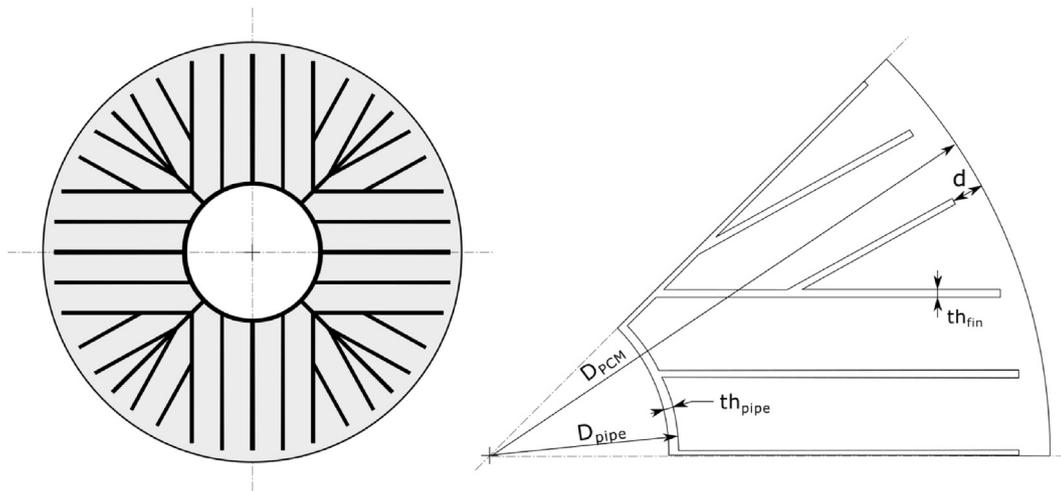


Fig. 1. Fin configuration scheme [24].

Table 1
Material properties^a.

	NaNO ₃	Aluminum	Carbon steel
Density [kg/m ³]:	2100	2719	7800
C _p [kJ/kg K]:	1.8	0.87	0.5
Latent heat [kJ/kg]:	177	—	—
Melting point [°C]	307	—	—
Thermal conductivity [W/m·K]	0.5	202.5	40

^a Values obtained from Abengoa internal studies.

application. The approach followed in this study is to treat the composite as a homogeneous material with equivalent properties.

The main concern on the homogeneous model is to ensure that both materials behave in a similar manner; this is, having similar temperature distributions. If the pore size is excessively big or the temperature difference too intense these two materials temperature map can be different enough to invalidate the homogeneous model, and each of this regions should be modeled independently.

The characteristic length of the pore for the foams considered ensures a high transfer area for small regions. This, joined to the small temperature variation found in the cases analyzed, are points to indicate that small offset between the phases is to be expected and therefore the model of homogeneous phase is considered representative to the real conditions.

For a correct characterization it is crucial to know the properties of the composite constituent materials. Although the chosen PCM material is well known in bibliography, there is lot of foam typologies with properties that greatly differ from each other. In order to limit the present study to a reasonable extension only three representative commercial foams have been selected, the properties of these foams are shown in Table 2. The foams selected are among the highest thermal conductivity foams found on the market, with the additional advantage of offering detailed information of three quality grades of products. This suits perfectly with the purpose of this work of making a sensibility analysis of the TCE media performance.

The weighted properties of the composite are given by the amount of PCM and TCE found in a representative volume of this compose. The PCM fills the available gaps between the matrix, defined by the porosity of the foam. It must be taken into account that the volume available for the PCM may not be correspondent with the total porosity of the foam, as some of the pores may be totally enclosed by the matrix. This factor is considered by the open

porosity fraction, which determines the amount of pores that are accessible from the exterior. Another point to consider is the rate of infiltration obtained on the composite. Despite that in general it is not possible to fill the whole available space, the infiltration procedures can achieve a very high infiltration rate [29,30]. Thus, on the present study it has been considered that the open volume is completely filled with PCM.

The fraction of PCM accommodated inside the matrix, the density and latent heat can be calculated as weighted combination of the two constituent materials.

The effective thermal conductivity is more complex to determine analytically. In the literature several approaches to get this value can be found [32,33]. The first approaches on the calculation of effective thermal conductivity employ the fraction of each component as the main predictor of the composite behavior. Further, the shape of the porous and their distribution is added to the models to have more accurate predictions. Recently, the analysis of these foams using finite element method (FEM) is frequently employed to model the effective conductivity. This approach has to be limited to analyses small samples because of the high computational cost associated with these models.

Naturally the degree of information of the foam required increases with the precision of the model to apply. This makes difficult to apply this approach to commercial foams where generally the amount of information available is limited to the direct application data. In the case of the graphite foams additional considerations must be taken into account as the foam's material itself present a structure dependence on its conductivity. The arrangement of the layers has an important effect on the thermal conductivity of the graphite.

Because all of this, for the present work, it has been considered more reliable to trust on the supplier data, obtained experimentally on empty samples using laser flash techniques. Although a variation of the thermal conductivity on samples infiltrated with salt may be expected, Abengoa internal tests in collaboration with the laboratory Institut de Mécanique et d'Ingénierie de Bordeaux (I2M) expose that the variation between these two factors are negligible for the cases here considered. This result is aligned with the conclusion obtained from other works [26].

The data employed for the calculation have been obtained from KFOAM[®] catalogue, according with three different grades. The resultant properties are shown in Table 3. It is interesting to notice the important reduction on the latent heat of the composites due to the important influence of the porosity. This is translated

straightforward to the energy density, penalizing it in a severe way.

The dimension of each case is obtained by keeping the amount of PCM and accommodating it on the available space in the foam. The total area is obtained by dividing the amount of PCM by the fraction of access porosity (ϵ).

$$A_t = \frac{A_{pcm}}{\epsilon} = \frac{\pi}{4} (D_{PCM}^2 - D_{pipe}^2) \quad (3)$$

3. Model

The model to evaluate the melting process has been developed under ANSYS® Fluent 14.5, making use of the melting and solidification option [34].

Internally Fluent solves the energy equation associated with the material on each cell of the domain.

$$\frac{\partial}{\partial t}(\rho H) = \nabla \cdot (k \nabla T) \quad (4)$$

The left side of the equation represents the internal energy variation on the cell. The right side of the equation represents the heat transferred to or by the cell's neighbors. As it can be observed no convection term appears on this energy equation. Due to the vertical arrangement of the embodiment, and the uniform characteristics of the boundary conditions no variation are expected in the axis directions, which allows a 2D modeling of the problem. This also means that no driving force is acting on the molten PCM and therefore no motion is expected.

The internal energy H is obtained by integrating the contribution of the c_p at each temperature, adding in the case of a PCM material the latent heat associated with the phase transition (L). This latent energy is released proportionally to the amount of material changing state, which is obtained by the liquid fraction parameter (β).

$$H = \begin{cases} h & \text{if mat} = \text{solid} \\ h + \Delta H & \text{if mat} = \text{PCM} \end{cases} \quad (5)$$

$$h = h_{ref} + \int_{T_{ref}}^T c_p dT \quad (6)$$

$$\Delta H = \beta L \quad (7)$$

$$\beta = \begin{cases} 0 & \text{if } T < T_{solidus} \\ 1 & \text{if } T > T_{liquidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & \text{if } T_{solidus} < T < T_{liquidus} \end{cases} \quad (8)$$

For this approach, as the PCM studied is a pure substance, a congruent melting point is considered. This means that $T_{solidus}$ is equal to $T_{liquidus}$. Representing that, on every cell, the liquid fraction

could be either 1 or 0 but cannot acquire any value between those.

The mesh considered in the model corresponds to a 2D representation of a section. In the case of finned pipes additional symmetry considerations allows reducing the mesh to a 45° of the total section, decreasing therefore the computational resources required for the simulation. On foam and pure PCM cases the size of the mesh can be reduced even further due to the homogeneity of the storage material. In these cases a slice of only 5° of the 2D section can be considered without misrepresenting the results.

The charge process is modeled considering a uniform initial temperature of 300 °C. The heat transfer is modeled by an imposed temperature on the inner surface of the pipe of 320 °C, corresponding to 112 bar of steam pressure. Imposed temperatures are appropriate approximation when a strong convection factor is expected inside the pipe, such as the phase change of steam. As the main interest of this paper is the behavior of the TCE, thermal losses are beyond the scope of this work, therefore a perfectly insulation condition has been applied to the outer surface of the PCM. This condition may be representative as well of central pipes of a well-designed heat exchanger.

The liquid fraction of the system is the main factor to follow as an indicator of the state of charge of the storage. Despite the sensible heat has been considered on the model, as the amount of energy stored in this form is small compared with the latent heat, the charge process is considered ended when the whole system is liquid, ignoring the contribution of further overheating.

Aside of the liquid fraction, the temperature has been measured in significant points. This allows following up the melting front and a better understanding of the heat distribution. The location of these points is shown in Fig. 2, as well as their exact position in mm. For homogeneous cases the temperature points have been positioned on radial equivalent distances so the results can be comparable.

4. Results

4.1. Charge time and energy density

From the charge results presented on Table 4, the massive improvement offered by the TCE systems is clear. Aside from the differences between systems, even the worst case is able to reduce the charge time to a third of the single PCM case.

Analyzing the differences among the groups it can be seen how, as predicted, the ones with aluminum fins behave better than carbon steel ones. In both cases, the charge time is reduced over time as long as the amount of TCE material increases, although not linearly, but shows a saturation tendency with the increment of fin fraction. Despite the very big charge time reduction on 5% and 10% cases, the improvement with 15% and 20% is limited. This may be explained by the sizing approach followed in this study, indicating that the branches of the fins are close to carry all the heat available on their surroundings and opening a new branch may be more profitable than thickening an already existing one. Further analysis should be performed on the subject of fin pattern optimization but, at sight of the present results, a thickness optimum can be found for a given fin pattern, providing the most advantages of the added TCE material.

Foams have the best thermal performance of all the systems evaluated, reducing the charging time to less than an hour. A clear link between the matrix conductivity and charge time can be deduced, but a slight saturation tendency is observed as well. Quantifying the contribution of the thermal conductivity on this saturation effect is not straight forward due to the fact of the accessible porosity. Although the value of the latter parameter is similar on all the cases considered, the range of variation is

Table 2
Graphite foam properties [31].

Property	KFOAM® Grade L1	KFOAM® Grade L1A	KFOAM® Grade D1
Bulk density [kg/m ³]:	490	390	460
Total porosity [%]	70	78	72
Open porosity [%]	77.5	77.5	77.5
Accessible Porosity [%]	54.25	60.45	55.8

Table 3
Composite effective properties.

Property	NaNO ₃ + KFOAM [®] Grade L1	NaNO ₃ + KFOAM [®] Grade L1A	NaNO ₃ + KFOAM [®] Grade D1
Density [kg/m ³]:	1629	1659	1631
Effective latent heat of the composite [kJ/kg]:	123.77	135.40	127.10
Thermal conductivity [W/m ² K]:	57.9	27.9	100

sufficient to have a notable impact on critical factors such as the latent heat of the mixture. Therefore it cannot be deduced that the saturation effect observed on the time is solely because of the effect of the thermal conductivity and further research is necessary to quantify the effect of each of those parameters. Unfortunately, the amount of data of commercial foams is scarce and the determination of the influence of each parameter on theoretical materials is out of the scope of the present work.

Concerning the energy density, fins have the lowest impact on the compactness of the solution keeping one of the main advantages of PCM storage systems. The foams on the other side are the systems which penalize this factor the most, with a required volume around 80% higher than the reference case. The penalization on energy density may be reduced with higher open porosity ratios. Current efforts on this technology are focused on achieve this goal, allowing an increase on the overall system compactness.

The capacity of each case has been included in the Table 4. This capacity has been obtained with the difference in the internal energy of the system between the initial and the final state. As the model considered is a 2D section the units of this capacity is expressed in linear terms of kJ/m. The comparison between the values obtained shown that, although the results are similar, there are differences in the capacity of these systems. The main cause of

these differences is the sensible energy stored, both in PCM superheating and in the TCE medium. Another point to consider is the specification given in the model to consider the system fully charged. As the data exposed in Table 4 is referred to the exact instant where the entire PCM medium reaches liquid state, the temperature profile will be, in general, different on each case, altering the amount of sensible heat stored.

The comparative among these systems may seem unfair, as there is much more amount of TCE material on foam cases than it is on the fin ones. As it has been discussed, for a given fin pattern there is an amount of material which optimizes the TCE material usage. Increasing the material further from this point will lead to marginal improvements. According to this, analyzing cases with higher fin proportion was discarded, such as the required for equalizing the TCE material to the foam cases, as the considered design will made a poor use of the additional material. For such cases, an optimized fin pattern should be employed, specially designed to maximize the use of the carrier material. Although the detailed design of this specific optimal fin pattern is beyond of the scope of this work, it is expected that the results here exposed may be useful for further developments on this line.

4.2. Temperature distribution

Temperature distribution is a useful indicator of the proper heat exchange in the storage material, as well as the general behavior of the melting front. In contrast to the liquid fraction, this parameter can be easily monitored on test facilities using thermocouples embedded on the storage material. This allows collecting information on experimental facilities to cross-check the models. Despite that the present work has no experimental part, the interpretation of these results may be useful for further works in which laboratory tests are involved.

For the single PCM case, the expected curves of temperature increment can be observed in Fig. 3. On the first instants of

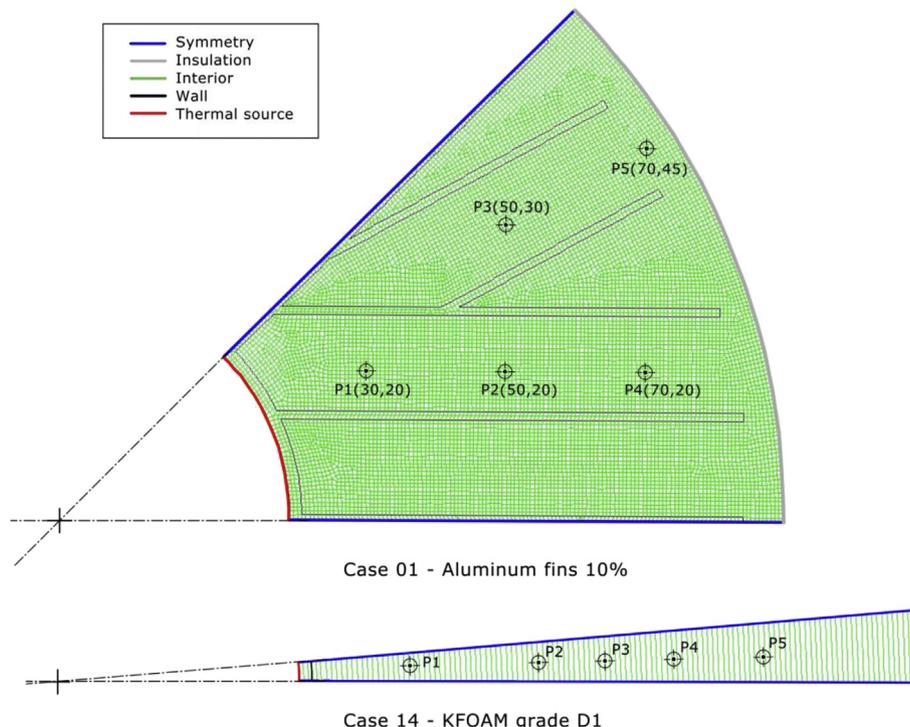


Fig. 2. Mesh detail and temperature measure point location for fin and homogeneous models (coordinates in mm from the center of the pipe).

Table 4
Time results and diameters of the cases simulated.

Case	PCM [%]	TCE [%]	Charge time [h]	Linear capacity [kJ/m]	PCM diameter [mm]	Averaged power [W/m]
Single PCM:	100.0	0	36.0	7770.9	171.8	60.0
Steel Fins 5%	95.0	5	11.8	7925.4	175.8	186.6
Steel Fins 10%	90.0	10	6.9	7915.8	180.1	318.2
Steel Fins 15%	85.0	15	5.3	7934.6	184.4	419.8
Steel Fins 20%	80.0	20	4.4	7926.8	190.0	503.9
Aluminum Fins 5%	95.0	5	3.9	7821.0	175.8	559.9
Aluminum Fins 10%	90.0	10	2.3	7669.3	180.1	968.4
Aluminum Fins 15%	85.0	15	1.8	7594.6	184.4	1172.0
Aluminum Fins 20%	80.0	20	1.6	7457.8	190.0	1311.2
KFOAM [®] L1	54.2	30	0.5	7574.3	227.3	4208.0
KFOAM [®] L1A	60.4	22	0.9	7747.6	216.1	2339.2
KFOAM [®] D1	55.8	28	0.3	7556.8	224.3	6771.4

operation, the temperature of all the measurement thermocouple points increases evenly until the melting temperature. Once this temperature is reached, the temperature of the points is locked until the melting front reaches the measured region. The molten zone continues increasing its temperature, presenting a temperature gradient from the pipe to the melting front. A drastic change on the behavior is observed when the storage media is totally melted. At this point the temperature increases rapidly in all the model's temperature points until thermal equilibrium is achieved at 320 °C. This effect is produced for the release of the constraint imposed by the last solid layer, which forced the maximum temperature on this point to be equal to the melting temperature. Once this restriction is surpassed, the temperature profile evolves as expected for a purely sensible storage material.

The same tendencies are observed on the foams with the major difference of the total melting time. This could be predicted with the homogeneous hypothesis made on this material, as the transference mechanisms are exactly the same, changing only the properties of the storage material. The order of the probe "activation" is equal in pure PCM and foam cases, but it can be observed how the instant in which the probes are activated differs. On the pure PCM case the activation of the probes is uniformly distributed along the time, finishing the melting process short before P5 starts overheating. For the foam case, a higher proportion of the time is elapsed between the melt of the point P5 and the total charge of the system. The explanation of this effect is related on the heat flux distribution along the time, having higher differences on the foam than on the pure PCM. This may be seem contra-intuitive as one of the targets of the TCE is to increase the heat flux uniformity but it is important to be aware that the time reduction between these two cases is very big, and the difference on heat transfer are referenced to different scales. This section will be further discussed in Section 4.3.

On the fins the temperature distribution is significantly different than the other two cases. Besides the plateau at the melting temperature is still present, here the order of the melting points is distorted and the overheating is much less regular than the other cases. This can be observed on both aluminum and steel fins. The fins allow a better distribution of the heat spreading the heat source over a wider area, extending the surface covered by the melting front and reaching farther regions earlier.

For illustrative purposes, the temperature and liquid fraction profiles have been represented for the case of aluminum fins 10%, although the same conclusion can be extracted from any of the other fin configurations. On Fig. 4 these profiles are presented at four instants of the process. After 0.5 h, the temperature of the whole storage material has already reached the melting point plateau. The liquid fraction is starting to grow, following the fin pattern. It may be interesting to notice that, as expected, the liquid

region around the fins is thicker close to primary fins (those which are connected directly with the pipe) than those close to secondary fins (those connected to the pipe trough another fin). This effect may be corrected by thickening the connection on these secondary fins and, therefore, allowing better heat evacuation.

Also in Fig. 4, the relation between the temperature distribution and the melting front can be analyzed. A temperature increase over the melting point is shown on the liquid region, being more pronounced on those parts closer to the pipe. A clear preference to overheating horizontal and vertical regions can be observed, being the diagonal regions cooler than the others. This can explain why the melting and overheating curves observed in Fig. 3 are different for fins than for homogenous cases. Again the effect of the secondary fins may be the cause of this effect, suggesting that an improvement on the present design will be incrementing the effective thermal conductivity on this direction. In the final instants some solid patches are still present, surrounding tertiary fins. The result is coherent with the loss of thermal improvement the farther the connection is. The performance of the system on this point is much worse than any of the prior instants, due to a very poor heat transference mechanism for small increments on the capacity.

4.3. Thermal flow distribution

One point to consider when using latent based storage systems is the variation of the net heat exchanged along time (Fig. 5). The energy is transmitted earlier to the closest points, giving a better response on the initial stages that will be fading away as long the energy of farther region is required. This may imply a difficulty on the control and applicability of this solution on many applications. Related to this point, the effect of the different TCE considered on the dispatch ability of the heat is presented and discussed here.

On the single PCM case the heat flux drops very rapidly on the first instants, leading to a very low heat transfer compared to the initial peak. During almost the entire melting process the heat flux is nearly constant, although very low, due to the strong importance of the thermal resistance of the PCM. Once this resistance has acquired a high value, its variations have minimal impact on the overall heat transfer, which is really poor once reached this point, due to the asymptotic behavior of the thermal flux with the resistance. The studied cases with lowest and highest fin fraction have been included for each of the materials considered. From low to high enhancement, the steel solution with 5%, with a similar behavior to the single PCM but with less difference between the heat flux peak and the average behavior and with a slight drop on the very end of the process, is found. As the performance of the fin increases (rather by increasing the amount of TCE material, rather by using a more conductive one) the heat flux on the mid-time tends to increase, dropping smoothly on a linear fashion until the

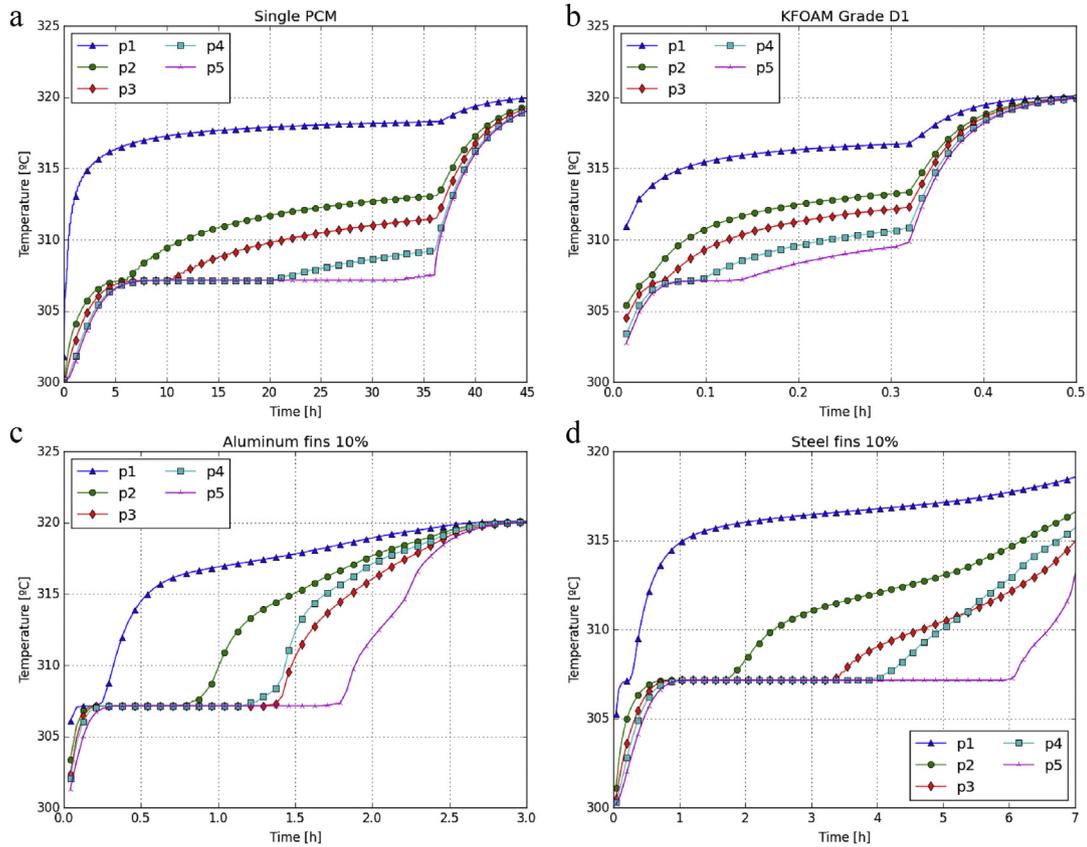


Fig. 3. Temperature distribution along the time for: (a) pure PCM, (b) KFOAM[®] grade D1, (c) Aluminum fins 10%, and (d) steel fins 10%. P1 to P5 are the thermocouples defined in Fig. 2.

normalized heat is approximately equal to the single PCM case. The results show an improvement on the heat transfer higher on the regions close to the pipe than on the farther ones, increasing the heat flow difference among the initial and final instants. This may be interpreted using the temperature and liquid fraction patterns shown in Fig. 4. On the last instants, the remaining solid patches are far from the efficient transmission region of the fins, leading to a worse heat transfer and, therefore, dropping dramatically the heat

flux. The improvement of the fin performance has little impact on melting these patches, explaining why the normalized differences increase with the fin performance. Probably this effect can be palliated with careful modifications on the fin pattern to increase the heat flux on the most disadvantageous points.

The foams have a normalized heat flux shape similar to the single PCM, but with a minimum heat flux of 20–40% of the maximum, depending the case. These are the best scenarios for

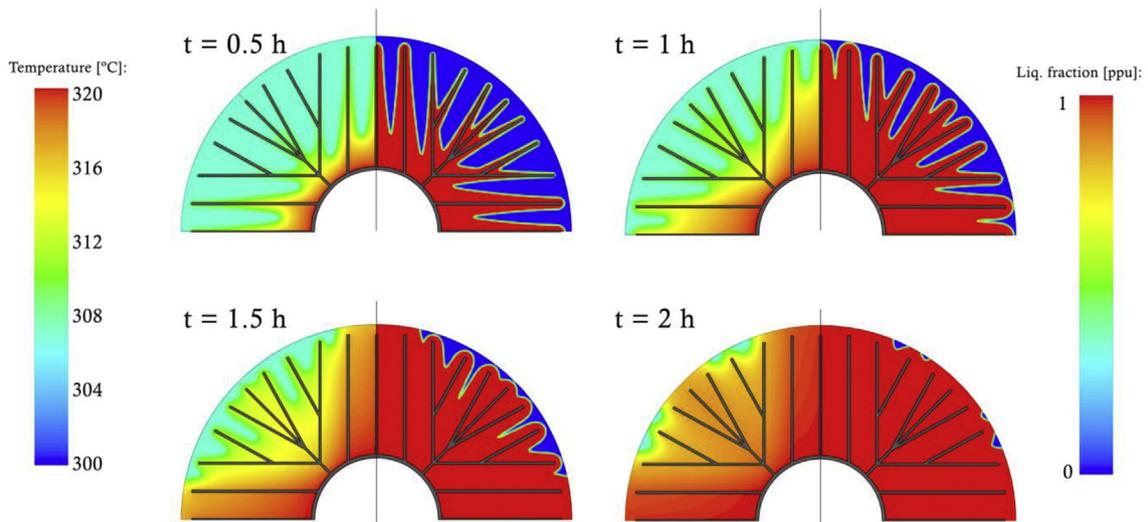


Fig. 4. Liquid fraction and temperature profiles for 10% aluminum case at $t = 0.5, 1, 1.5$ and 2 h

operating on a uniform condition but there is still a big difference on the heat flux along the time. The difference between the maximum and minimum heat flux seems to be linked with the conductivity of the matrix, so an even higher conductivity or less storage capacity per pipe may improve the behavior of the system in this sense.

The big variations occurring on the heat flux makes necessary to have extra consideration when operating the device, even using TCE systems, making necessary to adjust the operating condition for keeping constant the quantity or quality of the HTF involved.

5. Discussion

Besides the importance of the thermal behavior on the selection of the proper TCE system there are other important factors that are critical in the final decision. The cost of the system is one of the most crucial points in the successful of a TES. This includes not only the materials of the PCM and TCE respectively, but also de installation and maintenance cost. This point, although interesting, requires and extensive work and multiple hypothesis that exceed the scope of the present work. However there are some considerations that are interesting to keep in mind related to this topic that will be discussed in this point.

The fin solution had shown a significant improvement over the single PCM case, with a much lower impact on the energy density. The constituent material, installation and the more compact solution make this medium desirable from the cost perspective. From the heat distribution point, the results here exposed shown a possibility of improve the heat distribution with an optimized fin pattern. However, concerning further optimization, it is important to have in mind the limitation that fin manufacturing process can present. The complexity required to reach the optimum configuration may be limited for this factor.

Other point to address before selecting a TCE system is the compatibility of the materials involved. For a long term TES factors

such as corrosion have to be taken into consideration. Aside from ensuring the lifespan of the system, loosing of TCE material or acquiring an additional thermal resistance due to oxidation have obvious and undesirable impact on the performance of the TCE.

On the foam solution, the infiltration process may become an important cost of the total system, which may, added to the decrease in energy density, penalize the total competitiveness of the TCE system. Another point that has to be carefully studied is the contact between foam and the process pipe, trying to ensure the maximum contact without cracking the foam due to excessive dilatation of the pipe.

6. Conclusions

Different PCM heat transfer systems with and without TCE media have been simulated and their results presented and discussed. The effect of the TCE on the charge time and the energy distribution has been used as parameter to comprehend the particularities of each technology. Finally the heat flux of these systems is analyzed to evaluate the effect of these improvements on the stabilization on the absorption and release of energy.

Fins have shown to have a significant reduction on the charge time of the system, being more efficient the aluminum cases than steel ones. This kind of TCE has shown little impact on the compactness of the solution, keeping the high energy density proper of the latent storage systems. Incrementing the TCE amount is not a trivial task for this configuration, as for a given pattern the improvement of adding material becomes marginal rapidly. The pattern employed on this work, although presenting a considerable thermal improvement over the single PCM case, have shown signals of further improvement, mainly the selective thickening of some branches of the pattern and possibly geometry variations of the branches. These modifications should be focused on achieve better heat distribution which may lead to a more uniform heat flux on the system.

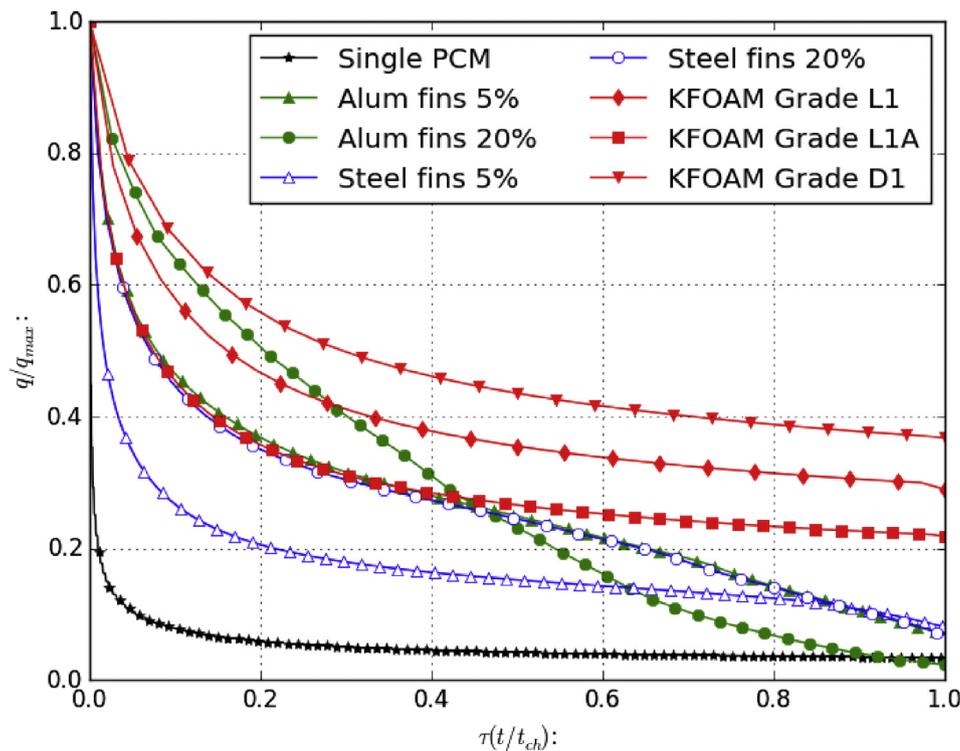


Fig. 5. Heat flux distribution with the time.

Foams have shown the best performance among the analyzed cases, both on charge time reduction and on heat flux uniformity. The only negative aspect of this solution is the decrement on energy density of the solution, being necessary a considerable increment on the size of the system. The last aspect may be improved with the development of foams with higher open porosity, allowing more PCM to fill the gaps on the foam and therefore achieve a more compact composite material.

None of the configurations studied on the scope of this work have shown capabilities to work on a quasi-steady regime with the HTF, having an important reduction of the heat flux with the time. This effect leads to a more complex control and loss of power on the final instants of operation which are both undesirable drawbacks. To overcome these points a much higher thermal conductivity in the storage material and/or composite is required, which seems difficult to achieve at sight of the high specifications of the materials already considered.

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References

- [1] EU Plan for a Competitive Low-carbon Economy by 2050, 2011.
- [2] Medium-term Renewable Market Report, International Renewable Energy Agency, 2015.
- [3] FAOSTAT: Emissions – Land Use, FAO (Food and Agriculture Organization), 2014 [En línea]. Available: http://faostat3.fao.org/fausat-gateway/go/to/download/G2/*E. [Último acceso: 2016 January].
- [4] Climate Analysis Indicators Tool (CAIS) 2.0: WRI's Climate Data Explorer, WRI (World Resource Institute), 2014 [En línea]. Available: <http://cait.wri.org> [Último acceso: January 2016].
- [5] J.S. Wagner, S.R. Edward, Economic implications of thermal energy storage for concentrated solar thermal power, *Renew. Energy* 61 (2014) 81–95.
- [6] D. Laing, C. Bahl, T. Bauer, D. Lehmann, W.-D. Steinmann, Thermal energy storage for direct steam generation, *Sol. Energy* 85 (2011) 627–633.
- [7] J. Birbnbaum, M. Eck, M. Fichtner, T. Hirsch, D. Lehmann, A direct steam generation solar power plant with integrated thermal storage, *J. Sol. Energy Eng.* 132 (2010).
- [8] M. Steiz, P. Cetin, M. Eck, Thermal storage concept for solar thermal power plants with direct steam generation, *Procedia* 49 (2014) 993–1002.
- [9] S. Kuravi, T. Jamie, D. Yogi Goswami, M.M. Rahman, E.K. Stefanakos, Thermal energy storage technologies and systems for concentrating solar power plants, *Prog. Energy Combust. Sci.* 39 (2013) 285–319.
- [10] T. Pirasaci, D.Y. Goswami, Influence of design on performance of a latent heat storage system for a direct steam generation power plant, *Appl. Energy* 162 (2016) 644–652.
- [11] R. Yogev, A. Kribus, Operation strategies and performance of solar thermal power plants operating from PCM storage, *Sol. Energy* (2013) 170–180.
- [12] M.M. Kenisarin, High-temperature phase-change materials for thermal energy storage, *Renew. Sustain. Energy Rev.* 14 (2010) 955–970.
- [13] M. Liu, W. Saman, F. Bruno, Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems, *Renew. Sustain. Energy Rev.* 16 (2012) 2118–2132.
- [14] C. Bruno, N. León, High temperature latent heat thermal energy storage: phase change materials, design considerations and performance enhancement techniques, *Renew. Sustain. Energy Rev.* (2013) 724–737.
- [15] K. Pielichowska, K. Pielichowski, Phase change materials for thermal energy storage, *Prog. Mater. Sci.* 65 (2014) 67–123.
- [16] T. Hirisch, A. Khenissi, A systematic comparison on power block efficiencies for CSP plants with direct steam generation, *Energy Procedia* 49 (2014) 1165–1176.
- [17] H. Michaels, R. Pitz-Paal, Cascade latent heat storage for parabolic trough solar power plants, *Sol. Energy* 81 (2006) 829–837.
- [18] R. Jacob, F. Bruno, Review on shell materials used in the encapsulation of phase change materials for high temperature thermal energy storage, *Renew. Sustain. Energy Rev.* 48 (2015) 79–87.
- [19] K. Ismail, C. Alves, M. Modesto, Numerical and experimental study on the solidification of PCM around a vertical axially finned isothermal cylinder, *Appl. Therm. Eng.* 21 (2001) 53–77.
- [20] Z. Li, Z.-G. Wu, Analysis of HTFs, PCMs and fins effects on the thermal performance of shell–tube thermal energy storage units, *Sol. Energy* 122 (2015) 382–392.
- [21] P. Wang, H. Yao, Z. Lan, P. Zhijian, Y. Huang, Y. Ding, Numerical investigation of PCM melting process in sleeve tube with internal fins, *Energy Convers. Manag.* 110 (2016) 428–435.
- [22] N. Tay, F. Bruno, M. Belusko, Comparison of pinned and finned tubes in a phase change thermal energy storage system using CFD, *Appl. Energy* (2013) 104.
- [23] F. Agyenim, P. Eames, M. Smyth, A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins, *Sol. Energy* 83 (2009) 1509–1520.
- [24] D. Laing, T. Bauer, N. Breidenbach, B. Hachmann, M. Johnson, Development of high temperature phase-change-material storages, *Appl. Energy* 109 (2013) 497–504.
- [25] K. Lafdi, O. Mesalhy, A. Elgafy, Graphite foams infiltrated with phase change materials as alternative materials for space and terrestrial therm energy storage applications, *Carbon*, 46 (2008) 159–168.
- [26] X. Py, R. Olvies, S. Mauran, Parafin/porous-graphite-matrix composite as a high and constant power thermal storage material, *Int. J. Heat Mass Transf.* 44 (2001) 2727–2737.
- [27] S. Pincemin, R. Olives, X. Py, M. Christ, Highly conductive composites made of phase change materials and graphite for thermal storage, *Sol. Energy Mater. Sol. Cells* 92 (2008) 603–613.
- [28] M.K. Rathod, J. Banerjee, Thermal performance enhancement of shell and tube Latent Heat, *Appl. Therm. Eng.* 75 (2015) 1084–1092.
- [29] A. J. Cook, Method of vacuum casting. *Unite States Patente* 5111871, 12 May 1992.
- [30] J. A. Cornie, S. S. Cornie, R. P. Mason y M. A. Ryals, Methods and apparatus for high throughput pressure infiltration castin. *Unite States Patente* US6360809, 26 March 2002.
- [31] KFOAM, <http://www.koppers.com/pages/kfoam>, [En línea].
- [32] K. Pietrak, T.S. Wisniewski, A review of models for effective thermal conductivity of composite materials, *J. Power Technol.* 95 (2015) 14–24.
- [33] G. Laschet, J. Suerhering, O. Reutter, T. Fend, J. Scheele, Effective permeability and thermal conductivity of open-cell metallic foams via homogenization on a microstructure model, *Comput. Mater. Sci.* 45 (2009) 597–603.
- [34] Chapter 18: Solidification and melting, de ANSYS Fluent Theory Guide.
- [35] A. Gil, M. Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Zalba, L.F. Cabeza, State of the art on high temperature thermal energy storage for power generation. Part 1- Concept- materials and modellization, *Renew. Sustain. Energy Rev.* 14 (2010) 31–55.