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Design of PCM Thermal Storage Unit for a HVAC system

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Summary

Nomenclature

A	surface	m^2
$\overline{C}$	Specific heat	$J \cdot kg^{-1} \cdot K^{-1}$
D	Diameter	m
E	Thermal energy	kWh
f	Factor in Nusselt correlation	
Δh	Enthalpy	$kJ \cdot kg^{-1}$
h	Convective heat transfer coefficient	$W \cdot m^{-2} \cdot K^{-1}$
H	Height of the tanks	m
k	Thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
L	Width of the tanks	m
Long	Longitude of the tanks	m
M	Mass	Kg
$\dot{m}$	Mass flow rate	$Kg \cdot s^{-1}$
n	Number of tubes	
Nu	Nusselt number	
Pr	Prandtl number	
$\dot{Q}$	Power of heat generation	W
R	Thermal resistance	$m^2 \cdot K \cdot W^{-1}$
Re	Reynolds number	
t	Storage time	h
ΔT	Temperature difference	ºC
T	temperature	ºC
U	Overall heat transfer coefficient	$W \cdot m^{-2} \cdot K^{-1}$
v	velocity	$m \cdot s^{-1}$
V	Volume	m^3

Symbols

ρ	Density	$kg \cdot m^{-3}$
π	Pi number	
μ	Kinematic viscosity	$m^2 \cdot s^{-1}$

Subscripts

ext	Outer
ext,un	Unitary outer
FlatICE	FlatICE container
FlatICE,tank	Tank with FlatICE macroencapsulation
FlatICE,height	FlatICE containers on height
FlatICE,long	FlatICE containers on longitude
FlatICE,row	FlatICE containers per row
h	hydraulic
HTF	Heat transfer fluid
HTF,in	Inlet heat transfer fluid
HTF,out	Outlet heat transfer fluid
HTF,tube	Heat transfer fluid in unitary tube
inf	influence
int	Inner
int,un	Unitary inner
lm	log mean
PCM	Phase change material
tank	Tank
total,FlatICE,tank	Total of FlatICE tank
tube,un	Unitary tube
tubes	Tubes
tubes,row	Tubes per row
virtual,tube	Unitary virtual tube
virtual,tubes	Virtual tubes
wall	Tube wall

1. Introduction

In the present project, PCM is included in HVAC solutions, specifically in a heat pump system coupled with an Air Handling Unit (AHU). Therefore, the design of the PCM storage must be addressed. The tanks should optimize the performance and enhance the energy efficiency of the HVAC system, using the PCM to store the energy and use it for heating and cooling applications.

Two different climate conditions were considered to apply this system. For heating applications Estonian winter conditions were assumed, which means very low outside temperature, about -20 ºC. On the other hand, Spanish summer conditions were taken into account for heating mode; this is about 38 ºC.

A simulation with Engineering Equation Solver (EES) software was developed in order to design and predict the behaviour of the tanks. This simulation describes the heat transfer between PCM and heat transfer fluid in charging and discharging modes.

Finally, the results of this project will be validated with the construction of two pilot plants, one in Estonia and the other in Spain.

2. Brief survey on related work

Nowadays Phase Change Materials (PCM) are under constant review to improve their thermal properties, TES (Thermal Energy Storage) application, and encapsulation technology. The necessity to encapsulate PCM arises in two main reasons such as to hold the liquid phase of the PCM, and to avoid contact of the PCM with the environment, which might harm the environment and change the composition of the PCM. Furthermore, the surface of the encapsulation acts as heat transfer surface. In some cases, the encapsulation also serves as a construction element, which means it adds mechanical stability.

Encapsulation materials used should fulfill some properties. First, the materials of the container wall must be compatible with the PCM. Then, taking into account the selected wall material, the container wall has to be sufficiently thick to assure the necessary diffusion tightness. Finally, the encapsulation must be designed in a way that is able to cope with the mechanical stress on the container walls caused by the volume change of the PCM [1].

Currently PCM macroencapsulation market offers a wide range of products that allows PCM materials obtain a commercial level. Companies like PCM Products, Rubitherm

Technologies GmbH, Climator, Dörken GmbH or PCP have found different ways to encapsulate their PCM like balls, tubes, plates, panels, etc.

These PCM have some interesting applications in building construction, heat/cold storage, HVAC (Heating, Ventilating, and Air Conditioning) and transport where they are used for example in thermal energy storage, radiant heating/cold floor or building walls [2].

A good design of latent heat thermal energy storage requires the knowledge of PCM and the heat exchange processes, especially the melting and solidification processes in a containment [3].

In order to ensure a good heat exchange between the surrounding heat transfer medium (water or a mixture of water and glycol in most of the cases) and the PCM, PCM containers should have a high ratio between surface area and volume, i.e. a high heat transfer area per volume unit. This implies that the PCM containers should in principle be as small as possible, which is of course a matter of cost. The advantages of this kind of integration are the possibility of a relatively simple integration of PCM into an existing storage tank and the possibility to use PCM with different melting points in one tank [4].

The heat exchanger to be used in a thermal energy storage system has to be designed specifically, in view of the low thermal diffusivity of PCM in general. The volume changes of the PCM during phase change also require special volume design of the containers of the whole PCM. It should be able to absorb these volume changes and should also be compatible with the PCM used.

In PCM thermal energy storage a chilled glycol or other antifreeze solution circulates through the tank and around the PCM containers at a low velocity. During the charge mode, the temperature of the heat transfer fluid is lower than the freezing temperature of the PCM, causing crystallisation of the encapsulated PCM. To discharge the cooling from storage, the warm fluid carrying energy from the load absorbs the energy of the PCM containers, thus melting the PCM [5].

3. Methodology

3.1. Description of the system

The aim of this project is the design of thermal storage tanks using PCM in HVAC system. These tanks should optimize the performance and enhance the energy efficiency of the HVAC system, using the PCM to store the energy and use it for heating and cooling applications. As shows Fig. 1 the installation is composed by a heat pump, two PCM storage tanks (for cooling and heating), and an Air Handling Unit (AHU).

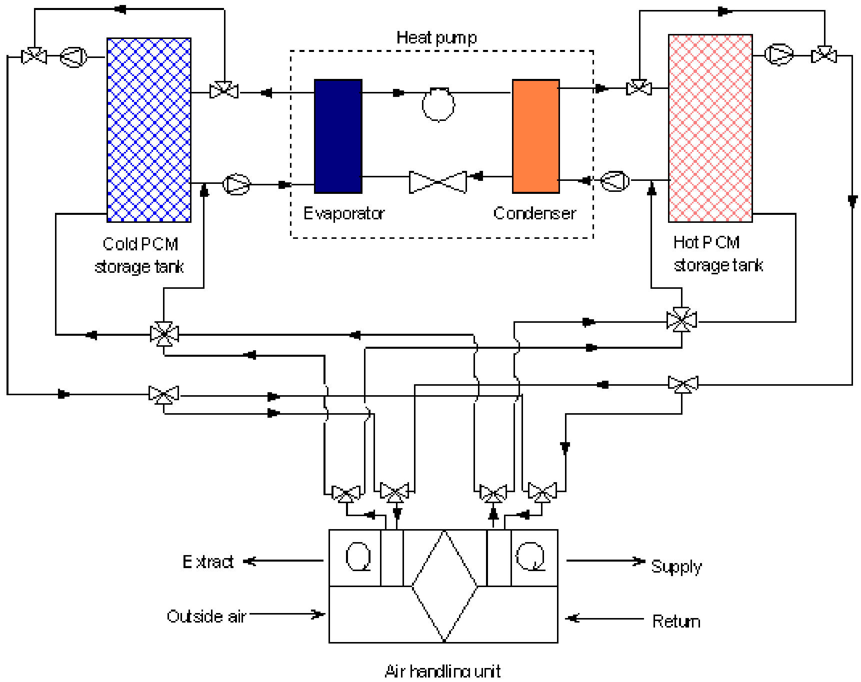

Fig. 1. Diagram of the installation.

The heat pump provides the thermal energy which is stored in the PCM storage tank using a heat transfer fluid. One of the main points of this installation consists in taking advantage of the low cost of the electricity during night time, so the PCM tank is charged during the night. The energy is discharged during the day and it is provided to the room through the coils installed in the air handling unit. Thus, the discharge time considered in order to design the tanks is 8 hours (workday time).

The energy supplied by the heat pump is stored in the PCM tanks in order to provide the thermal power to the AHU. Both tanks, heating and cooling, use PCM in order to store this thermal energy. The PCM were selected according to the working conditions of the installation to ensure good performance of it.

Two different types of PCM storage tank were considered for the system studied. The first one is to use PCM in bulk, so the tank operates as a heat exchanger where the heat transfer fluid flows through the pipes and the rest of the tank is filled by the PCM. The other type of tank considered uses commercial PCM macroencapsulation, such as tubes, modules or balls. In this case the heat transfer fluid flows through the external surface of the modules and the PCM is contained inside the modules.

The type of PCM used in the tank depends on the required melting temperature in order to ensure a good performance of the installation. In the design of the tanks the PCM considered are from the company PCMP Products [6], being a hydrated salt based PCM solution for the heating tank and a eutectic PCM solution for the cooling tank.

3.2. Requirements of the system

The application of the PCM in Hestor project is the design of PCM thermal energy storage systems included in HVAC solutions. The tanks should optimize the performance and enhance the energy efficiency of the HVAC system, using the PCM to store the energy and use it for heating and cooling applications.

To design the installation different climate conditions should be considered as requirements of the system. Thus, for winter conditions the temperatures from Estonia are considered while for summer the climate conditions from Spain are used. Table 1 shows the temperature conditions of the installation for each case.

Table 1. Temperature conditions of the system.

Parameters	Winter	Summer
Outside air temperature	-20 ºC	38 ºC
AHU supply air	27 ºC	18 ºC
AHU return air	18 ºC	24 ºC

The air-conditioned rooms have a surface of 1000 m^2. The tanks should store the thermal energy during the night time using a heat pump to take advantage of the lower price of the electricity. In day time the tanks should discharge the energy trying to use the heat pump as less as possible.

With these working conditions, the requirements of the system are to supply 60 kW of heating to the rooms in winter and 40 kW of cooling in summer. Moreover, due to the low temperatures of Estonia in winter, the heat pump should also work during the night time in order to maintain a minimum temperature in the room.

Phase change material should be selected according to working parameters of the system and the encapsulation solution. Commercial PCM should be selected with the suitable encapsulation to ensure good heat storage and heat transfer. In this project PCM macroencapsulation packages from the company PCMP Products were considered [66]. Thus, rectangular packages of HPDE plastic, known commercially as FlatICE, were selected to be used in the tanks (Fig. 2).

Fig. 2. FlatICE from PCMP Products Company [6].

In the design of the installation different climate conditions are considered depending on heating or cooling operations. Thus, for winter conditions the temperatures from Estonia are considered while for summer the climate conditions from Spain are used. Moreover, due to the low temperatures of Estonia in winter, the heat pump should work during the night time in order to maintain a minimum temperature in the room. The requirements of the system are to supply 60 kW of heating to the room in winter and 40 kW of cooling in summer, so the tanks should store this thermal energy at night and be able to supply this energy during the day.

The hot PCM storage tank provides hot water to the heating coils of the air handling unit. According to the hot water heating coil selected the PCM temperature considered was 58 ºC.

The heating requirement of the installation is 60 kW so this thermal power should be supplied in the heating coils. Moreover, the temperature drop due to heat losses in the tubes (from the tank to the coils) was considered to be 2 ºC.

Taking the commercial specifications of air handling unit manufacturer TROX TECHNIK [7], the heating coil present the specifications shown in Table 2.

Table 2. TBSN-50 heating coil specification of TROX TECHNIK.

Thermal power	60 kW
Water flow rate	10.195 m^3/h
Temperature difference	50 ºC / 45 ºC

The temperature difference of the heat transfer fluid in the hot tank was considered as 48 ºC / 52 ºC in order to achieve the specified temperatures in the heating coil. So the heat transfer in the tank ($\dot{Q}_{HTF}$) is higher than 60 kW because the higher temperature difference, resulting in a total power of 108 kW (Equation 12). Taking 8 hours as discharge time the storage energy required is 864 kWh.

The cold PCM storage tank works simultaneously with the hot tank and supplies cold to the cooling coil. In order to achieve the adequate temperature of the heat transfer fluid it was considered the use of a PCM with a melting temperature of 0 ºC, because its behaviour is well known. With this low working temperature water can not be used as heat transfer fluid so it was considered a mixture of water with 45 % of propylene glycol which has a freezing temperature of -26 ºC .

In this case it was also considered commercial coil specifications in order to obtain the parameters and the design of the tank. TROX TECHNIK coil in cooling applications has a temperature difference of 7 ºC / 12 ºC supplying 42.8 kW. In order to assume certain losses in the tubes that connect the tank with the coils it was assumed a higher temperature difference in the tank. The specifications of the cooling coil TBSN-50 of TROX TECHNIK are shown in Table 3.

Table 3. TBSN-50 heating coil specification of TROX TECHNIK.

Thermal power	42.8 kW
Water flow rate	7361 l/h
Temperature difference	7 ºC / 12 ºC

Considering a discharging time of 8 hours and a temperature difference of the heat transfer fluid of 5 ºC /14 ºC the power transferred in the tank is 76.87 kW and the stored energy 615 kWh (Equation 12). Both tanks hot and cold should charge the energy simultaneously in order to ensure the good performance of the heat pump cycle.

The use of macroencapsulated PCM in thermal energy storage is more common than bulk PCM. The packages of PCM should provide good heat transfer ratio between the heat transfer fluid and the PCM in order to ensure proper fusion and solidification during each cycle. Moreover, the packages should be resistance enough to support the weight of the stacked packages. However, in this project both bulk and macroencapsulated PCM will be considered at this stage of the design.

3.3. Bulk tanks

In order to store the energy these tanks are filled with PCM and the heat transfer fluid flows through pipes. They usually have high storage density (up to 95 vol.% is PCM) and the pipes are equally distributed in the storage volume. This type of tank is derived directly from the construction principle of any kind of heat exchanger to exchange heat between two fluids. To build the tank, on one side of the heat exchanger the fluid is replaced by the PCM.

According to the requirements of the installation there are two tanks, one for heating and the other for cooling. The PCM in each tank has different properties and therefore different melting temperatures. Thus, the melting temperatures of the PCM are 58 ºC for the heating tank and 0 ºC for the cooling tank.

The behaviour of the PCM storage tanks can be approximated to the shell and tubes heat exchangers, so the heat exchanger equations were used in order to calculate the parameters of the PCM tanks. The calculations were based on the heat flow and heat transfer coefficients during the phase change, taking into account the heat transfer resistances in the tank.

Only the conduction heat transfer coefficient was considered in order to calculate the parameters of the tanks, so convection was not considered.

The proposed design of the tanks is based on the heat exchanger between two fluids, where the pipes cross longitudinally the tank. Moreover, square section with the tubes uniformly distributed is considered (Fig. 3). In this configuration the main factors taken into account are described below.

An influence diameter of the tubes was considered (D_{inf}). This parameter sets the volume of PCM that one tube can heat and its value was fixed taking into account the previous experience in this type of projects. Therefore this diameter is the pitch, the distance between two consecutives tubes, and its value is constant according to the diameter of the tubes.

The width of the tank (L) depends on the number of tubes, following Equation 1.

$$L = n_{tubes,row} \cdot D_{\inf} \qquad \textbf{Equation 1}$$

A square section of the tank was considered:

- The number of tubes on each row and column are equal (Equation 2).

$$n_{tubes.row} = \sqrt{n_{tubes}} \qquad \textbf{Equation 2}$$

- The height (H) and the width (L) of the tank are equal.

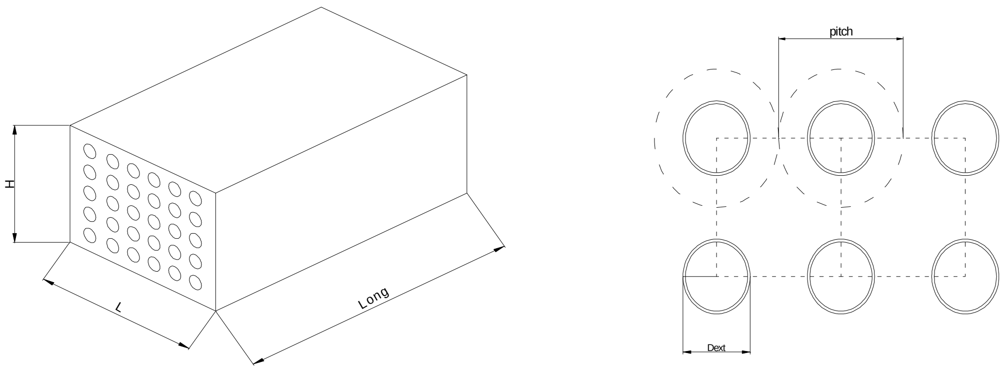

Fig. 3. Distribution of the tubes in the tank.

Diameters referred to the DIN 2440 standard were considered for the steel tubes. Table 4 shows the size of the tubes.

Table 4. DIN 2440 standard referred to the steel tubes [8].

External diameter		Thickness
Inches	**m**	**mm**
3/8	0.0172	2.35
¾	0.0269	2.65
1	0.0337	3.25
1·1/4	0.0424	3.25
1·1/2	0.0483	3.25

L, Long (longitude of the tubes) and *H* were calculated. In order to design the real size of the tank it wass considered that the tubes have a "U" distribution so the tubes enter and leave the tank from the same side (Fig. 4). Then, an approximation of the real size of the tank is obtained in Equation 3 to 5.

$$Length = \frac{Long}{2}$$ **Equation 3**

$$Width = 2 \cdot L$$ **Equation 4**

$$Height = L$$ **Equation 5**

The stored energy is a requirement of the system so the total mass of PCM needed was calculated tanking into account this energy and the latent heat capacity of the PCM (Equation 6). The total volume of PCM is then determined with Equation 7.

$$E = M_{PCM} \cdot \Delta h_{PCM}$$ **Equation 6**

$$M_{PCM} = V_{PCM} \cdot \rho_{PCM}$$ **Equation 7**

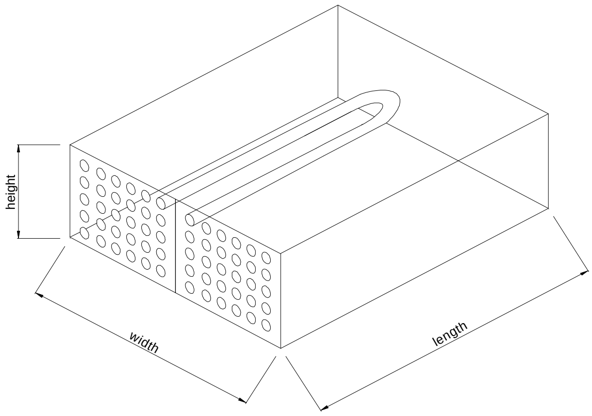

Fig. 4. Size of the tank and "U" distribution of the tubes.

The volume of the tank depends on the total volume of the PCM and the volume of the tubes in it (Equation 8 to Equation 10). On the other hand, the tank volume is also defined by its dimensions (Equation 11).

$$V_{\tan k} = V_{PCM} + V_{tubes}$$ **Equation 8**

$$V_{tubes} = V_{tube,un} \cdot n_{tubes}$$ **Equation 9**

$$V_{tube,un} = \frac{1}{4} \pi \cdot D_{ext}{}^{2} \cdot Long$$ **Equation 10**

$$V_{\tan k} = L^{2} \cdot Long$$ **Equation 11**

For the design of the tanks the working parameters were calculated according to the heat transferred between the heat transfer fluid and the PCM. Equation 12 and 13 show the heat transferred in charging and discharging processes respectively.

$$\dot{Q}_{HTF} = \dot{m}_{HTF} \cdot \overline{C}_{p_{HTF}} \cdot (T_{HTF,in} - T_{HTF,out})$$ **Equation 12**

$$\dot{Q}_{HTF} = \dot{m}_{HTF} \cdot \overline{C}_{p_{HTF}} \cdot (T_{HTF,out} - T_{HTF,in})$$ **Equation 13**

Where the specific heat capacity of the heat transfer fluid ($\overline{C}_{p_{HTF}}$) is the average between the inlet and outlet temperature.
The thermal power absorbed by the PCM during the process was calculated with the log mean temperature difference method. (Equation 14):

$$\dot{Q}_{PCM} = \frac{E_{PCM}}{t} = U \cdot A_{ext} \cdot \Delta\Delta_{lm}$$ **Equation 14**

Where E_{PCM} is the energy absorbed by the PCM and t is the time of the process, either charge or discharge. The log mean temperature difference ΔT_{lm} is defined in Equation 15 and 16 for charging and discharging processes respectively, where T_{PCM} is the melting temperature of the PCM.

$$\Delta T_{lm} = \frac{(T_{HTF.in} - T_{PCM}) - (T_{HTF.out} - T_{PCM})}{\ln\left[\frac{T_{HTF.in} - T_{PCM}}{T_{HTF.out} - T_{PCM}}\right]}$$ **Equation 15**

$$\Delta T_{lm} = \frac{(T_{PCM} - T_{HTF.out}) - (T_{PCM} - T_{HTF.in})}{\ln\left[\frac{T_{PCM} - T_{HTF.out}}{T_{PCM} - T_{HTF.in}}\right]}$$ **Equation 16**

The overall heat transfer coefficient can be calculated as the sum of the thermal resistances of the heat transfer fluid, the tube and the PCM (Equation 17 to 20).

$$U = \frac{1}{R_{tot}} = \frac{1}{R_{HTF} + R_{wall} + R_{PCM}}$$ **Equation 17**

$$R_{HTF} = A_{ext.un} \cdot \frac{1}{h_{HTF} \cdot A_{int.un}}$$ **Equation 18**

$$R_{wall} = A_{ext.un} \cdot \frac{\ln\left[\frac{D_{ext}}{D_{in}}\right]}{2\pi \cdot Long \cdot K_{tube}}$$ **Equation 19**

$$R_{PCM} = A_{ext.un} \cdot \frac{\ln\left[\frac{D_{inf}}{D_{ext}}\right]}{2\pi \cdot Long \cdot K_{PCM}}$$ **Equation 20**

The coefficients K_{tube} and K_{PCM} are the thermal conductivity of the tube and the PCM respectively, and $A_{ext.un}$ and $A_{int.un}$ are the external and internal unitary surface of the tubes (Equation 21 and 22).

$$A_{ext.un} = \pi \cdot D_{ext} \cdot Long$$ **Equation 21**

$$A_{int.un} = \pi \cdot D_{int} \cdot Long$$ **Equation 22**

Equation 23 shows the total external surface of the tubes which is the contact area between the tubes and the PCM.

$$A_{ext} = A_{ext.un} \cdot n_{tubes}$$ **Equation 23**

For the application of this method no heat losses are assumed in the storage tanks, so the thermal power transferred by the heat transfer fluid $\dot{Q}_{HTF}$ is equal to the thermal power absorbed by the PCM ($\dot{Q}_{PCM}$).

The behaviour of the heat transfer fluid is an important aspect of the system because it influences the heat transfer between the PCM and the fluid. The parameters obtained are described below:

- The velocity of the heat transfer fluid through each tube is shown in Equation 24, where $\dot{m}_{HTF,tube}$ is the mass flow rate of each tube.

$$v_{HTF} = \frac{\dot{m}_{HTF,tube}}{\rho_{HTF} \cdot 0.25\pi \cdot D_{int}^{2}}$$ **Equation 24**

- The Reynolds number gives a measure of the ratio of inertial forces to viscous forces of the heat transfer fluid. If Re_{HTF} is greater than 2300 the flow is turbulent, otherwise flow is laminar. Equation 25 shows the Reynolds equation, where μ_{HTF} is the kinematic viscosity of fluid.

$$\mathrm{Re}_{HTF} = v_{HTF} \cdot \frac{D_{int}}{\mu_{HTF}}$$ **Equation 25**

- The Prandtl number relates viscosity and conductivity of the fluid (Equation 26).

$$\mathrm{Pr}_{HTF} = C_{p,HTF} \cdot \mu_{HTF} \cdot \frac{\rho_{HTF}}{k_{HTF}}$$ **Equation 26**

- The Nusselt number is the ratio of convective and conductive heat transfer. In a laminar flow Nusselt is 3.66, otherwise Equation 27 is used where f factor is obtained in Equation 28.

$$Nu_{HTF} = \frac{(\mathrm{Re}_{HTF} - 1000) \cdot \mathrm{Pr}_{HTF} \cdot \frac{f}{2}}{1 + 12.7 \cdot \left(\mathrm{Pr}_{HTF}^{2/3} - 1\right)\sqrt{\frac{f}{2}}}$$ **Equation 27**

$$f = \left(1.58 \cdot \ln(\mathrm{Re}_{HTF}) - 3.28\right)^{-2}$$ **Equation 28**

- The heat transfer coefficient can be obtained in Equation 29.

$$h_{HTF} = \frac{k_{HTF} \cdot Nu_{HTF}}{D_{\text{int}}}$$ **Equation 29**

3.4. PCM macroencapsulated tanks

In this type of tanks, the heat is transferred to or from a heat transfer fluid as it flows through the voids in the bed. During charging mode, the hot heat transfer fluid carrying energy from the source is circulated through the tank. The PCM inside the capsules absorbs heat and melts. During discharging mode, cool heat transfer fluid from the load is circulated through the tank, freezing the encapsulated PCM. In both operating modes (charging and discharging), the difference between the mean temperature of the heat transfer fluid and the phase change temperature must be sufficient to obtain a satisfactory rate of heat transfer.

The macroencapsulation of PCM can: (i) avoids large phase separations; (ii) increase the rate of heat transfer and (iii) provide a selfsupporting structure for the PCM [4].

In the project studied the macoencapsulated PCM selected is from the company PCMP Products [6]. The FlatICE package is 500 mm x 250 mm x 32 mm (Fig. 5).

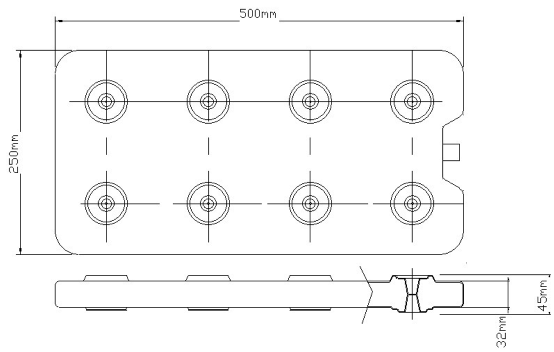

Fig. 5. Size of the FlatICE containers [6].

The phase change temperatures of the tanks are the same that in the case of the bulk PCM tanks, 58 ºC for the heating tank and 0 ºC for the cooling tank.

In this type of tanks the PCM is encapsulated in containers that are stacked within it. The heat transfer fluid flows inside the voids which are among the containers so the heat transfer takes place between the fluid and the encapsulation material, HPDE plastic in this case.

For the design of the tanks the voids were approximated to tubes through which the heat transfer fluid circulates. These virtual tubes were considered to be HPDE plastic. Thus, a hydraulic equivalent diameter of the voids was obtained.

The hydraulic diameter depends on the width of the tank. Equation 30 shows the hydraulic diameter, where *L* is the width of the tank and the value 0.013 m is the distance between two consecutives containers.

$$D_h = \frac{2 \cdot L_{FlatICE,\tan k} \cdot 0.013}{L_{FlatICE,\tan k} + 0.013} \qquad \textbf{Equation 30}$$

An approximate view of the tank with the FlatICE is shown in Fig. 6.

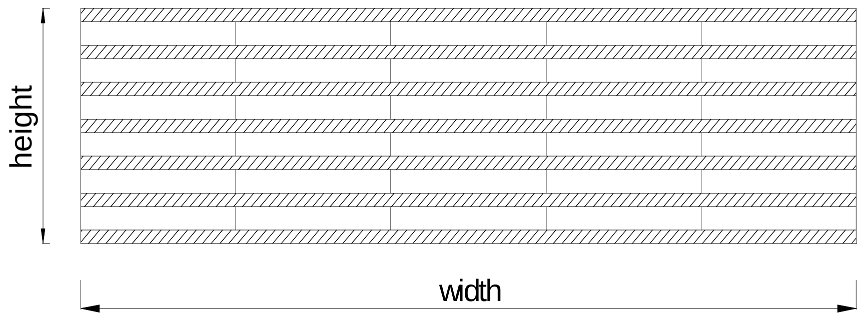

Fig. 6. Cross-section and distribution of the FlatICE in the tank.

The volume of PCM in the tanks is the volume of the containers used (V_{PCM}). The volume which is not filled by the containers is filled by the heat transfer fluid (V_{HTF}), so the volume of the tanks, for both heating and cooling, was calculated in Equation 31.

$$V_{FlatICE,\tan k} = V_{PCM} + V_{HTF} \qquad \textbf{Equation 31}$$

The tanks were considered with rectangular shape so their volume depends on three parameters: width ($L_{FlatICE,\tan k}$), length ($Long_{FlatICE,\tan k}$) and height ($H_{FlatICE,\tan k}$) (See Equation 32).

$$V_{FlatICE,\tan k} = L_{FlatICE,\tan k} \cdot Long_{FlatICE,\tan k} \cdot H_{FlatICE,\tan k} \qquad \textbf{Equation 32}$$

Each dimension of the tanks is function of the FlatICE dimensions and the number of containers used. Equation 33 to 35 show these relations, where 0.045 m is the height of the PCM container with its fixation system.

$$L_{FlatICE,\tan k} = n_{FlatICE,row} \cdot Width_{FlatICE}$$ **Equation 33**

$$Long_{FlatICE,\tan k} = n_{FlatICE,long} \cdot Long_{FlatICE}$$ **Equation 34**

$$H_{FlatICE} = n_{FlatICE,height} \cdot 0.045$$ **Equation 35**

The number of PCM containers used in the tanks was obtained in Equation 36.

$$n_{FlatICE} = n_{FlatICE,row} \cdot n_{FlatICE,height} \cdot n_{FlatICE,long}$$ **Equation 36**

Taking the thermal energy required, the total mass of PCM needed and its volume can be obtained in Equation 6 and 7 for heating and cooling tanks. This volume of PCM is approximate to the total volume of the containers filled with PCM (V_{PCM}) and also can be obtained in Equation 37, where $V_{FlatICE}$ is the unitary volume of the macoencapsulation container.

$$V_{PCM} = V_{FlatICE} \cdot n_{FlatICE}$$ **Equation 37**

The volume of heat transfer fluid was calculated with the unitary volume of the virtual tube and the total number of them (Equation 38.).

$$V_{HTF} = V_{virtual,tube} \cdot n_{virtual,tubes}$$ **Equation 38**

In order to determine the number of virtual tubes it was considered the factor $f_{FlatICE}$ that relates them with the number of PCM containers in the tank (Equation 39).

$$n_{virtual,tubes} = n_{FlatICE} \cdot f_{FlatICE}$$ **Equation 39**

The volume of one virtual tube was calculated with the hydraulic diameter previously determined (Equation 40).

$$V_{virtual,tube} = \frac{1}{4} \pi \cdot D_h^{\,2} \cdot Long_{FlatICE,\tan k}$$ **Equation 40**

In macroencapsulated PCM tanks the heat transfer between PCM and heat transfer fluid was calculated applying the log mean temperature difference method so Equation 12 to 17 are also valid in this case. To apply this method thermal resistances were obtained, which are based on the plane surface equations (Equation 41 to 43).

$$R_{HTF} = \frac{1}{h_{HTF}}$$ **Equation 41**

$$R_{wall} = \frac{0.002}{K_{wall}}$$ **Equation 42**

$$R_{PCM} = \frac{0.016}{K_{PCM}}$$ **Equation 43**

The value 0.002 m is the encapsulation thickness considered and 0.016 m is half of the FlatICE thickness which was considered as the part of the PCM affected by the HTF.
The total heat transfer surface was obtained taking into account the number of FlatICE containers used in the tank and the surface of each one (Equation 44 and 45).

$$A_{FlatICE} = L_{FlatICE} \cdot Long_{FlatICE} \cdot 2$$ **Equation 44**

$$A_{total,FLATICE,\tan k} = A_{FlatICE} \cdot n_{FlatICE}$$ **Equation 45**

4. Results analysis

4.1. Bulk tanks

In order to obtain the parameters of the tanks come inputs were considered. These are described below.

<u>Inputs:</u>

- Discharge time of 8 hours because this is the time considered as a workday.
- Thermal energy stored. The requirements of the installation are a heating power of 60 kW and a cooling power of 40 kW, both with a discharge time of 8 hours.
- PCM properties. Thermophysical properties of the PCM such as density, phase change temperature, thermal conductivity and latent heat capacity.
- Diameter of the tubes selected according to the European standard DIN 2440.
- Inlet temperature of the heat transfer fluid, in order to obtain the temperature difference of the tank.
- Heat transfer fluid properties such as density, viscosity, Reynolds, etc.

<u>Outputs:</u>

- Dimensions of the tanks considering a uniform distribution of the tubes and a square section of the tank.
- Mass flow rate of the heat transfer fluid in discharging operation.
- Outlet temperature of the heat transfer fluid.

4.1.1. Heating tank

This tank stores heat using a PCM with phase change temperature of 58 ºC. In order to calculate the dimensions of the tank a parametric study of the diameters of the tubes was done:

- Taking 33.7 mm (see Table 4) of diameter the results of the discharge of the tank are listed in Table 5 and Table 6. Table 5 shows the constant parameters obtained which are valid for each diameter considered.

Table 5. Constant parameters obtained.

Parameter	Value
Heat transfer	108 kW
Stored energy	864 kWh
Mass of PCM	21451 kg
PCM density	1505 kg/m^3
PCM latent heat capacity	145 kJ/kg
Inlet temperature	43 ºC
PCM temperature	58 ºC
PCM thermal conductivity	0.69 W/m^2·K
Tube thermal conductivity	13 W/m^2·K
Discharging time	8 h
Volume of the tank (V_{tank})	18.5 m³
V_{PCM} /V_{tank}	77.05 %

Table 6 presents the parameters that change according to the number of tubes and their diameter for the discharging process.

Table 6. Results obtained with 33.7 mm of diameter.

Tubes per row	L (m)	Long (m)	Outlet temperature (ºC)	Total tubes	Mass flow rate (kg/s)	Total exchange surface (m^2)	Reynolds
18	1.12	14.69	56.06	324	1.978	503.9	457.5
19	1.18	13.18	56.06	361	1.978	503.9	410.6
20	1.25	11.9	56.06	400	1.978	503.9	370.6
21	1.31	10.79	56.06	441	1.978	503.9	336.1
22	1.37	9.83	56.06	484	1.978	503.9	306.3
23	1.43	8.99	56.06	529	1.978	503.9	280.2
24	1.50	8.26	56.06	576	1.978	503.9	257.3
25	1.56	7.61	56.06	625	1978	503.9	237.2

- Taking 42.4 mm of diameter the parameters are shown in Table 7.

Table 7. Results obtained with 42.4 mm of diameter.

Tubes per row	L (m)	Long (m)	Outlet temperature (ºC)	Total tubes	Mass flow rate (kg/s)	Total exchange surface (m^2)	Reynolds
18	1.41	9.28	51.58	324	3.012	400.5	524.5
19	1.49	8.33	51.58	361	3.012	400.5	470.8
20	1.57	7.52	51.58	400	3.012	400.5	424.9
21	1.65	6.82	51.58	441	3.012	400.5	385.4
22	1.73	6.21	51.58	484	3.012	400.5	351.1
23	1.80	5.68	51.58	529	3.012	400.5	321.3
24	1.88	5.22	51.58	576	3.012	400.5	295
25	1.96	4.81	51.58	625	3012	400.5	271.9

- Taking 48.3 mm of diameter the parameters are shown in Table 8.

Table 8. Results obtained with 48.3 mm of diameter.

Tubes per row	L (m)	Long (m)	Outlet temperature (ºC)	Total tubes	Mass flow rate (kg/s)	Total exchange surface (m^2)	Reynolds
18	1.61	7.15	46.55	324	7.276	351.6	1058
19	1.70	6.42	46.55	361	7.276	351.6	949.3
20	1.79	5.79	46.55	400	7.276	351.6	856.8
21	1.88	5.25	46.55	441	7.276	351.6	777.1
22	1.97	4.79	46.55	484	7.276	351.6	708.1
23	2.05	4.38	46.55	529	7.276	351.6	647.9
24	2.14	4.02	46.55	576	7.276	351.6	595
25	2.23	3.71	46.55	625	7.276	351.6	548.3

With these results the selection of the size of the tank was considered according to the heat transfer outlet temperature. Thus, taking into account the specifications of the heating coil it was considered 42.4 mm of diameter for the tubes because the outlet temperature obtained (51.8 ºC) satisfies the heat losses assumed and the water flow rate is close to the specified by the manufacturer.

Moreover, the size of the tank considered was selected to have good proportionality in its dimensions. The final results are shown in Table 9.

Table 9. Parameters of the tubes in heating tank.

L	1.57 m
Long	7.51 m
Tubes per row	20

Table 10. Parameters of the tubes in heating tank (continuation).

Total tubes	400
Diameter of the tubes	42.4 mm

According to the "U" distribution form of the tubes inside the tank, an approximation of the real dimensions of the tank is shown in Table 11 and Fig. 7.

Table 11. Real size of the heating tank in bulk PCM.

Width	3.14 m
Length	3.75 m
Height	1.57 m

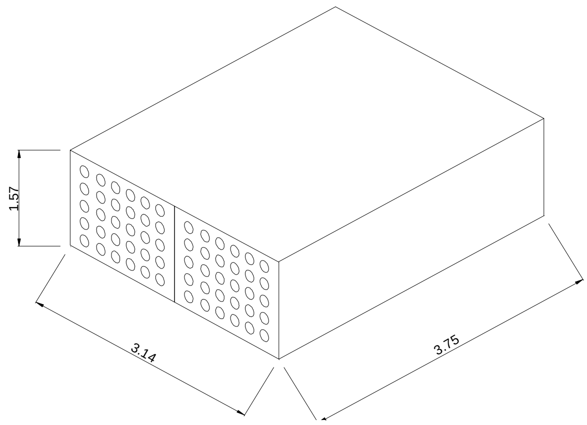

Fig. 7. Size of the heating tank, in meters.

According to the dimensions of the tank described, the parameters for the charging operation were calculated. In this case the inlet temperature should be high enough to charge the PCM. Thus, two inlet temperatures were considered, 70 ºC and 65 ºC, but the latest was finally selected because the heat transfer fluid is in turbulent flow in these conditions. Table 12 lists the main parameters with 65 ºC as inlet temperature; the parameters of the tank selected are in bold.

Table 12. Parameters of the heating tank with an inlet temperature of 65 ºC in charging operation.

Tubes per row	L (m)	Long (m)	Inlet temperature (ºC)	Outlet temperature (ºC)	Mass flow rate (kg/s)	Reynolds	Storage time (h)
18	1.41	9.28	65	63.24	14.64	3341	8
19	1.49	8.33	65	63.34	15.54	3184	8
20	**1.57**	**7.52**	**65**	**63.43**	**16.50**	**3053**	8
21	1.65	6.82	65	63.53	17.52	2943	8

Table 13. Parameters of the heating tank with an inlet temperature of 65 ºC in charging operation (continuation).

Tubes per row	L (m)	Long (m)	Inlet temperature (ºC)	Outlet temperature (ºC)	Mass flow rate (kg/s)	Reynolds	Storage time (h)
22	1.73	6.21	65	63.61	18.6	2849	8
23	1.80	5.68	65	63.69	19.75	2769	8
24	1.88	5.22	65	63.77	20.96	2700	8
25	1.96	4.81	65	63.84	22.23	2641	8

4.1.2. Cooling tank

The PCM of this tank has a melting temperature of 0 ºC so in order to charge it the inlet temperature has to be under 0 ºC. In order to calculate the dimensions of the tank a parametric study of the diameters of the tubes was done:

- Taking 17.2 mm of diameter the results are listed in Table 14 and Table 15. The constant parameters obtained (Table 14) are also valid for each diameter considered.

Table 14. Constant parameters obtained.

Parameter	Value
Heat transfer	76.87 kW
Stored energy	614.97 kWh
Mass of PCM	6668 kg
PCM density	1000 kg/m^3
PCM latent heat capacity	332 kJ/kg
Inlet temperature	14 ºC
PCM temperature	0 ºC
PCM thermal conductivity	0.58 W/m^2·K
Tube thermal conductivity	13 W/m^2·K
Discharging time	8 h
Volume of the tank (V_{tank})	8.65 m³
V_{PCM} /V_{tank}	77.05 %

Table 15 presents the parameters that change according to the number of tubes and their diameter for the discharging process.

Table 15. Results obtained with 17.2 mm of diameter.

Tubes per row	L (m)	Long (m)	Outlet temperature (ºC)	Total tubes	Mass flow rate (kg/s)	Total exchange surface (m^2)	Reynolds
18	0.57	26.38	0.12	324	1.319	462	240.7
19	0.60	23.68	0.12	361	1.319	462	216.1
20	0.64	21.37	0.12	400	1.319	462	195
21	0.67	19.38	0.12	441	1.319	462	176.9
22	0.7	17.66	0.12	484	1.319	462	161.2
23	0.73	16.16	0.12	529	1.319	462	147.2
24	0.76	14.84	0.12	576	1.319	462	135.4
25	0.79	13.68	0.12	625	1.319	462	124.8

- Taking 26.9 mm of diameter the parameters are shown in Table 16.

Table 16. Results obtained with 26.9 mm of diameter.

Tubes per row	L (m)	Long (m)	Outlet temperature (ºC)	Total tubes	Mass flow rate (kg/s)	Total exchange surface (m^2)	Reynolds
18	0.896	10.79	2.98	324	1.665	295.3	193.4
19	0.94	9.68	2.98	361	1.665	295.3	173.5
20	0.99	8.74	2.98	400	1.665	295.3	156.6
21	1.04	7.92	2.98	441	1.665	295.3	142.1
22	1.09	7.22	2.98	484	1.665	295.3	129.4
23	1.14	6.60	2.98	529	1.665	295.3	118.4
24	1.19	6.07	2.98	576	1.665	295.3	108.8
25	1.24	5.59	2.98	625	1.665	295.3	100.2

- Taking 33.7 mm of diameter the parameters are shown in Table 17.

Table 17. Results obtained with 33.7 mm of diameter.

Tubes per row	L (m)	Long (m)	Outlet temperature (ºC)	Total tubes	Mass flow rate (kg/s)	Total exchange surface (m^2)	Reynolds
18	1.12	6.87	8.67	324	3.451	235.7	345.5
19	1.18	6.17	8.67	361	3.451	235.7	310.1
20	1.25	5.56	8.67	400	3.451	235.7	279.8
21	1.31	5.05	8.67	441	3.451	235.7	253.8
22	1.37	4.6	8.67	484	3.451	235.7	231.1
23	1.43	4.21	8.67	529	3.451	235.7	211.6
24	1.5	3.87	8.67	576	3.451	235.7	194.3
25	1.56	3.56	8.67	625	3.451	235.7	179.1

According to the specifications of the cooling coil and the heat losses assumed, the design with tubes of 26.9 mm of diameter provide better outlet temperature of the tank and therefore better inlet temperature in the cooling coil. The final design of the tank was selected in order to ensure an adequate size for its real implementation. Table 18 shows the final parameters.

Table 18. Parameters of the tubes in cooling tank.

L	1.095 m
Long	7.22 m
Tubes per row	22
Total tubes	484
Diameter of the tubes	26.9 mm

The real size of the cooling tank is shown in Table 11 and Fig. 8.

Table 11. Real size of the cooling tank in bulk PCM.

Width	1.095 m
Length	3.61 m
Height	1.095 m

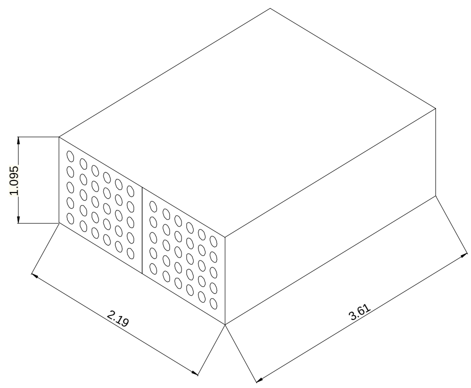

Fig. 8. Size of the cooling tank, in meters.

In charging operation the temperature of the heat transfer fluid has to be low enough to solidify the PCM. The fluid is a mixture of water and propylene glycol that ensures a proper freezing temperature according to the working temperatures of the tank.

The inlet temperature of the heat transfer fluid should satisfy the heat transfer and fluid properties equations so two temperatures were considered, -10 ºC and -15 ºC. Finally, the first one was selected because gives higher Reynolds number. Table 19 shows the results with this inlet temperature, the parameters of the tank selected are in bold.

Table 19. Parameters of the cooling tank with an inlet temperature of -10 ºC in charging operation.

Tubes per row	L (m)	Long (m)	Inlet temperature (ºC)	Outlet temperature (ºC)	Mass flow rate (kg/s)	Reynolds	Storage time (h)
18	0.89	10.79	-10	-8.46	14.27	109.4	8
19	0.94	9,68	-10	-8.46	14.27	98.19	8
20	0.99	8.74	-10	-8.46	14.27	88.62	8
21	1.04	7.92	-10	-8.46	14.27	80.38	8
22	**1.09**	**7.22**	**-10**	**-8.46**	**14.27**	**73.24**	**8**
23	1.14	6.60	-10	-8.46	14.27	67.01	8
24	1.19	6.07	-10	-8.46	14.27	61.54	8
25	1.24	5.59	-10	-8.46	14.27	56.72	8

4.2. PCM macroencapsulated tanks

The inputs and outputs considered for the design are presented below.

Inputs:

- Thermal energy stored for both heating and cooling tanks.
- Discharge time of 8 hours.
- PCM container. Some features of the macroencapsulation are important to obtain the paratemeters of the tank. The size and material of the macroencapsulation are considered.
- Thermophysical properties of the PCM.
- Heat transfer fluid properties such as density, viscosity, Reynolds, etc.
- Inlet temperature of the heat transfer fluid.
- The equivalent hydraulic diameter.
- One dimension of the tank.

Outputs:

- Size and volume of the tank.
- Outlet temperature and mass flow rate of the heat transfer fluid.
- Number of PCM containers needed.

4.2.1. Heating tank

The heating tank provides heat to the coils of the air handling units. The PCM temperature considered was 58 ºC so is high enough to heat the rooms. The size of the tank depends on the number of FlatICE needed to store the energy required by the system.

The size of the tank was based on the operational parameters and some assumptions on the design. The first one was to suppose a proportionality of the dimensions of the tank, and the second was to assume the height of the tank lower than 1.5 m. in order to ensure that the PCM containers could withstand its own weight. The constant parameters obtained in the calculation of the tank are described in Table 20.

Table 20. Constant parameters obtained for macroencapsulated PCM heating tank.

Parameter	Value
Heat transfer	108 kW
Stored energy	864 kWh
Mass of PCM	21451 kg
FlatICE volume	0.0038 m^3
Discharging time	8 h
PCM density	1505 kg/m^3
PCM latent heat capacity	145 kJ/kg
Volume of the tank (V_{tank})	21.21 m^3
V_{PCM}/V_{tank}	67.56 %
PCM temperature	58 ºC
Hydraulic diameter	0.02587 m
Total exchange surface	937.7 m^2
Number of PCM containers	3751
Width of the tank	3 m

Using the equations previously described the operational parameters on discharging mode and the proposed designs are listed in Table 21.

Table 21. Results of the PCM macroencapsulated heating tank on discharging mode.

$n_{tubes, height}$	Outlet temperature (ºC)	Inlet temperature (ºC)	Long (m)	Height (m)	Mass flow rate (kg/s)	Reynolds	$n_{tubes, row}$	$n_{tubes, long}$
36	56.56	48	4.34	1.62	3.019	93.68	12	8.68
35	56.56	48	4.45	1.57	3.019	96.36	12	8.93
34	56.56	48	4.6	1.53	3.019	99.19	12	9.19

Table 22. Results of the PCM macroencapsulated heating tank on discharging mode (continuation).

$n_{tubes, height}$	Outlet temperature (ºC)	Inlet temperature (ºC)	Long (m)	Height (m)	Mass flow rate (kg/s)	Reynolds	$n_{tubes, row}$	$n_{tubes, long}$
33	56.56	48	4.73	1.48	3.019	102.2	12	9.47
32	56.56	48	4.88	1.44	3.019	105.4	12	9.77
31	56.56	48	5	1.40	3.019	108.8	12	10.08

The design selected for the heating tank is described in Table 23 and Fig. 9.

Table 23. Size of the heating tank with PCM macroencapsulted.

Parameter	Dimension	Number of PCM containers
Width	3 m	12
Length	5 m	10
Height	1.5 m	33
Total		3751

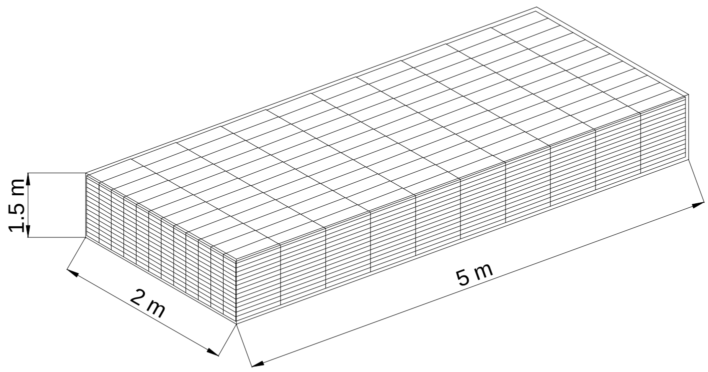

Fig. 9. Schematic design of the PCM macroencapsulted heating tank

For the charging mode an inlet temperature of the heat transfer fluid of 65 ºC was considered to ensure that the PCM stores the energy needed. Table 24 lists the parameters for this case.

Table 24. Results of the macroencapsulated PCM heating tank on charging mode.

$n_{tubes, height}$	Outlet temperature (ºC)	Inlet temperature (ºC)	Long (m)	Height (m)	Mass flow rate (kg/s)	Reynolds	$n_{tubes, row}$	$n_{tubes, long}$
36	60.54	65	4.34	1.62	5.787	211.9	12	8.68
35	60.54	65	4.45	1.57	5.787	217.9	12	8.93
34	60.54	65	4.6	1.53	5.787	224.3	12	9.19
33	60.54	65	4.73	1.48	5.787	231.1	12	9.47
32	60.54	65	4.88	1.44	5.787	238.3	12	9.77
31	60.54	65	5	1.40	5.787	246	12	10.08

4.2.2. Cooling tank

The cooling tank is the device of the system which has to store thermal energy in order to supply cold to the rooms. As it works in a low range of temperatures, the PCM melting temperature considered was 0 ºC.

Taking the equations previously described, Table 25 shows the constant parameters obtained; the width of the tank was set in order to calculate the rest of the parameters

Table 25. Constant parameters obtained for macroencapsulated PCM cooling tank.

Parameter	Value
Heat transfer	76.87 kW
Stored energy	615 kWh
Mass of PCM	6668 kg
FlatICE volume	0.0038 m^3
PCM density	1000 kg/m^3
PCM latent heat capacity	332 kJ/kg
Discharging time	8 h
Volume of the tank (V_{tank})	9.87 m^3
V_{PCM}/V_{tank}	67.56 %
PCM temperature	0 ºC
Hydraulic diameter	0.02583 m
Total exchange surface	438.7 m^2
Number of PCM containers	1755
Width of the tank	2 m

Table 26 lists the design parameters of the cooling tank, where the inlet temperature selected for the heat transfer fluid was 14 ºC.

Table 26. Results of the macroencapsulated PCM cooling tank on discharging mode.

$n_{tubes, height}$	Outlet temperature (ºC)	Inlet temperature (ºC)	Long (m)	Height (m)	Mass flow rate (kg/s)	Reynolds	$n_{tubes, row}$	$n_{tubes, long}$
36	5.39	14	3.05	1.62	2.51	6.94	8	6.1
35	5.39	14	3.13	1.57	2.51	7.14	8	6.27
34	5.39	14	3.23	1.53	2.51	7.35	8	6.45
33	5.39	14	3.32	1.48	2.51	7.57	8	6.65
32	5.39	14	3.42	1.44	2.51	7.81	8	6.69
31	5.39	14	3.54	1.40	2.51	8.06	8	7.07

The selected design is shown in Table 27 and Fig. 10.

Table 27. Size of the cooling tank with PCM macroencapsulted.

Parameter	Dimension	Number of PCM containers
Width	2 m	8
Length	3.5 m	7
Height	1.5 m	33
Total		1755

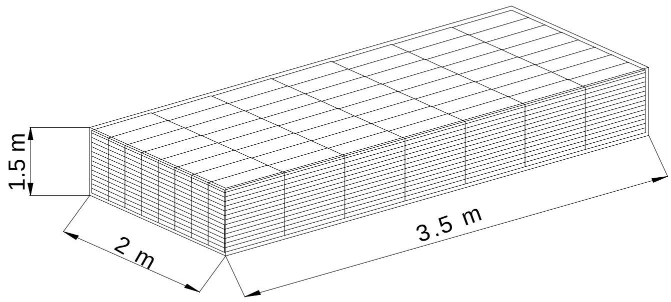

Fig. 10. Schematic design of the PCM macroencapsulted cooling tank.

In charging operation the tank works with an inlet temperature of -10 ºC to store the thermal energy in the PCM. Table 28 lists the parameters of the tank in charging operation.

Table 28. Results of the PCM macroencapsulated cooling tank on charging mode.

$n_{tubes, height}$	Outlet temperature (ºC)	Inlet temperature (ºC)	Long (m)	Height (m)	Mass flow rate (kg/s)	Reynolds	$n_{tubes, row}$	$n_{tubes, long}$
36	-8.1	-10	3.05	1.62	11.42	31.52	8	6.1
35	-8.1	-10	3.13	1.57	11.42	32.42	8	6.27
$n_{tubes, height}$	Outlet temperature (ºC)	Inlet temperature (ºC)	Long (m)	Height (m)	Mass flow rate (kg/s)	Reynolds	$n_{tubes, row}$	$n_{tubes, long}$
34	-8.1	-10	3.23	1.53	11.42	33.37	8	6.45
33	-8.1	-10	3.32	1.48	11.42	34.39	8	6.65
32	-8.1	-10	3.42	1.44	11.42	35.46	8	6.69
31	-8.1	-10	3.54	1.40	11.42	36.6	8	7.07

5. Concluding remarks

This work presents the design of PCM thermal storage tanks for HVAC solutions. The tanks should enhance the energy efficiency of the system and the PCM should store the thermal energy and use it for heating and cooling applications.

Simulation of charging and discharging cycles was developed in order to design the tanks and predict the behaviour of them. These designs will be validated with their real implantation in two pilot plants, one in Estonia and the other in Spain.

The behaviour of PCM in thermal storage units is difficult to predict and also to simulate with any software. In this project an approximation of the heat transfer between the PCM and the heat transfer fluid was done. It will be interesting to validate the results obtained in the real implementation of the tanks.

The sizes of the tanks have been shown in the results of this project. These sizes can be reduced if the efficiency of the AHU is considered because this device incorporates a heat recovery. However, it should be considered the overall efficiency of the AHU.

The cost of the HVAC system studied in this project, a heat pump coupled with an AHU and the PCM thermal storage tanks, is a point to take into account if this system expects to be patented in the future.

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Appendix 1. EES code: heating tank with bulk PCM. Discharging mode.

```
Function Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_ext)

If (Re_HTF<2300) THEN
Funcio_Nu:=3,66
ELSE
Funcio_Nu:=((Re_HTF-1000)*Prandtl_HTF*f/2)/(1+12,7*(Prandtl_HTF^(2/3)-1)*sqrt(f/2))
ENDIF

END Funcio_Nu


"Heat transfer equations"

Q=m_tot_HTF*Cp_HTF*(T_HTF_out-T_HTF_in)

Q=(U*A_ext*DELTAT_lm)/1000

DELTAT_lm*ln((T_PCM-T_HTF_out)/(T_PCM-T_HTF_in))=(T_PCM-T_HTF_out)-(T_PCM-
T_HTF_in)
U=1/((R_HTF+R_tube+R_PCM))
        R_HTF=D_ext/(D_int*h_HTF)
        R_tube=D_ext*((ln(D_ext/D_int))/(2*k_tube))
        R_PCM=D_ext*((ln(D_inf/D_ext))/(2*k_efectiva))


"!Requirements"
t_storage=8[h]
E=864 [kWh]
Q=E/t_storage
E=M_PCM*DELTAh_PCM*Convert(kJ;kWh)

"!Assumptions"
T_HTF_in=43 [C]
DELTAh_PCM=145 [kJ/kg]
rho_PCM=1505 [kg/m^3]
k_efectiva=0,69 [W/m-k]
T_PCM=58 [C]

"!Tubes"
D_inf=D_ext*1,85
D_ext=0,0424
D_int=D_ext-0,0032
k_tube=13 [W/m-k]
n_tubes_row=sqrt(n_tubes)
L=n_tubes_row*D_inf

"!Hot tansfer fluid properties"
"Inlet liquid"
P_HTF=1500 [kPa]
Cp_HTF_in=Cp(Water;T=T_HTF_in;P=P_HTF)
k_HTF_in=Conductivity(Water;T=T_HTF_in;P=P_HTF)
rho_HTF_in=Density(Water;T=T_HTF_in;P=P_HTF)
mu_HTF_in=Viscosity(Water;T=T_HTF_in;P=P_HTF)

"outlet liquid"
Cp_HTF_out=Cp(Water;T=T_HTF_out;P=P_HTF)
```

```
k_HTF_out=Conductivity(Water;T=T_HTF_out;P=P_HTF)
rho_HTF_out=Density(Water;T=T_HTF_out;P=P_HTF)
mu_HTF_out=Viscosity(Water;T=T_HTF_out;P=P_HTF)

"averge"
Cp_HTF=(Cp_HTF_in+Cp_HTF_out)/2
rho_HTF=(rho_HTF_in+rho_HTF_out)/2
mu_HTF=(mu_HTF_in+mu_HTF_out)/2
visc_HTF=mu_HTF/rho_HTF
k_HTF=(k_HTF_in+k_HTF_out)/2

"Surfaces"
A_int_un=pi*D_int*Long
A_ext_un=pi*D_ext*Long
A_ext=A_ext_un*n_tubes

"!Volumes"
M_PCM=V_PCM*rho_PCM
V_PCM2=V_tank2-V_tubes
V_PCM=V_PCM2
V_tank=L^2*Long
V_tank=V_tank2
V_tube_un=0,25*pi*D_ext^2*Long
V_tubes2=V_tube_un*n_tubes
V_tubes=V_tubes2

IPF=100*(V_PCM/V_tank)


"Massic flow and velocity"
m_tube=m_tot_HTF/n_tubes
v_HTF=m_tube/(rho_HTF*0,25*pi*D_int^2)

"Adimensional properties HTF"
Re_HTF=v_HTF*D_int/visc_HTF
Prandtl_HTF=(Cp_HTF*convert(kJ/kg-C;J/kg-C))*visc_HTF*rho_HTF/k_HTF
Nusselt_HTF=Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_ext)
f=(1,58*ln(Re_HTF)-3,28)^(-2)

"Coeficient de transferencia de calor"
h_HTF2=(k_HTF*Nusselt_HTF)/D_int
h_HTF2=h_HTF
```

Appendix 2. EES code: heating tank with bulk PCM. Charging mode.

```
Function Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_ext)

If (Re_HTF<2300) THEN
Funcio_Nu:=3,66
ELSE
Funcio_Nu:=((Re_HTF-1000)*Prandtl_HTF*f/2)/(1+12,7*(Prandtl_HTF^(2/3)-1)*sqrt(f/2))
ENDIF

END Funcio_Nu


"Heat transfer equations"
```

```
Q=m_tot_HTF*Cp_HTF*(T_HTF_in-T_HTF_out)
Q=(U*A_ext*DELTAT_lm)/1000

DELTAT_lm*ln((T_HTF_in-T_PCM)/(T_HTF_out-T_PCM))=(T_HTF_in-T_PCM)-(T_HTF_out-
T_PCM)

U=1/((R_HTF+R_tube+R_PCM))
        R_HTF=D_ext/(D_int*h_HTF)
        R_tube=D_ext*((ln(D_ext/D_int))/(2*k_tube))
        R_PCM=D_ext*((ln(D_inf/D_ext))/(2*k_efectiva))

"!Requirements"
t_storage=8[h]
E=864 [kWh]
Q=E/t_storage
E=M_PCM*DELTAh_PCM*Convert(kJ;kWh)

"!Assumptions"
T_HTF_in=65 [C]
DELTAh_PCM=145 [kJ/kg]
rho_PCM=1505 [kg/m^3]
k_efectiva=0,69 [W/m-k]
T_PCM=58 [C]

"!Tubes"
D_inf=D_ext*1,85
D_ext=0,0424
D_int=D_ext-0,0032
k_tube=13 [W/m-k]
n_tubes_row=sqrt(n_tubes)
L=n_tubes_row*D_inf

"!Hot tansfer fluid properties"
"Inlet liquid"
P_HTF=1500 [kPa]
Cp_HTF_in=Cp(Water;T=T_HTF_in;P=P_HTF)
k_HTF_in=Conductivity(Water;T=T_HTF_in;P=P_HTF)
rho_HTF_in=Density(Water;T=T_HTF_in;P=P_HTF)
mu_HTF_in=Viscosity(Water;T=T_HTF_in;P=P_HTF)

"outlet liquid"
Cp_HTF_out=Cp(Water;T=T_HTF_out;P=P_HTF)
k_HTF_out=Conductivity(Water;T=T_HTF_out;P=P_HTF)
rho_HTF_out=Density(Water;T=T_HTF_out;P=P_HTF)
mu_HTF_out=Viscosity(Water;T=T_HTF_out;P=P_HTF)
"averge"
Cp_HTF=(Cp_HTF_in+Cp_HTF_out)/2
rho_HTF=(rho_HTF_in+rho_HTF_out)/2
mu_HTF=(mu_HTF_in+mu_HTF_out)/2
visc_HTF=mu_HTF/rho_HTF
k_HTF=(k_HTF_in+k_HTF_out)/2

"Surfaces"
A_int_un=pi*D_int*Long
A_ext_un=pi*D_ext*Long
A_ext=A_ext_un*n_tubes

"!Volumes"
M_PCM=V_PCM*rho_PCM
```

```
V_PCM2=V_tank2-V_tubes
V_PCM=V_PCM2
V_tank=L^2*Long
V_tank=V_tank2
V_tube_un=0,25*pi*D_ext^2*Long
V_tubes2=V_tube_un*n_tubes
V_tubes=V_tubes2

IPF=100*(V_PCM/V_tank)


"Massic flow and velocity"
m_tube=m_tot_HTF/n_tubes
v_HTF=m_tube/(rho_HTF*0,25*pi*D_int^2)

"Adimensional properties HTF"
Re_HTF=v_HTF*D_int/visc_HTF
Prandtl_HTF=(Cp_HTF*convert(kJ/kg-C;J/kg-C))*visc_HTF*rho_HTF/k_HTF
Nusselt_HTF=Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_ext)
f=(1,58*ln(Re_HTF)-3,28)^(-2)

"Coeficient de transferencia de calor"
h_HTF2=(k_HTF*Nusselt_HTF)/D_int
h_HTF2=h_HTF
```

Appendix 3. EES code: cooling tank with bulk PCM. Discharging mode.

```
Function Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_ext)

If (Re_HTF<2300) THEN
Funcio_Nu:=3,66
ELSE
Funcio_Nu:=((Re_HTF-1000)*Prandtl_HTF*f/2)/(1+12,7*(Prandtl_HTF^(2/3)-1)*sqrt(f/2))
ENDIF

END Funcio_Nu


"Heat transfer equations"
Q=m_tot_HTF*Cp_HTF*(T_HTF_in-T_HTF_out)
Q=(U*A_ext*DELTAT_lm)/1000

DELTAT_lm*ln((T_HTF_in-T_PCM)/(T_HTF_out-T_PCM))=(T_HTF_in-T_PCM)-(T_HTF_out-
T_PCM)

U=1/((R_HTF+R_tube+R_PCM))
        R_HTF=D_ext/(D_int*h_HTF)
        R_tube=D_ext*((ln(D_ext/D_int))/(2*k_tube))
        R_PCM=D_ext*((ln(D_inf/D_ext))/(2*k_efectiva))
"!Requirements"
t_storage=8[h]
E=614,97 [kWh]
Q=E/t_storage
E=M_PCM*DELTAh_PCM*Convert(kJ;kWh)

"!Assumptions"
T_HTF_in=14 [C]
```

```
DELTAh_PCM=332 [kJ/kg]
rho_PCM=1000 [kg/m^3]
k_efectiva=0,58 [W/m-k]
T_PCM=0 [C]

"!Tubes"
D_inf=D_ext*1,85
D_ext=0,0424
D_int=D_ext-0,0032
k_tube=13 [W/m-k]
n_tubes_row=sqrt(n_tubes)
L=n_tubes_row*D_inf

"!Hot tansfer fluid properties"
rho_HTF=1055
Cp_HTF=3,49
mu_HTF=visc_HTF*rho_HTF
visc_HTF=0,00002
k_HTF=0,35

"Surfaces"
A_int_un=pi*D_int*Long
A_ext_un=pi*D_ext*Long
A_ext=A_ext_un*n_tubes

"!Volumes"
M_PCM=V_PCM*rho_PCM
V_PCM2=V_tank2-V_tubes
V_PCM=V_PCM2
V_tank=L^2*Long
V_tank=V_tank2
V_tube_un=0,25*pi*D_ext^2*Long
V_tubes2=V_tube_un*n_tubes
V_tubes=V_tubes2

IPF=100*(V_PCM/V_tank)


"Massic flow and velocity"
m_tube=m_tot_HTF/n_tubes
v_HTF=m_tube/(rho_HTF*0,25*pi*D_int^2)

"Adimensional properties HTF"
Re_HTF=v_HTF*D_int/visc_HTF
Prandtl_HTF=(Cp_HTF*convert(kJ/kg-C;J/kg-C))*visc_HTF*rho_HTF/k_HTF
Nusselt_HTF=Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_ext)
f=(1,58*ln(Re_HTF)-3,28)^(-2)

"Coeficient de transferencia de calor"
h_HTF2=(k_HTF*Nusselt_HTF)/D_int
h_HTF2=h_HTF
```

Appendix 4. EES code: cooling tank with bulk PCM. Charging mode.

```
Function Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_ext)

If (Re_HTF<2300) THEN
Funcio_Nu:=3,66
```

```
ELSE
Funcio_Nu:=((Re_HTF-1000)*Prandtl_HTF*f/2)/(1+12,7*(Prandtl_HTF^(2/3)-1)*sqrt(f/2))
ENDIF

END Funcio_Nu


"Heat transfer equations"
Q=m_tot_HTF*Cp_HTF*(T_HTF_out-T_HTF_in)
Q=(U*A_ext*DELTAT_lm)/1000

DELTAT_lm*ln((T_PCM-T_HTF_out)/(T_PCM-T_HTF_in))=(T_PCM-T_HTF_out)-(T_PCM-
T_HTF_in)
U=1/((R_HTF+R_tube+R_PCM))
        R_HTF=D_ext/(D_int*h_HTF)
        R_tube=D_ext*((ln(D_ext/D_int))/(2*k_tube))
        R_PCM=D_ext*((ln(D_inf/D_ext))/(2*k_efectiva))

"!Requirements"
t_storage=8[h]
E=614,97 [kWh]
Q=E/t_storage
E=M_PCM*DELTAh_PCM*Convert(kJ;kWh)

"!Assumptions"
T_HTF_in=-10 [C]
DELTAh_PCM=332 [kJ/kg]
rho_PCM=1000 [kg/m^3]
k_efectiva=0,58 [W/m-k]
T_PCM=0 [C]

"!Tubes"
D_inf=D_ext*1,85
D_ext=0,0424
D_int=D_ext-0,0032
k_tube=13 [W/m-k]
n_tubes_row=sqrt(n_tubes)
L=n_tubes_row*D_inf

"!Hot tansfer fluid properties"
rho_HTF=1055
Cp_HTF=3,49
mu_HTF=visc_HTF*rho_HTF
visc_HTF=0,00002
k_HTF=0,35

"Surfaces"
A_int_un=pi*D_int*Long
A_ext_un=pi*D_ext*Long
A_ext=A_ext_un*n_tubes

"!Volumes"
M_PCM=V_PCM*rho_PCM
V_PCM2=V_tank2-V_tubes
V_PCM=V_PCM2
V_tank=L^2*Long
V_tank=V_tank2
V_tube_un=0,25*pi*D_ext^2*Long
V_tubes2=V_tube_un*n_tubes
```

```
V_tubes=V_tubes2

IPF=100*(V_PCM/V_tank)


"Massic flow and velocity"
m_tube=m_tot_HTF/n_tubes
v_HTF=m_tube/(rho_HTF*0,25*pi*D_int^2)

"Adimensional properties HTF"
Re_HTF=v_HTF*D_int/visc_HTF
Prandtl_HTF=(Cp_HTF*convert(kJ/kg-C;J/kg-C))*visc_HTF*rho_HTF/k_HTF
Nusselt_HTF=Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_ext)
f=(1,58*ln(Re_HTF)-3,28)^(-2)

"Coeficient de transferencia de calor"
h_HTF2=(k_HTF*Nusselt_HTF)/D_int
h_HTF2=h_HTF
```

Appendix 5. EES code: heating tank with macroencapsulated PCM. Discharing mode.

```
Function Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_h)

If (Re_HTF<2300) THEN
Funcio_Nu:=3,66
ELSE
Funcio_Nu:=((Re_HTF-1000)*Prandtl_HTF*f/2)/(1+12,7*(Prandtl_HTF^(2/3)-1)*sqrt(f/2))

ENDIF
END Funcio_Nu

"Heat transfer equations"
Q=m_tot_water*Cp_HTF*(T_HTF_out-T_HTF_in)

Q=(U*A_ext*DELTAT_lm)/1000

DELTAT_lm*ln((T_PCM-T_HTF_out)/(T_PCM-T_HTF_in))=(T_PCM-T_HTF_out)-(T_PCM-
T_HTF_in)
U=1/((R_HTF+R_wall+R_PCM))
    R_HTF=1/(h_HTF)
    R_wall= 0,002/(k_wall)
    R_PCM=0,016/(k_efectiva)

A_ext_un_tube=pi*D_h*Long
A_ext_tube=A_ext_un_tube*n_water

"!Requirements"
t_storage=8[h]
E=864 [kWh]
Q=E/t_storage
E=M_modules_PCM*DELTAh_PCM*Convert(kJ;kWh)

"!Assumptions"
T_HTF_in=48 [C]
DELTAh_PCM=145 [kJ/kg]
```

```
rho_PCM=1505 [kg/m^3]
k_efectiva=0,69 [W/m-k]
T_PCM=58 [C]
L=3

"!Surfaces"
A_ext_un=L_module_PCM*Long_module_PCM
A_ext=A_ext_un2*n_modules_PCM*2
A_ext_un=A_ext_un2

"!LATICE de PCM"
Long_module_PCM=0,5[m]
L_module_PCM=0,25 [m]
w_module_PCM=0,032 [m]
k_wall=0,5 [W/m-k]

"!Hot tansfer fluid properties"
"Inlet liquid"
P_HTF=1500 [kPa]
Cp_HTF_in=Cp(Water;T=T_HTF_in;P=P_HTF)
k_HTF_in=Conductivity(Water;T=T_HTF_in;P=P_HTF)
rho_HTF_in=Density(Water;T=T_HTF_in;P=P_HTF)
mu_HTF_in=Viscosity(Water;T=T_HTF_in;P=P_HTF)

"outlet liquid"
Cp_HTF_out=Cp(Water;T=T_HTF_out;P=P_HTF)
k_HTF_out=Conductivity(Water;T=T_HTF_out;P=P_HTF)
rho_HTF_out=Density(Water;T=T_HTF_out;P=P_HTF)
mu_HTF_out=Viscosity(Water;T=T_HTF_out;P=P_HTF)

"averge"
Cp_HTF=(Cp_HTF_in+Cp_HTF_out)/2
rho_HTF=(rho_HTF_in+rho_HTF_out)/2
mu_HTF=(mu_HTF_in+mu_HTF_out)/2
visc_HTF=mu_HTF/rho_HTF
k_HTF=(k_HTF_in+k_HTF_out)/2

"!Fictitious HTF tubes"
D_h=(2*L*0,013)/(L+0,013)   "Hydraulic diameter"

"!Dimensions"
L=n_modules_PCM_row*L_module_PCM
H=n_modules_PCM_H*0,045
Long=n_modules_PCM_Long*Long_module_PCM
n_modules_PCM=n_modules_PCM_Long*n_modules_PCM_row*n_modules_PCM_H

"!Volumes"
V_module_PCM=0,0038 [m^3]
M_module_PCM=V_module_PCM*rho_PCM

V_tank2=V_modules_PCM+V_water
V_tank=L*H*Long
V_tank=V_tank2

M_modules_PCM=V_modules_PCM2*rho_PCM
V_modules_PCM2=V_module_PCM*n_modules_PCM
V_modules_PCM=V_modules_PCM2

V_water2=V_water_un*n_water
```

```
V_water_un=0,25*pi*D_h^2*Long
V_water=V_water2

IPF=100*(V_modules_PCM/V_tank)

"!Fictitious HTF tubes condition"
n_water=n_modules_PCM*factor

"!Mass flow rate and velocity"
m_water_un=m_tot_water/n_water
v_HTF=m_water_un/(rho_HTF*0,25*pi*D_h^2)

"Adimensional properties HTF"
Re_HTF=v_HTF*D_h/visc_HTF
Prandtl_HTF=(Cp_HTF*convert(kJ/kg-C;J/kg-C))*visc_HTF*rho_HTF/k_HTF
Nusselt_HTF=Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_h)
f=(1,58*ln(Re_HTF)-3,28)^(-2)
h_HTF2=(k_HTF*Nusselt_HTF)/D_h
h_HTF2=h_HTF
```

Appendix 6. EES code: heating tank with macroencapsulated PCM. Charing mode.

```
Function Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_h)

If (Re_HTF<2300) THEN
Funcio_Nu:=3,66
ELSE
Funcio_Nu:=((Re_HTF-1000)*Prandtl_HTF*f/2)/(1+12,7*(Prandtl_HTF^(2/3)-1)*sqrt(f/2))

ENDIF
END Funcio_Nu

"Heat transfer equations"
Q=m_tot_water*Cp_HTF*(T_HTF_in-T_HTF_out)
Q=(U*A_ext*DELTAT_lm)/1000
DELTAT_lm*ln((T_HTF_in-T_PCM)/(T_HTF_out-T_PCM))=(T_HTF_in-T_PCM)-(T_HTF_out-
T_PCM)

U=1/((R_HTF+R_wall+R_PCM))
    R_HTF=1/(h_HTF)
    R_wall= 0,002/(k_wall)
   R_PCM=0,016/(k_efectiva)

A_ext_un_tube=pi*D_h*Long
A_ext_tube=A_ext_un_tube*n_water

"!Requirements"
t_storage=8[h]
E=864 [kWh]
Q=E/t_storage
E=M_modules_PCM*DELTAh_PCM*Convert(kJ;kWh)

"!Assumptions"
T_HTF_in=65[C]
```

```
DELTAh_PCM=145 [kJ/kg]
rho_PCM=1505 [kg/m^3]
k_efectiva=0,69 [W/m-k]
T_PCM=58 [C]
L=3

"!Surfaces"
A_ext_un=L_module_PCM*Long_module_PCM
A_ext=A_ext_un2*n_modules_PCM*2
A_ext_un=A_ext_un2

"!FLATICE de PCM"
Long_module_PCM=0,5[m]
L_module_PCM=0,25 [m]
w_module_PCM=0,032 [m]
k_wall=0,5 [W/m-k]

"!Hot tansfer fluid properties"
"Inlet liquid"
P_HTF=1500 [kPa]
Cp_HTF_in=Cp(Water;T=T_HTF_in;P=P_HTF)
k_HTF_in=Conductivity(Water;T=T_HTF_in;P=P_HTF)
rho_HTF_in=Density(Water;T=T_HTF_in;P=P_HTF)
mu_HTF_in=Viscosity(Water;T=T_HTF_in;P=P_HTF)

"outlet liquid"
Cp_HTF_out=Cp(Water;T=T_HTF_out;P=P_HTF)
k_HTF_out=Conductivity(Water;T=T_HTF_out;P=P_HTF)
rho_HTF_out=Density(Water;T=T_HTF_out;P=P_HTF)
mu_HTF_out=Viscosity(Water;T=T_HTF_out;P=P_HTF)
Cp_HTF_out=4,179

"averge"
Cp_HTF=(Cp_HTF_in+Cp_HTF_out)/2
rho_HTF=(rho_HTF_in+rho_HTF_out)/2
mu_HTF=(mu_HTF_in+mu_HTF_out)/2
visc_HTF=mu_HTF/rho_HTF
k_HTF=(k_HTF_in+k_HTF_out)/2

"!Fictitious HTF tubes"
D_h=(2*L*0,013)/(L+0,013)   "Hydraulic diameter"

"!Dimensions"
L=n_modules_PCM_row*L_module_PCM
H=n_modules_PCM_H*0,045  "0,045 m és el gruix del FlatICE contant les potetes"
Long=n_modules_PCM_Long*Long_module_PCM
n_modules_PCM=n_modules_PCM_Long*n_modules_PCM_row*n_modules_PCM_H

"!Volumes"
V_module_PCM=0,0038 [m^3]
M_module_PCM=V_module_PCM*rho_PCM

V_tank2=V_modules_PCM+V_water
V_tank=L*H*Long
V_tank=V_tank2

M_modules_PCM=V_modules_PCM2*rho_PCM
V_modules_PCM2=V_module_PCM*n_modules_PCM
V_modules_PCM=V_modules_PCM2
```

```
V_water2=V_water_un*n_water
V_water_un=0,25*pi*D_h^2*Long
V_water=V_water2

IPF=100*(V_modules_PCM/V_tank)

"!Fictitious HTF tubes condition"
n_water=n_modules_PCM*factor

"!Mass flow rate and velocity"
m_water_un=m_tot_water/n_water
v_HTF=m_water_un/(rho_HTF*0,25*pi*D_h^2)

"Adimensional properties HTF"
Re_HTF=v_HTF*D_h/visc_HTF
Prandtl_HTF=(Cp_HTF*convert(kJ/kg-C;J/kg-C))*visc_HTF*rho_HTF/k_HTF
Nusselt_HTF=Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_h)
f=(1,58*ln(Re_HTF)-3,28)^(-2)
h_HTF2=(k_HTF*Nusselt_HTF)/D_h
h_HTF2=h_HTF
```

Appendix 7. EES code: cooling tank with macroencapsulated PCM. Discharging mode.

```
Function Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_h)

If (Re_HTF<2300) THEN
Funcio_Nu:=3,66
ELSE
Funcio_Nu:=((Re_HTF-1000)*Prandtl_HTF*f/2)/(1+12,7*(Prandtl_HTF^(2/3)-1)*sqrt(f/2))

ENDIF
END Funcio_Nu

"Heat transfer equations"

Q=m_tot_water*Cp_HTF*(T_HTF_in-T_HTF_out)

Q=(U*A_ext*DELTAT_lm)/1000
DELTAT_lm*ln((T_HTF_in-T_PCM)/(T_HTF_out-T_PCM))=(T_HTF_in-T_PCM)-(T_HTF_out-
T_PCM)

U=1/((R_HTF+R_wall+R_PCM))
      R_HTF=1/(h_HTF)
      R_wall= 0,002/(k_wall)
      R_PCM=0,016/(k_efectiva)

"!Requirements"
t_storage=8[h]
E=614,97 [kWh]
Q=E/t_storage
E=M_modules_PCM*DELTAh_PCM*Convert(kJ;kWh)

"!Assumptions"
T_HTF_in=14 [C]
DELTAh_PCM=332 [kJ/kg]
rho_PCM=1000 [kg/m^3]
```

```
k_efectiva=0,58 [W/m-k]
T_PCM=0 [C]
L=2

"!Surfaces"
A_ext_un=L_module_PCM*Long_module_PCM
A_ext=A_ext_un2*n_modules_PCM*2
A_ext_un=A_ext_un2

"FLATICE de PCM"
Long_module_PCM=0,5[m]
L_module_PCM=0,25 [m]
w_module_PCM=0,032 [m]
k_wall=0,5 [W/m-k]

"!Hot tansfer fluid properties"
"Water-propylene glycol mixture. 45%"
rho_HTF=1047 [kg/m^3]
k_HTF=0,355 [W/m-K]
Cp_HTF=3,55 [kJ/kg-K]
visc_HTF=0,0000085 [m^2/s]

"!Fictitious HTF tubes"
D_h=(2*L*0,013)/(L+0,013)   "Hydraulic diameter"

"!Dimensions"
L=n_modules_PCM_row*L_module_PCM
H=n_modules_PCM_H*0,045
Long=n_modules_PCM_Long*Long_module_PCM
n_modules_PCM=n_modules_PCM_Long*n_modules_PCM_row*n_modules_PCM_H

"!Volumes"
V_module_PCM=0,0038 [m^3]
M_module_PCM=V_module_PCM*rho_PCM

V_tank2=V_modules_PCM+V_water
V_tank=L*H*Long
V_tank=V_tank2

M_modules_PCM=V_modules_PCM2*rho_PCM
V_modules_PCM2=V_module_PCM*n_modules_PCM
V_modules_PCM=V_modules_PCM2

V_water2=V_water_un*n_water
V_water_un=0,25*pi*D_h^2*Long
V_water=V_water2

IPF=100*(V_modules_PCM/V_tank)

"!Fictitious HTF tubes condition"
n_water=n_modules_PCM*factor

"!Mass flow rate and velocity"
m_water_un=m_tot_water/n_water
v_HTF=m_water_un/(rho_HTF*0,25*pi*D_h^2)

"Adimensional properties HTF"
Re_HTF=v_HTF*D_h/visc_HTF
Prandtl_HTF=(Cp_HTF*convert(kJ/kg-C;J/kg-C))*visc_HTF*rho_HTF/k_HTF
```

```
Nusselt_HTF=Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_h)
f=(1,58*ln(Re_HTF)-3,28)^(-2)
h_HTF2=(k_HTF*Nusselt_HTF)/D_h
h_HTF2=h_HTF
```

Appendix 8. EES code: cooling tank with macroencapsulated PCM. Charging mode.

```
Function Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_h)

If (Re_HTF<2300) THEN
Funcio_Nu:=3,66
ELSE
Funcio_Nu:=((Re_HTF-1000)*Prandtl_HTF*f/2)/(1+12,7*(Prandtl_HTF^(2/3)-1)*sqrt(f/2))

ENDIF
END Funcio_Nu

"Heat transfer equations"
Q=m_tot_water*Cp_HTF*(T_HTF_out-T_HTF_in)

Q=(U*A_ext*DELTAT_lm)/1000

DELTAT_lm*ln((T_PCM-T_HTF_out)/(T_PCM-T_HTF_in))=(T_PCM-T_HTF_out)-(T_PCM-
T_HTF_in)

U=1/((R_HTF+R_wall+R_PCM))
     R_HTF=1/(h_HTF)
     R_wall= 0,002/(k_wall)
    R_PCM=0,016/(k_efectiva)

"!Requirements"
t_storage=8[h]
E=614,97 [kWh]
Q=E/t_storage
E=M_modules_PCM*DELTAh_PCM*Convert(kJ;kWh)

"!Assumptions"
T_HTF_in=-10 [C]
DELTAh_PCM=332 [kJ/kg]
rho_PCM=1000 [kg/m^3]
k_efectiva=0,58 [W/m-k]
T_PCM=0 [C]
L=2

"!Surfaces"
A_ext_un=L_module_PCM*Long_module_PCM
A_ext=A_ext_un2*n_modules_PCM*2
A_ext_un=A_ext_un2

"!FLATICE de PCM"
Long_module_PCM=0,5[m]
L_module_PCM=0,25 [m]
w_module_PCM=0,032 [m]
k_wall=0,5 [W/m-k]
```

```
"!Hot tansfer fluid properties"
"Water-propylene glycol mixture. 45%"
rho_HTF=1047 [kg/m^3]
k_HTF=0,355 [W/m-K]
Cp_HTF=3,55 [kJ/kg-K]
visc_HTF=0,0000085 [m^2/s]

"!Fictitious HTF tubes"
D_h=(2*L*0,013)/(L+0,013)   "Hydraulic diameter"

"Dimensions"
L=n_modules_PCM_row*L_module_PCM
H=n_modules_PCM_H*0,045
Long=n_modules_PCM_Long*Long_module_PCM
n_modules_PCM=n_modules_PCM_Long*n_modules_PCM_row*n_modules_PCM_H

"!Volumnes"
V_module_PCM=0,0038 [m^3]
M_module_PCM=V_module_PCM*rho_PCM

V_tank2=V_modules_PCM+V_water
V_tank=L*H*Long
V_tank=V_tank2

M_modules_PCM=V_modules_PCM2*rho_PCM
V_modules_PCM2=V_module_PCM*n_modules_PCM
V_modules_PCM=V_modules_PCM2

V_water2=V_water_un*n_water
V_water_un=0,25*pi*D_h^2*Long
V_water=V_water2

IPF=100*(V_modules_PCM/V_tank)

"!Fictitious HTF tubes condition"
n_water=n_modules_PCM*factor

"!Mass flow rate and velocity"
m_water_un=m_tot_water/n_water
v_HTF=m_water_un/(rho_HTF*0,25*pi*D_h^2)

"Adimensional properties HTF"
Re_HTF=v_HTF*D_h/visc_HTF
Prandtl_HTF=(Cp_HTF*convert(kJ/kg-C;J/kg-C))*visc_HTF*rho_HTF/k_HTF
Nusselt_HTF=Funcio_Nu(Re_HTF;Prandtl_HTF;f;D_h)
f=(1,58*ln(Re_HTF)-3,28)^(-2)
h_HTF2=(k_HTF*Nusselt_HTF)/D_h
h_HTF2=h_HTF
```