COMHPTES

Flexible Compact Modular Heat Pump and PCM based Thermal Energy Storage System for Heat and Cold Industrial Applications

D3.1 Preliminary COMHPTES TES concept and media selection

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Executive summary

In this deliverable the COMHPTES thermal energy storage system (TES) is preliminary defined. The TES will store the heat pump (HP) thermal energy as latent heat in a phase change material (PCM). Therefore, Section 2 will be focused on understanding the operational conditions of the COMHPTES system to adequately integrate the TES with the HP and the industrial processes demand. In this sense, three different cases of application of the system for industrial processes were analysed in order to identify the requirements of the TES. The first conclusion was that the HP can provide a high lift of temperature in the hot side, thus a cascaded PCM arrangement with different levels of temperature was required.

Once the requirements of the TES were identified, a screening of the PCM available in the literature was carried out to find candidates for the cascaded PCM in Section 3. From these candidates, a pre-selection was performed based on the melting temperature, a high latent heat, a low cost and a low hazard level. Inorganic salt PCM have been identified as a target group due to their high melting temperature and high latent heat. However, this component presents low conductivity which is drawback in the TES application. Therefore, enhancement techniques were analysed to improve the thermal conductivity of the PCM in Section 4.

From the three industrial cases analysed, the steam generation at 10 barg was selected to be prototyped and tested in the test-bench at Universidad de Sevilla. The other scenarios, which required a lower range of temperature between 120-190 °C, were discharged because limited options of PCM were found.

Finally, in Section 5, a preliminary design of the TES system is proposed for the two cascaded defined in Section 3.3. A first estimation of the PCM modules size and geometry is presented in this section.

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1. Introduction

The main objective of this deliverable is to develop a conceptual design of the thermal energy storage for the COMHPTES system. For this conceptual design it is required to understand the heat pump (HP) requirements and the industrial process to define the correct range of temperature of the cascaded PCM.
Therefore, in the Section 2, a layout analysis is carried out to identify the temperature requirements for three different industrial processes. One of these configurations will be selected to be tested in the University of Sevilla (USE) testing facilities.
Based on the results obtained of temperature required from the TES integration analysis a screening of PCM candidates will be carried out in Section 3. This screening will be mainly focused on PCM from literature and commercial data sheets. The desirable properties of a PCM can be summarized in the next bullet points:

- High latent heat storage capacity.
- Melting temperature in the range of interest of the system.
- High specific heat and thermal conductivity
- Easiness in handling and not imposing health hazards to the people or the environment.
- Thermal cycling stability: thermal properties need to remain almost constant during a certain number of thermal cycles.
- Thermal stability: maximum working temperature.
- Compatibility with the metal selected to build the heat exchanger that will contain the PCM.
- Suitable price.
- Atmospheric stability: PCM should be stable in the atmospheric conditions of the storage tank.
- Minimum volume variation and low vapor pressure to reduce the mechanical requirements of the container.

After completion of the literature screening a first selection of possible PCM candidates will be based on the next properties: high latent heat, lower cost and lower hazard level. PCMs with issues in stability or corrosiveness will be dismissed from the final selection.

2. Layout integration between the Heat Pump & TES

In this section the thermal energy storage (TES) medium will be selected to better fit the COMHPTES system, which is depicted in Figure 1. A latent heat medium was selected due to its higher storage density than a sensible heat, implying a footprint and cost reduction. The most important factor in the TES integration is to fit with the requirements of the Heat Pump (HP) heat sink. The heat sink corresponds to the heat exchanger (HX) between the CO_2 from the compressor and the Hot HTF. The main objective of the TES is to store the heat produced by the Heat Pump (HP). Therefore, the HP can be uncoupling for the industrial demand and work when waste heat is available, increasing the COP, or when electricity is cheap, reducing the cost of heat.

The company SynchroStor, dedicated to the HP development, have previously evaluated different scenarios for the HP integration with industry, which are part of deliverable *"D2.1 Definition of HP cycles and boundary conditions for validation".* Three main heat applications were identified in several industral sectors like food, chemical, pulp & paper; these are: steam at 10 barg, open loop drying with air and a combination of heating a cooling.

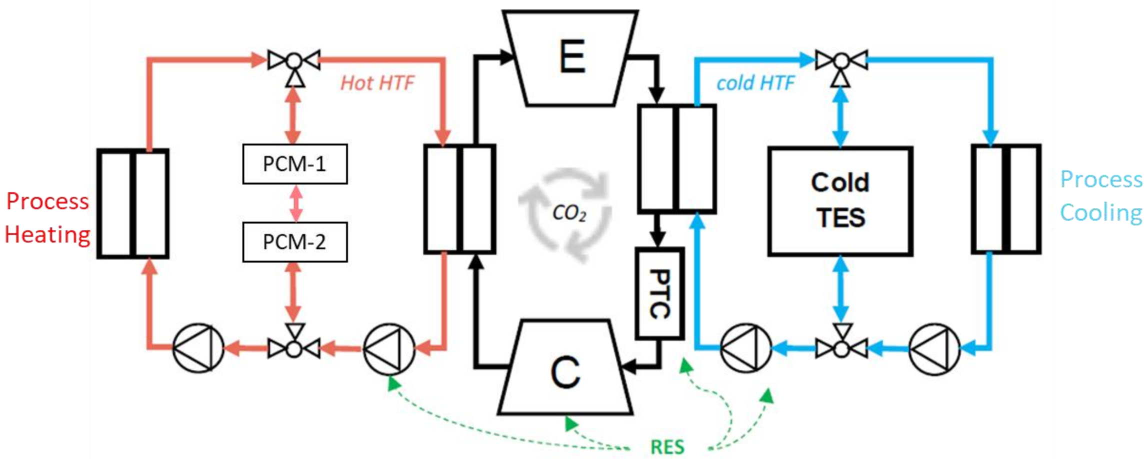

Figure 1: Integration diagram for the COMHPTES system.

2.1 Steam 10 barg

Figure 2 depicts the Pressure vs Enthalpy diagram for the HP for the steam generation scenario. The diagram shows that a high temperature is reached in the heat sink, with a maximum of 400 °C. Therefore, molten salts have been chosen as the hot HTF due to their good heat transfer properties at high temperatures. To maintain a COP of 1.6, a high temperature (150 °C) is required in the source, thus, a Parabolic Trough Collector (PTC) is used to boost the temperature from the waste heat.

The cascaded PCM will be charged directly with the molten salts coming from the CO_2/MS HX. For the discharge, the hot MS from the cascaded PCM will be directed to the Steam/MS HX. Figure 3 shows the temperature profiles in the different fluids of the system. The lower temperature level is imposed by the steam requirements which are 185 °C. In the upper boundary the limitation is 400 °C, which is defined by the HP maximum temperature. Thus, the temperatures for the PCM cascade are defined between 200 – 380 °C. In Section 3, the PCM with melting temperature inside this range are presented.

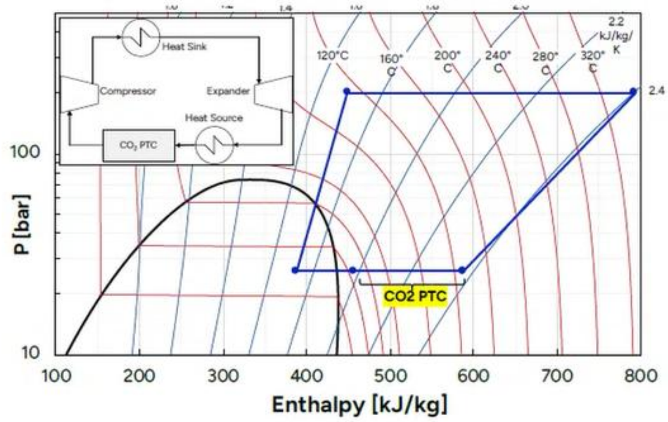

Figure 2: Heat pump pressure versus enthalpy diagram for Steam.

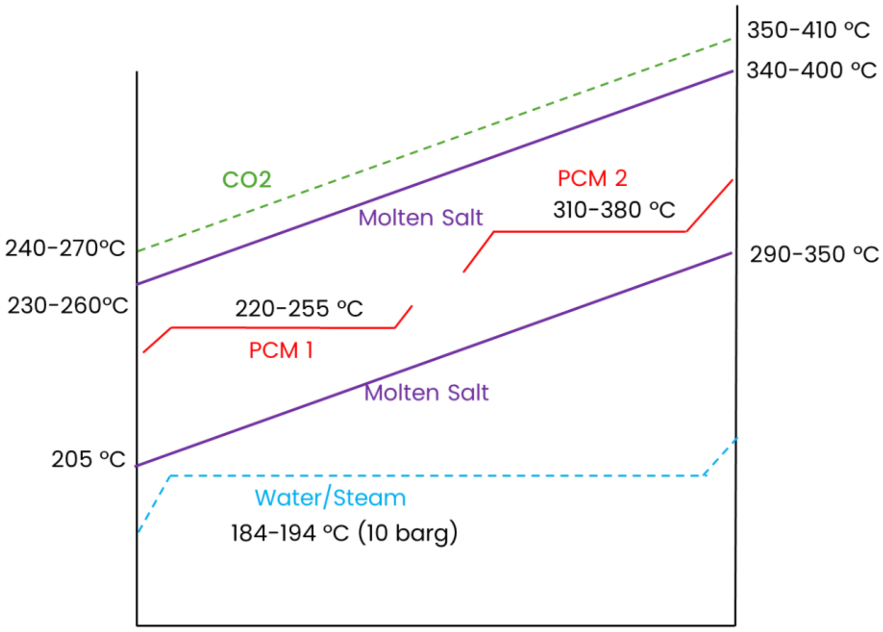

Figure 3: Temperature profiles in the different fluids of the system with cascade PCM, from the top: CO_2/ MS HX, MS/PCM/MS, MS/ Steam.

As the HP is capable of higher lifts of temperature, the alternative of using a sensible TES is also analysed. The benefit of using molten salts instead of a PCM is that the same media can be used as the HTF and the storage tank, which reduces the pinch point between the temperature profiles as is depicted in Figure 4. The main disadvantage is that two storage tanks are required, one for the cold salt and the second for the hot salt, as is illustrated in Figure 5.

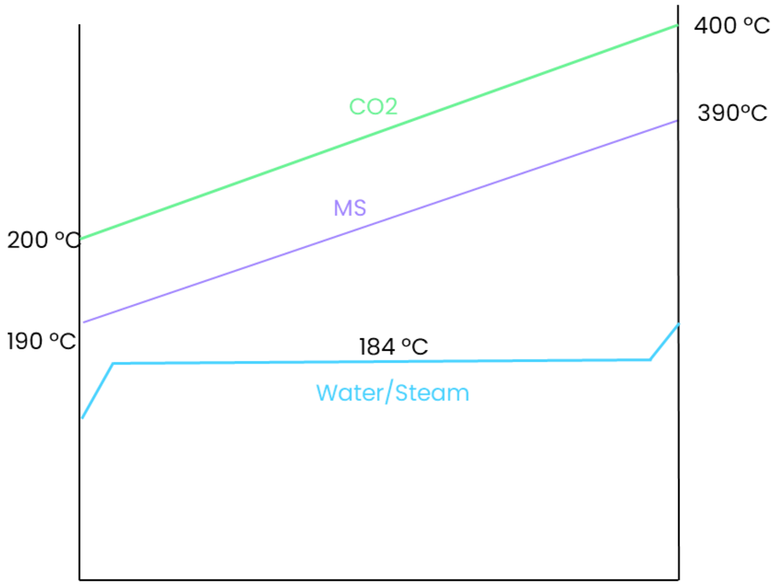

Figure 4: Temperature profiles in the different stages of the system with sensible heat TES for steam.

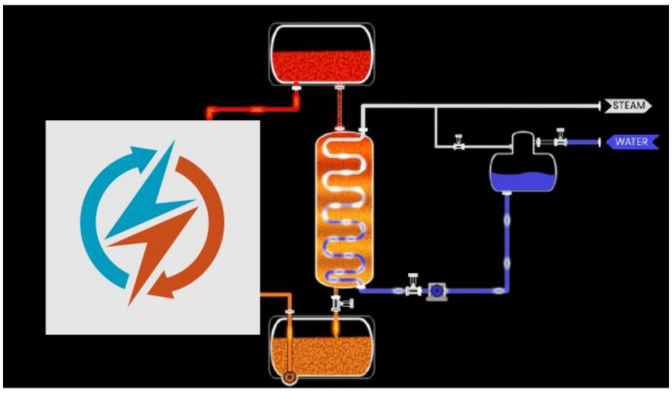

Figure 5: System diagram for the hot side of the HP integrated with two sensible storage tanks.

2.2 Open loop drying

The second scenario identified is the open loop drying, which is depicted in Figure 6. In this scenario, the air is taken from the atmosphere and heated to 150 °C. The heat sink requires a huge range from 40 °C to 220 °C. The latent heat PCM with three or two cascades can be an interesting alternative, applied in combination with a water storage for the lower temperatures up to 95 °C. The cascaded PCM will range from 120 to 190 °C as is shown in Figure 7. The alternative using sensible heat can be a thermocline thermal oil tank.

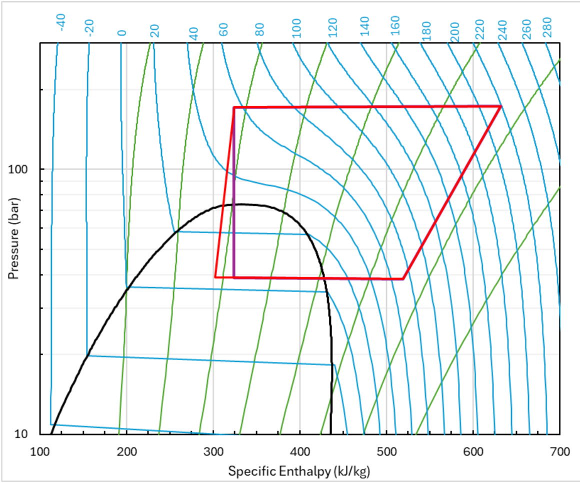

Figure 6: Heat pump pressure vs enthalpy diagram for open loop drying.

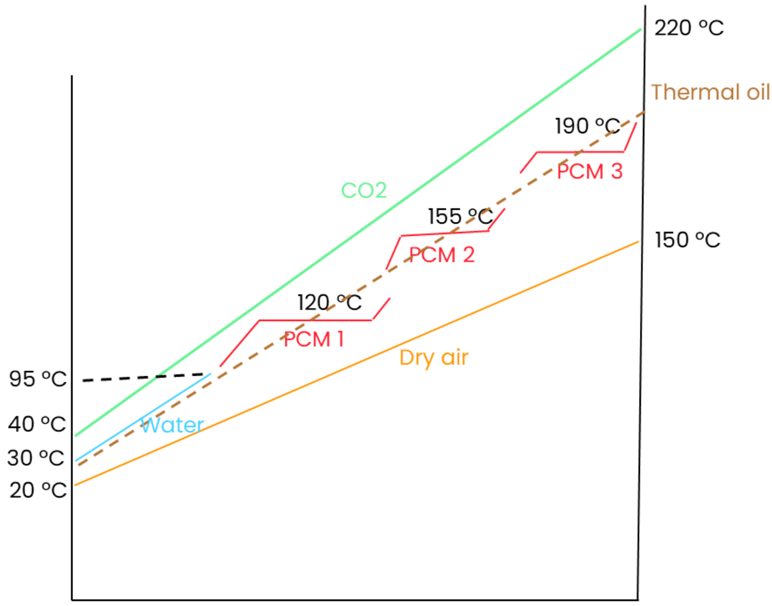

Figure 7: Temperature profiles in the different fluids of the system with latent cascade or sensible heat TES for open loop drying.

2.3 Heating and cooling

The last scenario involves a Heating and Cooling application, in which the HP can increase its COP by adding heat exchange in the cold side. However, this deliverable is only focused on the hot side of the HP, thus, only the heating demand will be analysed. As the pressure versus enthalpy diagram depicts in Figure 8, the heat sink range temperature is between 60-200 °C. For this case, cascaded PCM with two stages, between 120 and 170 °C is applicable. In this case, a thermocline thermal oil tank is also applicable as sensible storage.

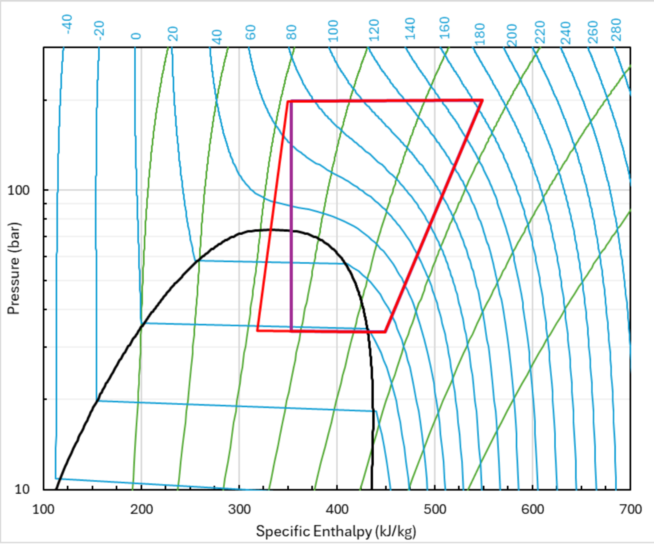

Figure 8: Heat pump pressure vs enthalpy diagram for heating and cooling.

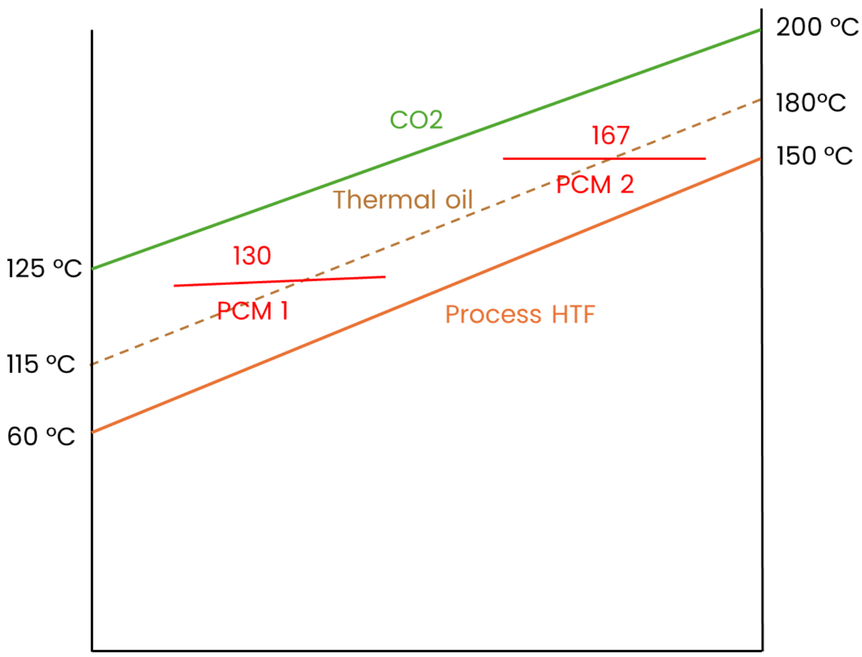

Figure 9: Temperature profiles in the different fluids of the system with latent heat or sensible heat TES for heating and cooling.

3. Preliminary selection of PCM

Latent thermal energy storage can be classified depending on the type of the phase change materials, as is depicted in Figure 10. Inside the solid-liquid category, the PCM can be classified by composition: organic, inorganic and eutectics mixtures. The three industrial cases can be clustered in two different ranges of temperatures required in the heat sink: the first from 120 – 190 °C for the open loop drying and the heating a cooling, and the second from 200 – 380 °C for the 10 barg steam. Figure 11 depicts the different groups of PCM in a chart melting enthalpy versus melting temperature. The salts and the eutectic mixtures are identified as group of interest, due to their high melting enthalpies and medium to high melting temperatures.

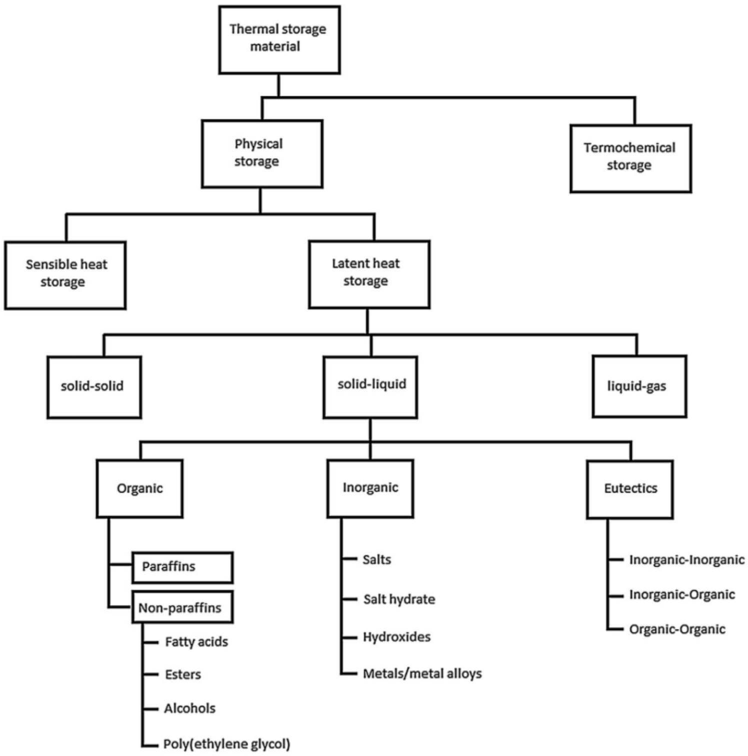

Figure 10: Classification of thermal energy storage materials and PCM[1]

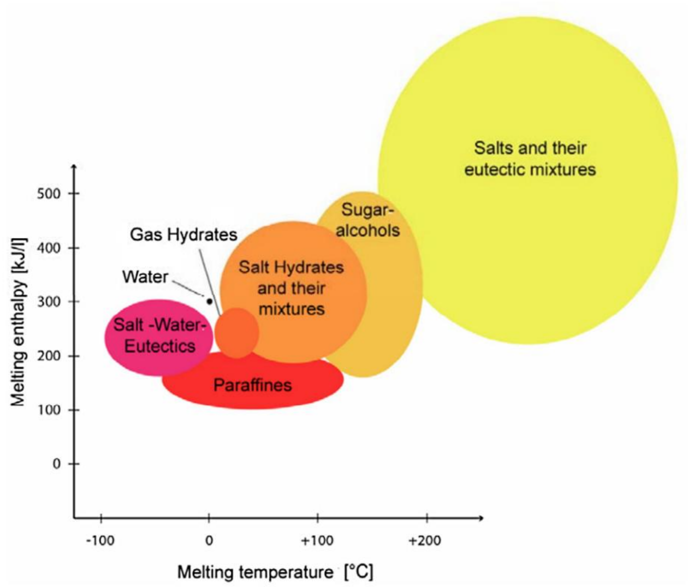

Figure 11: PCM latent heat vs melting temperature diagram[1].

3.1 Methodology

The first stage will be a screening of the PCM available from the literature and commercial data sheets. The PCM properties of melting temperature, melting enthalpy and degradation temperature are collected in Section 3.2, along with the material safety data sheet (MSDS) information and the cost of the PCM. The PCM are categorized by hazard from MSDS safety information: Oxidizer, Irritant, Corrosive, Toxic, Environmental Hazard and Health Hazard[2]. After clustering and analysing the gathered information, a proposal for the PCM candidates will be presented in Section 3.3 based in the lower cost, high melting enthalpy and low hazard level.

3.2 PCM Screening

3.2.1 Salts and their eutectic mixtures

Table 1 and Table 2 summarise the cost, the materials properties and the MSDS chemical safety information. In the range 120-200 °C only 10 salt PCM were found. Between 120 and 142 °C ternary mixtures of Nitrates are available, but their melting enthalpy is low compared with other salts. In the upper range from 150 – 190 °C lithium binary and ternary mixtures are found with a high melting enthalpy, but with also a high cost.

Table 1: Potential candidates for salts PCM between the range of 120 °C and 200 °C[3].

Materials	Cost*	Material properties			MSDS**
		$T_{melting}$ (ºC)	$\Delta H_{melting}$ (J/g)	$T_{degradation}$ (°C)	
$Ca(NO_3)_2$-KNO_3-$NaNO_3$ (45-48-7 wt%)	-	120-130	54.4	500	O, C, I
$Ca(NO_3)_2$-KNO_3-$NaNO_3$ (42-43-15 wt%)	-	131	50	525	O, C, I
KNO_3–$NaNO_2$–$NaNO_3$ (53-40-7 wt%)	-	142	80	535	O, T, Eh
$LiNO_3$-$NaNO_3$-KNO_3 (20-28-52 wt%)	+	150	-	550	O, I
$LiNO_3$-$NaNO_3$-KCl (55.4–4.5-40.1 wt%)	++	160	266	-	O, I
$LiNO_3$-KCl (58.1–40.9 wt%)	++	166	272	-	O, I
NaOH-KOH (50-50 mol%)	--	170	213	-	C, I
$LiNO_3$-LiCl-$NaNO_3$ (47.9–1.4-50.7 wt%)	++	180	265	-	O, I
$LiNO_3$-$NaNO_3$ (57-43 wt%)	++	193	248	-	O, I
$LiNO_3$-$NaNO_3$ (49-51 wt%)	++	194	265	-	O, I

Notes:
**Economic criteria: -- = low, - = medium, + = high cost, ++ =very high cost*
***MSDS: O= oxidizer, C= corrosive, I= irritant, T= toxic, Eh = environmental hazard, Hh = health hazard.*

For the 200 - 390 °C range 52 PCM were found, and many of them with attractive thermal properties and reasonable prices. The cheapest salts are the hydroxide, but the drawbacks is its corrosiveness.

Table 2: Potential candidates for salts PCM between the range of 200 °C and 390 °C[4].

Materials	**Cost***	**Material properties**			**MSDS****
		$T_{melting}$ (°C)	**$\Delta H_{melting}$ (J/g)**	**$T_{degradation}$(°C)**	
$LiNO_3$-$NaNO_3$ -$Sr(NO_3)_2$ (45-47-8 wt%)	++	200	199		O, C, I
Sr $(NO_3)_2$ - $NaNO_3$ - KNO_3 (26-45-29 wt%)	-	208	91		O, C, I
NaOH-LiOH (70-30mol%)	+	210-216	278-329		C, I, T
KNO_3–$NaNO_3$ (50-50 wt%)	-	220	110.7	600	O, I
$Ca(NO_3)_2$-$NaNO_3$ (45-55 wt%)	-	230	110		O, I, C
NaOH-$NaNO_2$ (20–80mol%)	-	230-232	206-252		O, T, Eh, C
NaOH-$NaNO_2$ (73-27mol%)	-	237	242		O, T, Eh, C
$NaNO_3$–NaCl–NaOH (18.3-3.6-78.1 wt%)	--	242	242		O, C, I
$NaNO_3$–NaCl–NaOH (40.2-4.2-55.6 wt%)	--	247	213		O, C, I
$NaNO_3$–NaOH (70-30 wt%)	--	247	158		O, C, I
$LiNO_3$	++	250	360	470	O, I
LiCl-$Ca(NO_3)_2$ (59.15-40.85mol%)	++	270	167	-	O, C, I
$NaNO_2$	-	270	200	500-700	O, T, Eh
LiOH-LiCl (65.5-34.5 mol%)	++	274	339	-	C, I, T
$ZnCl_2$	++	280	75	-	C, I, Eh
NaCl-Na_2CO_3–NaOH (7.8-6.4-85.5 wt.%)	--	282	316	NaCl > 800; Na_2CO_3 > 800; NaOH > 323	O, C, I
$NaNO_3$-NaCl-Na_2SO_4 (87.44-5.88-6.68 %wt.)	-	287	117	NaCl > 800; Na_2CO_3 > 800; NaNO3> 527	O, I, Hh
NaOH-NaCl–Na_2CO_3 (87.3-6.1-6.6 mol%)	--	291	287	NaCl > 800; Na_2CO_3 > 800; NaOH > 323	O, C, I
NaOH-Na_2SO_4 (81.5-18.5 wt.%)	-	294.4	287	NaOH > 323, Na2SO4 > 884	C, O, I, Hh
LiOH-Li_2SO_4 (42.52-57.48 wt.%)	++	295	591		C, I,T
NaCl-$NaNO_3$ (4.70-95.30 wt.%)	-	297.5	189.1	NaCl > 800; $NaNO_3$ > 310	O, I
NaOH-NaCl–Na_2CO_3 (85.8-7.8-6.4 mol%)	--	298	286	NaCl > 800; Na_2CO_3 > 800; NaOH > 323	O, C, I
$NaNO_3$-Na_2SO_4 (91.89-8.11 wt.%)	-	298.8	179	Na_2SO_4 > 884, $NaNO_3$ >527	Hh, O, I

LiOH-LiBr (45.27-54.73wt.%)	+	303.9	802.8		C, I, T
Na_2CO_3-$NaNO_3$ (2.27-97.73 wt.%)	-	306	181.1	Na_2CO_3 > 800, $NaNO_3$ >527	O, I
$NaNO_3$	-	310	172	527	O, I
LiOH-LiCl (36.1-63.9 wt.%)	++	314	534.8		C, I, T
LiOH-KOH (40-60 wt.%)	+	314	341	-	C, I, T
NaOH	--	318	165	Higher than 323	O, C, I
LiCl-NaCl-KCl (54.2-39.4-6.4 wt.%)	++	320	170	-	O, I
KNO_3-KCl (94-6 wt.%)	-	320	74	KCl > 770; KNO_3 >550	O, I
KNO_3-K_2CO_3 (65-35 wt.%)	+	325	71.58	K_2CO_3 > 891; KNO_3 > 550	O, I
KNO_3-KBr(91-9 wt%)	-	329	100.93	KBr > 730; KNO_3 > 550	O, I
$MgCl_2$-KCl-NaCl (42-39-19 wt.%)	+	331	198.45	NaCl > 800; KCl > 770; $MgCl_2$ > 712	C, I
KNO_3	--	335	95	550	O, I
$CaCl_2$-KCl-LiCl (10-53-37 wt.%)	++	338	241.24	-	I
LiI-NaI (65.25-34.75 wt.%)	++	342	113		I
NaCl-KCl-LiCl (33-24-43 wt.%)	+	346	281	-	I
$MnCl_2$-KCl-NaCl (45-28.7-26.3wt.%)	-	350	215	NaCl > 800; KCl 770; $MnCl_2$ > 650	I
LiCl-KCl (45.25-54.75 wt.%)	+	352	267		I
KOH	--	360	134	-	C, I
LiOH-RbOH (37.72-62.28 wt.%)	+	363	393		C, I
K_2CO_3-KOH (22-78 wt. %)	--	365	164.35	-	C, I
LiCl-LiI (15.05-84.95 wt.%)	+	368	160		I
NaOH-NaCl (80-20 wt.%)	--	370	370	NaCl > 800; NaOH > 323	C, I
K_2SO_4-KOH (16.5-83.5 wt.%)	--	376	174.09	-	C, I
$MgCl_2$-KCl-NaCl (60-20.4-19.6 wt.%)	-	380	400	700	C, I
$MnCl_2$-KCl-NaCl (43-48-9 wt.%)	-	380	177.27	NaCl > 800; KCl >770; $MnCl_2$ > 650	I
$MgCl_2$-KCl-NaCl (51-27-22 wt.%)	-	385	290	NaCl > 800; KCl > 770; $MgCl_2$ > 712	C, I

Notes:
**Economic criteria: -- = low, - = medium, + = high cost, ++ =very high cost*
***MSDS: O= oxidizer, C= corrosive, I= irritant, T= toxic, Eh = environmental hazard, Hh = health hazard.*

3.2.2 Organic

Sugar, alcohols, and acid organic components can be an alternative for salts PCM in the range of 120-190 °C. A literature screening was conducted to find potential candidates, and the results are depicted in Table 3. They have high melting enthalpies, but exhibit supercooling, whereby solidification occurs at lower temperature than the melting point, which is inefficient for TES application. Furthermore, many of them show degradation after a couple of thermal cycles. PCM with stability issues are denoted by a strikethrough in Table 3.

Table 3: Potential candidates for organic PCM between the range of 120 °C and 190 °C[5]

Material	$T_{melting}$ (°C)	$\Delta H_{melting}$ (J/g)	$T_{degradation}$ (°C)	$T_{subcooling}$ (°C)	Test conclusions	MSDS**
Sebacic Acid	130-134	228	220	5	[5] ok	
~~Maleic Acid~~	~~131-140~~	~~235~~	~~145~~		[5]~~- not stable~~	~~I~~
Adipic Acid	151-155	260	210	5	[5] not stable in inert atm	I
~~Glucose D~~	~~149-152~~	~~174-192~~	~~211~~		[5]~~-not stable~~	
HDPE	130	211-233	448		[5] ok	
Benzoic acid	121-123	114-147			[5] not stable in inert atm	C, Hh
Dimethyl terephthalate	142	170			[5] not stable in inert atm	I
~~Urea~~	~~133-135~~	~~170-258~~			[5]~~-not stable~~	
Benzamide	125	175			[6]	I, Hh
~~Erythritol~~	~~118~~	~~331~~		~~61~~	~~[7]Low subcooling point~~	~~I~~
D-mannitol	167	296-316		150	[7]non-stable in oxygen atm	
D-dulcitol	187	115			[8]	I
72 % D-mannitol 20% KBr 8% expanded graphite (EG)	140.73	218.6		134.33	[8]	I
70 % D-mannitol 20% KBr 10% EG	136.9	215.7		131.5	[8]	I
68% D-mannitol 20% KBr 12% EG	140.7	211.8		135.7	[8]	I
Hydroquinone	172.4	114-208		160	[9]	C, I, Hh, Eh
~~Salicylic acid~~	~~157~~	~~113-199~~			[5] ~~not stable~~	
~~Galactitol~~	~~164-167~~	~~330-357~~		~~120-60~~	[7]~~-subcooling, variation of properties after cycling~~	
Myo-inositol	210	170-210		190-170	[7] subcooling, variation of properties after cycling	

Notes:
***MSDS: O= oxidizer, C= corrosive, I= irritant, T= toxic, Eh = environmental hazard, Hh = health hazard.*

3.3 PCM candidates for COMHPTES

In this section a pre-selection based on the adequate melting temperature, high melting enthalpy, low cost and low hazard level is presented for the scenarios identified in Section 2. From the potential candidates a preselection was conducted by discarding PCM with the next characteristics:

- Present Hazard to the Environment or Health
- Excessive cost
- Corrosiveness

3.3.1 Steam 10 barg

The PCM that passed the defined conditions are shown in Table 4, where some corrosive components were admitted due to the fact that no alternative was found in the same range of temperature and they also presented a low cost.

Table 4: Preselected candidates for Steam 10 barg scenario.

Materials	Cost*	Material properties		MSDS**
		$T_{melting}$ (°C)	$\Delta H_{melting}$ (J/g)	
KNO_3–$NaNO_3$ (50-50 wt.%)	-	220	110.7	O, I
$NaNO_3$–NaCl–NaOH (18.3-3.6-78.1 wt.%)	--	242	242	O, C, I
$NaNO_3$–NaCl–NaOH (40.2-4.2-55.6 wt.%)	--	247	213	O, C, I
$NaNO_3$–NaOH (70-30 wt.%)	--	247	158	O, C, I
NaCl-Na_2CO_3–NaOH (7.8-6.4-85.5 wt.%)	--	282	316	O, C, I
NaOH-NaCl–Na_2CO_3 (87.3-6.1-6.6 mol%)	--	291	287	O, C, I
NaCl-$NaNO_3$ (4.70-95.30 wt.%)	--	297.5	189.1	O, I
Na_2CO_3-$NaNO_3$ (2.27-97.73 wt.%)	-	306	181.1	O, I
$NaNO_3$	-	310	172	O, I
KNO_3-KBr	-	329	100	O,I
KNO_3	--	335	95	O, I
$MnCl_2$-KCl-NaCl (45-28.7-26.3wt.%)	-	350	215	I
NaOH-NaCl (80-20 wt.%)	--	370	370	C, I
$MnCl_2$-KCl-NaCl (43-48-9 wt.%)	-	380	177.27	I

Notes:
**Economic criteria: -- = low, - = medium, + = high cost, ++ =very high cost*
***MSDS: O= oxidizer, C= corrosive, I= irritant, T= toxic, Eh = environmental hazard, Hh = health hazard.*

After analysing the pre-selected PCM a configuration for the system is illustrated in Figure 12. The first cascade employs the binary mixture of 54% KNO_3 - 46% $NaNO_3$, with an enthalpy of 110.7 J/g and melting temperature of 220 °C. An alternative with a higher enthalpy of 242 J/g is the ternary mixture of $NaNO_3$–NaCl–NaOH, but it is a corrosive salt. Therefore, it must be analysed if the tank material and the metal wools (which must be a stronger steel) compensates the higher enthalpy. For the second cascade $NaNO_3$ is a good match with a melting temperature of 310 °C and latent heat of 172 J/g.

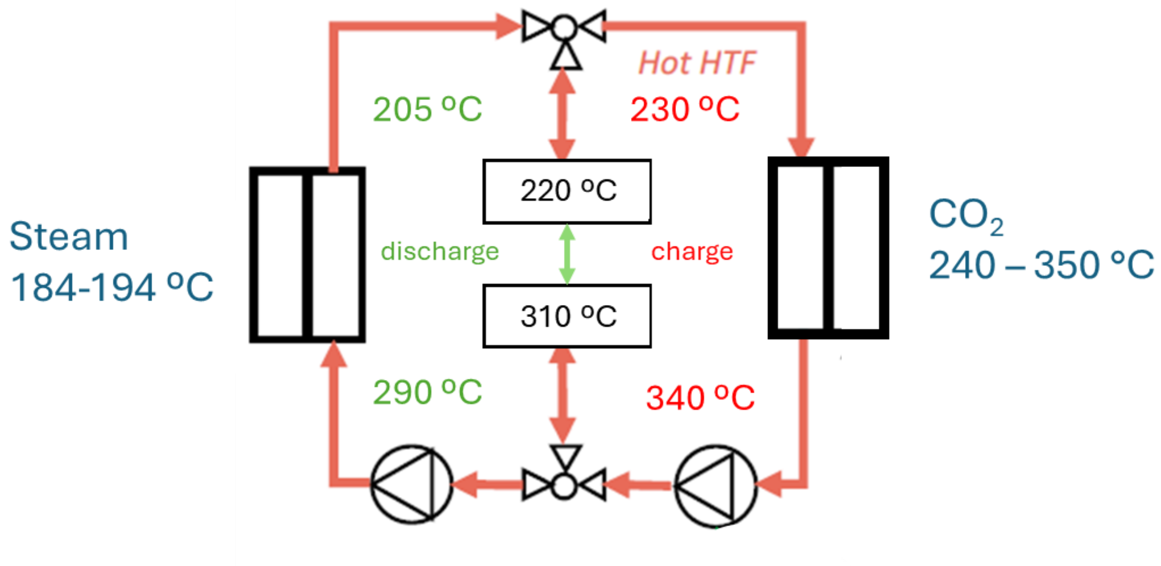

Figure 12: Selected configuration for Steam 10 barg.

3.3.2 Open loop drying or Heating and Cooling

For these two scenarios there are limited options in the salt's components list, one alternative is to select lithium binary and ternary mixtures, which vary from 150 to 190 °C, but the cost of these salts are high. Another option is using an organic PCM, for example, Sebacic acid with a temperature of 130 °C has shown a satisfactory performance in laboratory experiments [5]. For the second cascade D-mannitol with a 167 °C melting temperature can be selected, which has presented stability in laboratory [7] and pilot plant testing [9].

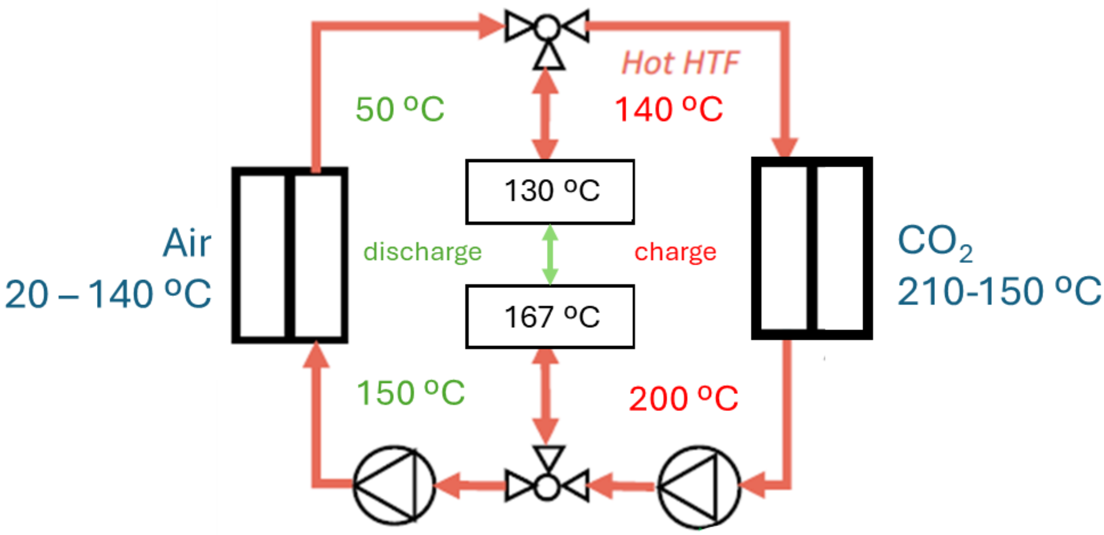

Figure 13: Selected configuration for open loop drying.

4. Metal wool for conductivity enhancement

The primary drawback of the solid-liquid salt PCM is their lower conductivity in the solid phase which reduced the heat transference and increases the time to charge and discharge. Therefore, there are different methods to enhance the thermal conductivity of the salts. For example, some researchers have proposed to add extended surfaces (fins or heat pipes) or the combination of highly conductive materials with PCM: graphite, metal foams and nano-additives[10]. Metal fibres have been selected as an enhancement method due to the easy integration with the PCM, the low cost, the easy disposal and the opportunity to use waste materials form other industries.

Salts PCM can be corrosive; thus, it is important to evaluate the compatibility between the salt and the metal fibres. The binary mixture of KNO_3 and $NaNO_3$ is well characterised as it has been used as HTF in the last two decades in the CSP industry. This industry has been using carbon steel and stainless steel without issues. Furthermore, a group of researchers have carried out static corrosion tests for a large list of salt PCM using immersion method with three different metals fibres: SS314, SS434 and Alloy 20 [11]. The results of this testes are shown in Table 5 for the selected candidates.

Table 5: Results of the three-month corrosion test[11].

Materials	SS314	SS434	Alloy 20
NaCl-Na_2CO_3–NaOH (7.8-6.4-85.5 wt.%)	X	X	Passed
NaOH-NaCl–Na_2CO_3 (87.3-6.1-6.6 mol%)	X	X	Passed
NaCl-$NaNO_3$ (4.70-95.30 wt.%)	Passed	Passed	Passed
Na_2CO_3-$NaNO_3$ (2.27-97.73 wt.%)	X	X	Passed
$NaNO_3$	Passed	Passed	Passed
KNO_3-KBr	Passed	Passed	Passed
KNO_3	Passed	Passed	Passed
$MnCl_2$-KCl-NaCl (45-28.7-26.3wt.%)	X	X	X
NaOH-NaCl (80-20 wt.%)	X	X	Passed
MnCl2-KCl-NaCl (43-48-9 wt.%)	X	X	X

5. PCM module preliminary design

The steam at 10 barg scenario was selected to be tested at the University of Seville pilot plant. For this scenario, two cascaded PCM were defined: the first cascade is filled with KNO_3-$NaNO_3$ and the second with $NaNO_3$. The PCM module will be defined as a shell and tube heat exchanger, where the PCM and the wool will be placed in the shell and the HTF in the tubes. The tank will have a cover gas at the top to allow for thermal expansion of the PCM and reduce the thermal stress. The HTF, in this case, the Hitec molten salt, will be circulating through the tubes. The metal wool can be placed in the shell around the tubes as is shown Figure 14.

Figure 14: Metal wool and tube for HTF fluid[14].

A preliminary design can be carried out with the thermal properties of the selected PCM and the operation conditions. The operational temperatures of the PCM modules were selected to have an adequate balance of temperature in the system, avoiding large temperature gradients. The first cascade is heated from 200 °C to 260 °C, with a 220 °C melting temperature. The second cascade is heated from 260 °C to 340 °C, with a 310 °C melting temperature. Therefore, the PCM will be stratified from the top to the bottom and will store latent and sensible heat. Table 6 shows the preliminary results for the PCM cascade modules design.

Table 6: Preliminary design of the PCM cascade modules

Parameter	**KNO_3-$NaNO_3$**	**$NaNO_3$**
Latent heat (kJ/kg)	110.7	172
T melting (°C)	220	310
PCM mass (kg)	3252.03	2093.02
Cp (kJ/kg.K)	1.59	1.82
Density (kg/m^3)	1780	1929
Volume (m^3)	1.827	1.085
T start (°C)	205	230
T end (°C)	260	340
Sensible heat (kWh)	89.05	116.395
Latent heat (kWh)	100	100
Total Heat (kWh)	189.05	216.395

The internal tubes' diameter and number will depend on the geometry of the tank, the velocity of the HTF and the residence time. A recommend velocity for molten salts is 1m/s; the mass flow of the HTF defines the charge and discharge time. A rough estimation can be done by a balance of energy considering 100 % efficiency and no thermal losses by using Eq. 1. Where the temperature of the molten salts is reduced from 340 °C to 230 °C.

$$E \cdot \Delta t = \dot{m}_{HTF} \cdot c_p \cdot (T_{in} - T_{out}) \quad (1)$$

Table 7 shows the results for a design with a charge time of around two hours with a 0.6 kg/s mass flow rate. To achieve a velocity of 1 m/s the diameter of the internal tubes is ¾ ''. Finally, by having a total length of 40 m of internal piping, the HTF achieves a residence time of 37 seconds.

Table 7 : Preliminary design values for the HTF.

Parameter	**Value**
Flow mass rate (kg/s)	0.6
Power charge (kW)	90.42
Charge time (h)	2.046
Pipe diameter (mm)	19.5
Pipe area (m^2)	0.00030
Volumetric flow rate (m^3/s)	0.00032
Velocity (m/s)	1.0801
Pipe total length (m)	40
Residence time (s)	37.03

6. Next steps

The next step involves the optimization and detailed design of the PCM modules. Therefore, computational fluid dynamics (CFD) simulations will be carried out to study the behaviour of the new module of PCM. The optimization will be focused on thermal capacity and responsiveness of the TES, as well as cost. Furthermore, finite element modelling will be implemented to evaluate the structural integrity of the TES tank, which can be suffer from mechanical stress from the thermal expansion of the PCM during the phase change.

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