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Thermal Storage System Development for a 1 MW CSP Pilot Plant Using an Organic Rankine Cycle

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Abstract

Molten salt has been widely used for heat storage on Concentrated Solar Power plants and even as heat transfer fluid in some cases. Morocco has become in the past years a highly attractive place for CSP projects, one of the most promising projects under development is a 1 MW Pilot CSP using an Organic Rankine Cycle. The plant's particular configuration imposes working temperatures ranging from 170°C up to 270°C-285°C, so that the use of salt as a conventional sensible heat storage medium is no more possible. In this work we focus on how to implement molten salt as a phase change material for storage purposes. A comparison with other technologies has to be studied in order to define the economical ant technical competitiveness of this solution toward those other possibilities, and then a numerical model may help describe the systems behavior in terms charge/discharge processes, HTF temperatures and rated thermal power output. A small scale prototype shall be built later to test those parameters in real environmental conditions.

Key-words: Concentrated Solar Power, Organic Rankine Cycle, molten salt, phase change material…

1. Introduction

Morocco is engaged since 2008 in a highly ambitious renewable energy policy, this led to the establishment of the Moroccan solar plan which aims the achievement of 2000 MW solar capacity by 2020. To support this solar program by tightening the link between academics and industrials and reinforcing their presence and participation to research and innovation in this field, IRESEN was created in 2011 under the frame of the ministry of energy and mines as a research institute and funding agency for universities and industries. Among the main roles of IRESEN as a research center is to procure research facilities for Moroccan researchers, this task is now being achieved through the construction of the GREEN ENERGY PARK platform in the New City Mohammed VI – Benguerir. This new research facility shall include many laboratories and demonstration projects for both photovoltaic and thermal solar technologies.

Thermal storage is both a strong point for solar thermal power plants and a component with high improvement potential. The Research Institute on Solar Energy and New Energies (IRESEN) is currently developing a pilot solar power plant using an Organic Rankine cycle in the framework of the recently launched GREEN ENERGY PARK research platform, this plant shall operate at relatively low temperatures in comparison with large scale commercial plants, and then shall require a well suited storage system in order to improve economic efficiency and enable production shifting to peak hours.

The main features and advantages of the targeted CSP-ORC pilot plant are:

- Modularity of the power block that makes transport, installation operation much easier,
- The use of relatively low pressures on turbine inlet and atmospheric pressure on the condenser which results in low maintenance requirements,

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- The low evaporation temperature of the organic fluids and their other properties allow the use of relatively low working temperatures or "medium grade" heat (TSF-outlet<300C°),
- The use of low working temperatures on the power block reduces the needed temperatures at the heat source (solar field) and then gives more opportunity to profit from the solar collectors and optimize them.

A study based on the cost and storage capacity has led to the choice of two systems: sensible heat storage in a rock (quartzite) packed bed and latent heat storage on encapsulated molten salt. A model has subsequently been developed in order to enable the assessment of both systems' performances and in particular for the encapsulated salt solution for which a hexagonal close packing with spherical capsules was selected taking inspiration from hexagonal crystal structures. This model calculates the heat exchange between the heat transfer fluid HTF and the storage medium by computing the dimensionless numbers and HTF flow on each horizontal plane following flow direction and for a whole discharge duration. The results enable to tell whether the output of the encapsulated salt system is high enough to justify its cost. It also allows choosing the best design, sizing and the best configuration to optimize the systems' output to the maximum.

2. Basic comparison of the proposed technologies

Among the existing thermal storage technologies, four alternatives were considered for prototyping, each of them representing a different approach:

- Sensible heat storage using a direct approach: this is the simplest way of storing thermal energy and is best suited for small capacities; the efficiency depends on the HTF used;
- Sensible heat storage using an indirect approach: this approach is now used for large solar plants and has proven a high efficiency and reliability;
- Sensible heat storage using Thermocline approach: this technology is still being improved and new materials are being studied in order to reduce storage cost;
- Latent heat storage using Thermocline approach: this solution combines the advantages of a direct storage approach and thermocline technology, the use of phase change materials shall increase further systems density and reduce costs.

Other TES technologies can be considered for study in the near future. Chemical heat storage for example is a promising technology that is on development stage and can be deployed on the long term.

2.1. Sensible heat storage using a direct approach

This approach consists on using the heat transfer fluid as a storage medium a storage tank is intended to store the heated HTF. In this case storage capacity depends on tank volume, HTF thermal properties and temperature difference between hot stream and cold stream on the solar field. When charging the storage system, the hot HTF is filed into the tank and is kept at high temperature using a proper thermal insulation. When discharging the system, a second tank is required in order to store the cold HTF and prevent it from mixing with the hot fluid.

Storage capacity can be defined as follows:

$$\Delta h = \Delta T \times C \times \rho \times V$$

(eq. 1)

where ΔT is cold/hot stream temperature difference used on the plant, C & ρ are the specific heat and density of the fluid and V the total storage volume. In our case the fluid to be considered is Therminol VP-1 (Solutia).

Cold/Hot stream temperatures are respectively 185°C and 285°C meaning a temperature difference of 100°C.

The parameter that needs to be calculated is the required storage volume in order to achieve the desired storage capacity. Considering storage for 3 hours, this means a storage capacity of 15 MWh. The required storage volume can then be deducted as follows:

$$V = \frac{\Delta h}{\Delta T \times C \times \rho}$$

(eq. 2)

Considering Therminol VP-1 properties at 285°C (ρ_{285}=888kg/m3 & $C_{m185\text{-}285}$=555kJ/kg°K) the total required volume is 200m3.

In this regard additional piping and a certain amount of HTF needs to be envisaged in addition to two storage tanks. There is no need in this case for any additional heat exchanger; this must be taken into account when calculating system's investment cost.

The table below gives an estimated volume requirement for a 15 MWh storage capacity with various heat transfer fluids.

Tab. 1: Volume requirement calculation for various heat transfer fluids

fluid	density at 285°C	average C at 185-285°C		Total HTF amount (t)	Total volume (m3)
		kJ/kg K	Wh/kgK		
pressurized water at 75 bar	0,752	4,79	1,33	112,74	149,91
saturated steam at 65 bar	0,032	7,41	2,06	72,875	2277,33
Therminol VP-1	0,833	2,12	0,59	254,72	305,78
Delco therm Solar E15	0,645	2,65	0,74	203,77	315,93

It clearly appears that fluid properties and especially specific heat are the most influential factors affecting the storage volume requirement. Here for example the approach is more relevant for a cycle with pressurized water than for oil or steam.

2.2. Sensible heat storage using an indirect approach

In order to overcome the HTF specific heat barrier, an interesting alternative consists on using a high volumes' specific heat storage medium/fluid which is different from the used HTF. Consequently the storage fluid must be placed in a separate circuit and a heat exchanger is needed to transfer the heat from the HTF to the storage and vice-versa, for this reason it is referred to as indirect storage.

The most common material used for indirect storage in large commercial CSP plants is "solar salt" a binary eutectic mixture of Sodium Nitrate (60%) and Potassium Nitrate (40%). However, this mixture has the disadvantage of freezing at temperatures within the range of solar field working temperatures for the CSP-ORC pilot project. This makes it non relevant for the project as the temperature range in which the mixture can be used is limited by its freezing temperature and HTF hot stream peak temperature. Other binary and tertiary mixtures with lower freezing temperatures were developed for solar plants (Agyenim et al. 2009). One of the most famous is HITEC salt which is a mixture of Potassium Nitrate, Sodium Nitrate and Sodium Nitrite (Coastal Chemical Co.). The table below summarizes the main properties of tree different salt mixtures and their storage volume requirement.

Tab. 2: Required volume and thermal properties for some salt mixtures (Janz et al. 1972; Blake et al. 2002; Villada et al. 2014)

Salt mixture	Freezing temperature	density at 300°C	average C at 300°C		Total salt amount (t)	Total volume (m3)
			kJ/kg°K	Wh/kg°K		
Hitec XL (42% CaNO3, 15% NaNO3, 43% KNO3) in 59% water	120	1,992	1,447	0,402	373,19	187,34
Hitec (7% NaNO3, 53% KNO3, 40% NaNO2)	142	1,67	1,621	0,45	333,13	199,48
Solar salt (60% NaNO3, 40% KNO3)	220	1,899	1,495	0,415	361,2	190,21

The table shows that in general, salts enable a lower volume requirement than heat transfer oils for the same heat storage capacity. The required quantity is however much higher for salts than for oils which can affect the cost of the system. Note that Solar Salt is given here for comparison purposes and cannot be envisaged in this case for the previously mentioned reasons.

2.3. Thermocline approach (sensible heat)

Thermocline systems with rocks and slags packed bed were considered since later 90's in order to reduce storage cost per MWh. It is a passive solution which means that storage material is contained in a separate tank, the HTF flows into the tank and collects/stores the heat stored in the filling material (rocks/slags/sands) during a discharge/charge process. In that case one tank is sufficient and no additional heat exchanger is required as the HTF is placed directly in contact with the filling material. Systems storage density is dictated here by the filling material and its physical properties, a material with a higher specific heat will enable a higher storage capacity per storage volume. Several materials have been envisaged as Marble, Quartzite rocks, NM limestone, Taconite pellets and some local rocks in Morocco. Table 3 shows some Moroccan rocks which were studied for thermal storage purposes and some of their most relevant properties.

Tab. 3: Volume requirement calculation for various Moroccan rocks (Grirate et al. 2000)

Rock	density	average C at 300°C		Total salt amount (t)	Total volume (m3)
		kJ/kgK	Wh/kgK		
Granite	2,82	0,62	0,172	870,968	308,854
Bazalte	3,02	0,95	0,264	568,421	188,219
Quartzite	2,57	0,84	0,233	642,857	250,139
Marble	2,68	0,93	0,258	580,645	216,659
Hornfels	2,74	0,88	0,244	613,636	223,955

The required amounts of rocks that are needed to fulfill the required storage capacity are tremendous when compared with the previously studied solutions; this is due to the high density of these materials. However, even though the mass is high, volume requirement is still around 200m 3. This is also compensated with the relatively low cost of those materials. It is important to note that the table shows only the amount and volume of materials that can store the specified 15 MWh of heat, in this particular case the total needed amount of filler material shall be reduced and compensated with a certain amount of HTF that is sufficient to cover the lost storage capacity. This HTF addition is due to the structure of the packed bed and the added quantity of HTF shall depend on rocks size and disposition. This will be discussed in parts 2.4 and 2.5.

2.4. Thermocline approach (latent heat):

In this approach we try to replace the rocks or slag pellets as for the system described in 2.3 with an encapsulated phase change material. Phase change materials are substances with freezing/melting temperatures in the range of temperatures encountered in the solar field, and preferably closer to the hot stream temperature. For our CSP-ORC project we taught it would be sound to opt for solar salt as PCM due to its compatibility with the range of HTF temperatures.

In order to prevent molten salt from mixing with the HTF and penetrating the solar field piping, an appropriate encapsulation has to be envisaged in order to separate those components and allow a proper heat transfer between them. The first encapsulation mode that was considered was inspired from crystal's hexagonal close packing; hence the chosen encapsulation shall have a spherical shape (Nallusamy et al. 2007). Solar salt properties were exposed earlier in part 2.2, based on these data we can calculate the gross necessary amount and volume as follows:

$$V = \frac{\Delta h}{\Delta T_s \times C_s + \Delta T_l \times C_l + L_f}$$

(eq. 3)

Where L_f is the latent heat of fusion which equals 161kJ/kg, $C_l = 1.495kJ/kg°K$ is the sensible heat at liquid phase, $C_s = 0.8kJ/kg°K$ is the sensible heat at the solid phase, $\Delta Ts = 35°K$ is temperature difference between cold HTF stream and salt melting temperature in which salt is on the solid phase and $\Delta Tl = 65°K$ is temperature difference between hot HTF stream and salt melting temperature in which salt is on the liquid phase. The resulting volume is around $100m^3$. This volume is much lower than those observed for other systems and demonstrates the advantage of exploiting the latent heat of PCM's. As for the previous thermocline system, salt is not the only component that must be taken into account but also oil and in that particular case, steel that constitutes capsule's outer coating for each must be accounted.

In that case, and due to the hexagonal close packing, the volume occupied by the capsules is 74% of the total storage system volume; this means a ratio of 26m^3 of oil (HTF) for 74m^3 of capsules. Capsules coating is 5mm thick for a capsule diameter of 20cm. This results in 63.5m^3 of salt and 10.5m^3 of steel for a 100m^3 total volume. These values however do not allow reaching the desired storage capacity and have to be updated for a proper economical comparison of all systems.

2.5. Economical comparison of the proposed technologies

Storage density is not the only determining factor for the choice of the appropriate storage technology, the cost per kWh storage capacity will define which technology is most relevant for the CSP ORC plant in terms of economic efficiency.

For comparison purposes, the following elements were taken into account (Pacheco et al. 2001):

- Quartzite, marble and a mixture of them both shall be studied as filler material for the “sensible” thermocline system with the following respective prices (50$/t, 127$/t and 88.5$/t for the mixture);
- A volume ratio of 74% filler material and 26% HTF shall be used for all thermocline systems;
- For the “latent heat” thermocline system or “PCM system”, the cost set for steel capsules varies from 1 to 6$/unit covering a total of ~18000 capsules;
- The cost of salt/oil heat exchanger was assumed to be 240000$ for a 5MW heat flow;
- The cost of tanks was assumed to be 155$/m3 except for Water for which a pressurized tank is intended with an estimated cost of 1500 $/m3.

The following table shows a comparison of volume (with recalculated volumes for thermocline systems) and system cost for all solutions and with various materials.

Tab. 1: Comparison of total cost and volume requirement for the proposed storage solutions

Storage solution	Configuration	filling material		Tanks and heat exchangers	total volume	total cost (k$)	Specific cost ($/kWh)
		material	Cost (k$)				
Sensible heat storage using the HTF	pressurized water at 75 bar	Demineralized Water	0	450000	300	450	30
	Therminol VP-1 (thermal oil)	Therminol VP-1	1009	94891	612,2	1104	73,64
	Delco therm Solar E15	Delco therm Solar E15	609	96875	625	706	47,10
Sensible heat storage with molten salt	two tanks with Hitec	Hitec salt	310	302000	400	612	40,84
	two tanks with Hitec XL	Hitec XL salt	534	298125	375	832	55,48
Thermocline with rocks and slags	thermocline with marble	marble	58	36022	232,4	293	19,58
		Therminol VP-1	200				
	thermocline with quartzite	quartzite	248	40695,25	262,55	290	19,38
		Therminol VP-1	225				
	mixed marble & quartzite	mixet rocks	54	38207,5	246,5	304	20,27
		Therminol VP-1	211				
Thermocline with PCM	solar salt and Therminol VP-1	Therminol VP-1	176	31852,5	205,5	365 to 510 k$	23 to 29 $/kWh
		Solar salt	121				
		Steel capsules	180 to 108 k$				

The table shows that both volume and cost requirement for systems with "HTF tanks" using a direct approach and systems with based on salt (indirect storage) are much higher than thermocline systems. These appear to be the only capable of achieving a specific cost below 30 $/kWh.

For thermocline system with encapsulated salt, cost highly depends on encapsulation process and the cost per capsule.

From this first comparison we can conclude that the technologies that have the potential for increasing the economic efficiency if integrated to a CSP plant are thermocline technologies with both the sensible heat “quartzite system” and latent heat “PCM system” options.

The economic aspect was very helpful to define the most eligible technologies; however, a technical comparison between both systems performance is required to decide which one is the most appropriate for the CSP-ORC project.

3. Thermal output analysis for thermocline solutions

A thermal storage system can be characterized by its storage capacity and its ability to store energy and to deliver energy with the appropriate heat flow during discharge to allow a sufficient heat input to the Organic cycle. The studied system was dimensioned to supply a 1MWe Organic Rankine Cycle for three hours of continuous operation. Assuming that the power block has a rated efficiency of 20%, this means a thermal input of 5MW. A simple model based on a deterministic approach was developed in order to study heat exchanges that occur inside the selected storage systems and to evaluate their heat output behavior.
As explained in section 2.4, both selected systems are configured with a close packing of spherical elements, this spherical shape was selected to allow a larger contact surface with the circulating fluid (HTF) and a better convective heat transfer. This is also intended to make comparison between systems more relevant as it is easier to imagine rock pebbles with a spherical shape. Hence, to simplify calculations and put both systems in an equitable simulation level, quartzite blocks/pebbles were assumed to have a quasi-spherical shape and an approximate diameter of 20cm.

3.1. Assumptions and boundary conditions

Regarding the existing CSP plants and especially the planed CSP-ORC pilot operation mode, systems charging will not constitute a big issue, despite the low thermal conductivity limitation, thermal storage systems have generally sufficient time for charging as solar resource is basically available all day time and peak solar irradiation can span up to eight hours in summer days. A greater attention was granted to discharging mode as the system will have to deliver a specific power to the organic cycle to enable an operation load that guaranties acceptable cycle’s efficiency.

The following assumptions were made for the results presented in this work:

- Convective heat transfer was the only heat exchange considered for calculations;
- Flow velocities were supposed homogeneous at all point on horizontal planes, the average flow velocity only depends of height;
- Capsules were considered as solid volumes and heat transfer inside each capsule was not taken into account;
- The selected rock is quartzite;
- Heat losses are not considered.

Initial and boundary conditions were defined as follows:

- Mass flow is set to 0.03 m3/s;
- Initial HTF and capsules/pebbles temperatures are respectively 170°C and 270°C;
- Initial stored energy density is 185kWh/m3 for PCM capsules and for rock pebbles;
- PCM freezing temperature is 260°C;
- Storage tanks for both systems were programmed with a vertical cylinder shape, base diameter is the identical for both systems 5m, and only height is different due to the difference in total tank volume;

- The system is divided into small volume elements “thin horizontal discs”; each disc is 2.8 mm thick (figure 1).

3.2. Calculation process

The model is built in such a way that enables to calculate the average heat transfer rate at each horizontal plane and the total heat exchanged at each volume element (disc) between two successive planes. The diagram on figure 1 shows model operation and the different calculation phases.

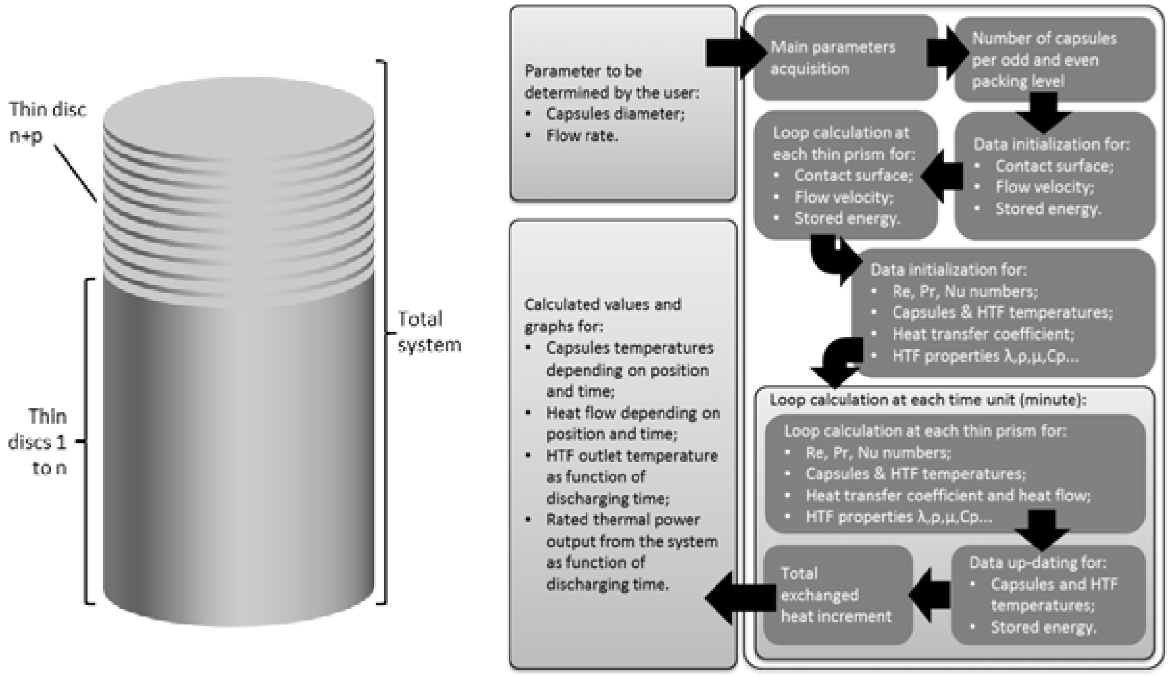

Fig. 1: system discs cuttings & layers disposition (left) and algorithm operation steps (right)

Calculations start at the bottom of the system, a first phase calculates steady values for the whole system, including:

- Contact surface Ac_i;
- Initially stored energy at time (t=0) $Qc_{i,0}$;
- Flow velocity V_i,…

The second phase concentrates on dimensionless numbers and heat transfer. Before running those specific parts, the model starts by calculating the number of capsules needed for the system at each packing level depending on capsule diameter, this number shall determine the contact surface and flow section but will have no effect on the stored energy quantity. Flow velocity (V_i) is determined from flow section (A_i) and the volume flow rate ($\frac{dv}{dt}$) as follows:

$$V_i = \frac{dv}{dt} \Big/ A_i \qquad \text{(eq. 4)}$$

i is the plane (disc) coefficient.

HTF properties are calculated at each loop as function of the temperature; these properties in addition to the parameters calculated earlier (flow velocity, stored energy and contact surface) are necessary to determine the dimensionless numbers (Re, Pr, Nu). These are calculated for all volume elements and for each minute from discharge process trigger to complete systems discharging (3 hours later).

Convective heat transfer coefficient (h) and heat flow ($\dot{Q}$) are calculated through equations (5) and (6). The amount of energy that was transferred is then deducted from the stored heat on the capsules which leads HTF and capsules temperatures to be updated at the end of each calculation loop.

$$h_{i,t} = \frac{k_{i,t} Nu_{i,t}}{L} \qquad \text{(eq. 5)}$$

$$\dot{Q}_{i,t} = h_{i,t} Ac_i \left(Tc_{i,t} - Tf_{i,t}\right) \qquad \text{(eq. 6)}$$

Where L is the characteristic length, k the thermal conductivity of the HTF, Tc and Tf are PCM/Quartzite and HTF temperatures.
The total heat output (P) of the system is measured by summing-up heat flow at a specific time and for the whole system.

$$P_t = \sum_i \dot{Q}_{i,t} \qquad \text{(eq. 7)}$$

4. Results and conclusions

The algorithm was applied to thermocline systems with encapsulated molten salt and with quartzite pebbles. Preliminary results for heat output and outlet temperatures are shown for both systems in the next figures.

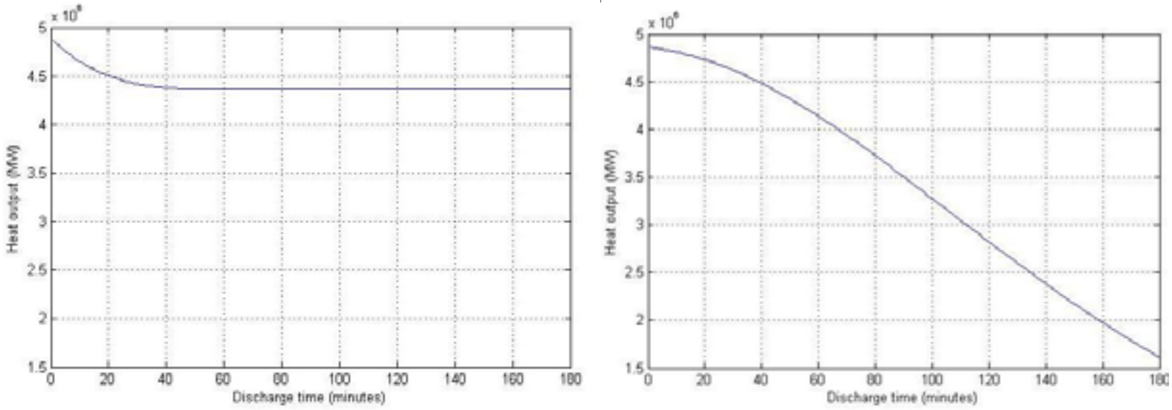

Fig. 2: Heat output during 3 hours of discharge for PCM system (left) and Quartzite system (right)

Heat output simulation has shown that both studied systems did not achieve the required 5MWth output. For the system with PCM capsules, heat flow decreases during the first 40 minutes of discharging than stabilizes at around 4.4MWth. The first decrease in heat flow is due to a first PCM temperature drop during the liquid phase, given that the PCM is at 285°C, meaning 25°C higher than freezing temperature, the first minutes of discharging process cause an automatic PCM temperature drop. A second heat flow decrease was expected at the end of the process due to PCM temperature drop during the solid phase (Nithyanandam et al. 2012); Figure 2 does not show such a feature because in that particular case, heat output was not sufficient to totally empty the system within the 3 hours of discharge. Detailed heat flow simulation has also shown that the lower PCM layers (discs) are more subject to these temperature drops as temperature gradient with the HTF is higher at the bottom of the system.

System with Quartzite shows a completely different behavior, heat output starts to decrease during the first 40 minutes of discharge with a less steep gradient than for PCM system. After the first hour, heat flow decrease starts to accentuate until the end of the process.

When comparing the studied systems, following comments can be made:

- PCM System allows a more stable heat supply that the Quartzite system;
- By supplying only 4.4MWth, heat delivered by the PCM system is only sufficient to drive the ORC at 80% to 90% capacity;
- During the first hour of discharging, quartzite system can feed sufficient heat to drive the ORC at more than 80% of its capacity. During the second hour, the average operation rate of the ORC is barely around 50% of the total power capacity. During the last hour of discharging, Power Block efficiency starts decreasing critically until the heat flow becomes insufficient to activate the ORC; hence no power is generated anymore.

Temperature simulations resulted in similar shapes for both systems; however, temperature gradient for the quartzite system is slightly less accentuated than heat flow gradient.

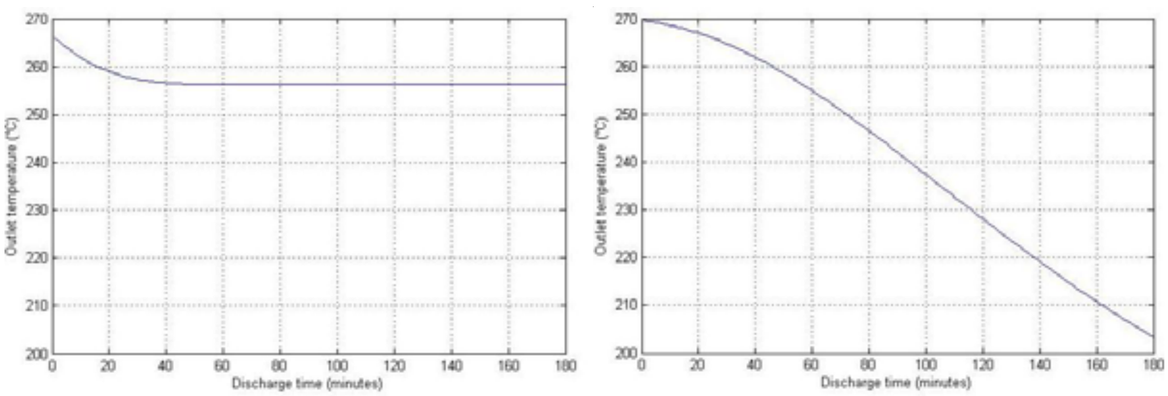

Fig. 3: Outlet temperature during 3 hours of discharge for PCM system (left) and Quartzite system (right)

Temperature variation inside the system tends to confirm the analysis that was done for heat output. For PCM system, a more appropriate salt mixture selection can enable achieving a higher freezing temperature this combined with a particular operation can lead to a system with a stable 5MWth output. In addition, while quartzite system power output can still be controlled through mass flow with some difficulty, it is impossible to maintain outlet temperature when the temperature inside the system. Ultimately the effective "useful" storage capacity is 50% to 60% the gross capacity for which the system was dimensioned, in other words, the quartzite system can only deliver half of the stored energy with the appropriate flow and temperature.

As a final conclusion we can say that for the studied systems, cost disadvantage of the PCM solution in comparison to a rock thermocline is largely compensated by the lower efficiency of the second system.

5. Acknowledgement

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