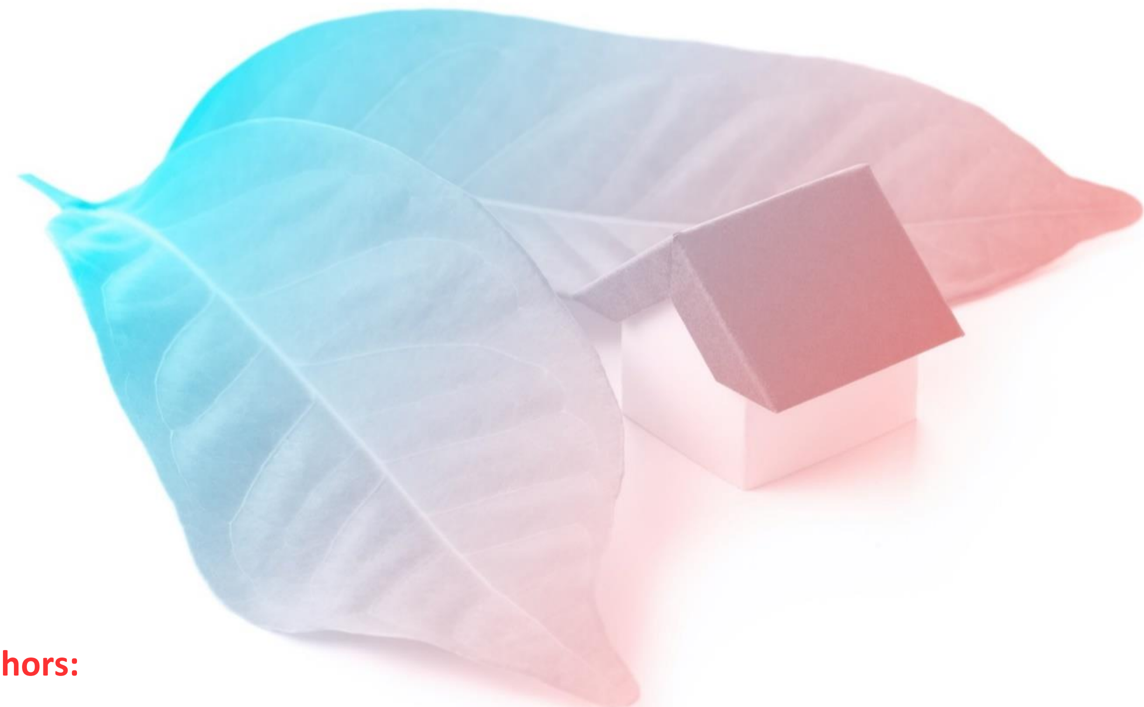
D4.3 Design and development of ancillary equipment for heating/cooling storage



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This project has received funding from the European Union´s Horizon 2020 research and innovation programme under the grant agreement No 869821

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D4.3 Design and development of ancillary equipment for heating and cooling storage

Summary

Deliverable D4.3 is related to the TCM and PCM storage system development. It details the operation of the storage systems, as well as the design and specifications of the different components implemented in them according to the seasonal operating conditions and the solar resource available at each demo site. The TCM storage process ensures the dual function of storing the thermal energy from the solar collectors during the day and its restitution during the night in the form of cold in summer or heat in winter. Such heat or cold is stored by PCM thermal storage units for use during the following days, independent of the operation of the TCM storage unit. The TCM unit exploits the low temperature thermal energy delivered by PVT or FPC collectors during the day or a backup system if needed when the solar resource is too low. During the day the hot PCM units store the heat rejected at the condenser of a mechanical HP and during the night the heat produced by the TCM reactor. The cold PCM stores the cold that is produced by the TCM evaporator during the night in summer. In addition, this report also details the control strategy of the TCM unit and PCM storage.

Deliverable	Work Package
D4.3	WP4
Lead Beneficiary	**Deliverable Author(S)**
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Planned Delivery Date	**Actual Delivery Date**
31/01/2021	03/11/2021 Revised Version

Type of deliverable	R	Report	X
Dissemination Level	CO	Confidential, only for members of the consortium (including the Commission)	
	PU	Public	X

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List of Abbreviations and Acronyms

Abbreviation	Definition
Comp	Compressor
Cond	Condenser
G	Reactive gas (ammonia)
De	Energy density (kWh/m^3 of composite)
ENG	Expanded Natural Graphite
Evap	Evaporator
FPC	Solar thermal Flat Plate Collectors
h	hour
hsw	Thermal conductance between the wall of the reactor and the TCM material (W/m^2.K)
HP	Heat Pump
HTF	Heat transfer fluid
K	Permeability (m^2)
L	Litres
$\dot{m}$	Mass flow rate of the heat transfer fluid (kg/s)
M, Mm	Mass (kg) or Molar mass (kg/mole)
min	Minutes
NH_3	Ammonia
P	Pressure (Bar)
PCM	Phase Change Material
PV	Photovoltaic
PVT	Photovoltaic-thermal collector
R	Perfect gas constant (J/mol.K)
Q_{swept}	Swept volumetric flow rate of the NH^3 compressor (m^3/s)
Qv	Volumetric flow rate (m^3/s)
So	Reactive salt with low content of reactive gas G
S1	Reactive salt with high content of reactive gas G
T	Temperature (°C)
TCM	Thermochemical Material
U	Overall heat transfer coefficient (W/m^2.K)
V	Volume (m^3)
Vm	Molar volume (m^3/mole)
X	Salt conversion ratio (moles of charged salt/ total moles of salt)
ΔH	Enthalpy of reaction or phase change (J/mol)
ΔS	Entropy of reaction or phase change (J/mol.K)
ΔX	Advancement rate of the reaction
ν	Stoichiometric coefficient of the reaction

1. Introduction: scope and objective of the deliverable

This report presents the work undertaken in WP4, Task 4.3 which relates to the "Design of the ancillary equipment for TCM reactor and PCM storage". This work was undertaken in the period from month 3 to month 15.

The MiniStor system implements a thermochemical material heat storage system (TCM unit) that stores and exploits the low temperature heat that is delivered by solar collectors for delayed heat/cold production, and units containing phase change material (PCM) for heat/cold energy storage. Moreover, a conventional HP enables the recovery of low grade condensation heat released by the TCM unit and upgrades it during the winter period to a higher temperature suitable for storage in the hot PCM units.

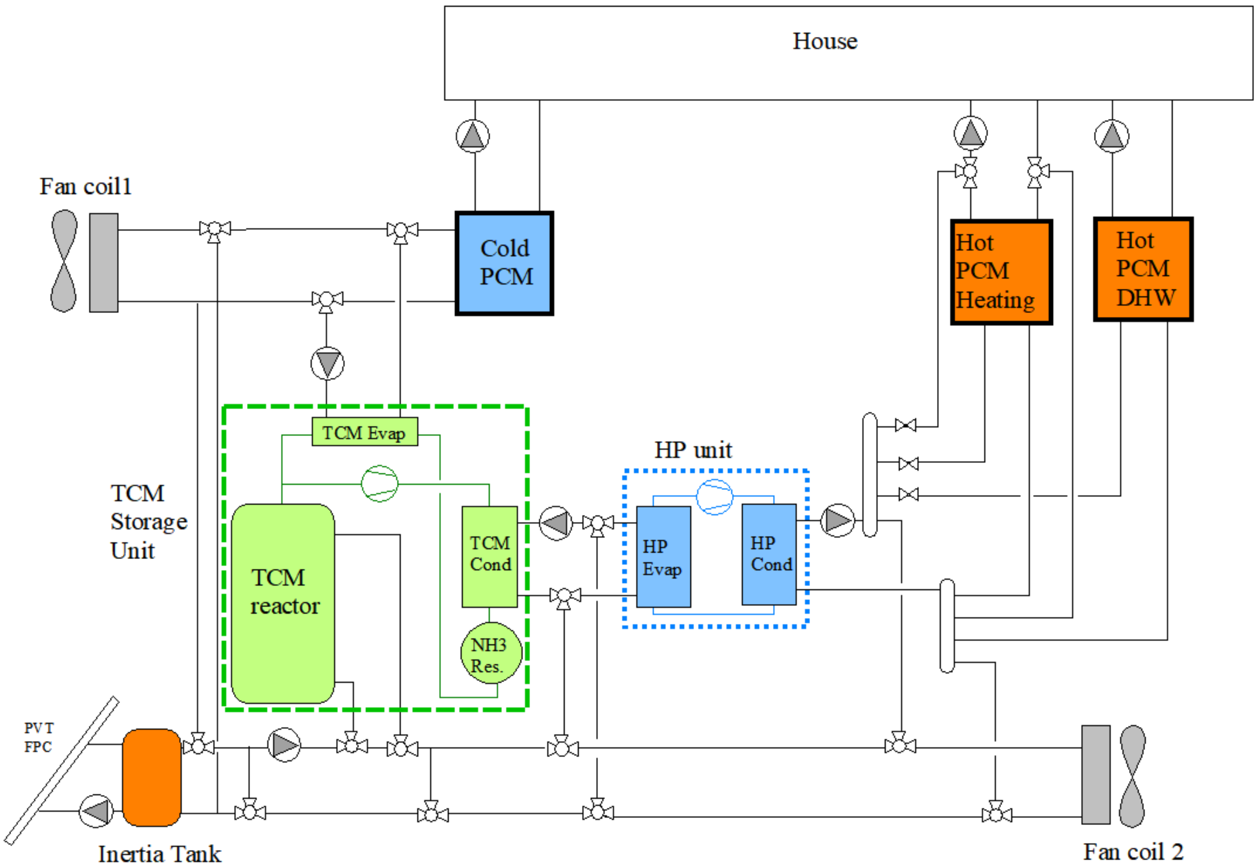

Figure 1: Schematic representation of the MiniStor system

Figure 1 presents a scheme of the system. It shows a slightly different configuration to previous deliverables, in that there is a direct connection from the inertia tank to the cold PCM. This is done with the aim to improve efficiency by using the cold PCM to aid in the evaporation of ammonia. This change will be described in full in Section 2.3 and in future deliverables of WP3 and WP4.

The TCM unit is based on a reversible chemical reaction between an ammoniated salt and ammonia taking place in a TCM reactor. Depending on the operating steps of the TCM unit, the reactor is either connected to the condenser during the charging phase when the TCM reactor is heated by the solar loop, or to the evaporator during the discharging phase when the TCM reactor is cooled. During this latter phase, the heat produced by the TCM reactor is either released to ambient via a fan coil in summer or recovered by the hot PCM storage in winter. The closed loop ammonia system enables recovery of the ammonia released during the charging phase through condensation into a liquid reservoir, which can then feed the evaporator during the discharging phase. In order to exploit the low temperature heat delivered by the solar collectors a compressor is implemented.

The aim of this deliverable is to present and detail the results achieved in Task 4.3 relative to the design of the TCM unit and PCM storage. The task focused on two main topics, the first one being the description of the operation of the TCM unit and PCM storage during different seasonal periods and their coupling with the other equipment of the MiniStor system (solar collectors, fan coils, etc.). The objective is to present an efficient control strategy of the TCM unit for best energy management. The second topic focuses on the design of the different components implemented in the TCM unit and PCM storages according to the solar resource available at the different demo sites. A compact design of the TCM storage is targeted.

The outcome of the Deliverable D4.3 aims to indicate the nominal operating and control strategy of the TCM unit and the PCM storage, and also to provide an optimal design of each component of the TCM unit, as well as the hot and cold PCM storage, in order to meet the energy storage requirements of the MiniStor project.

2. The thermochemical storage unit (TCM unit)

2.1 The components of the TCM unit

The main components of the TCM storage unit are:

- the TCM reactor, where the reversible reaction between the calcium chloride salt and ammonia takes place. The design of this reactor has been undertaken in T4.1 and is described in Deliverable D4.1.
- the ammonia compressor, where the low temperature of the solar heat source is used to decompose the ammoniated salt and produce ammonia vapour during the charging phase.
- the condenser, where the ammonia is liquefied before being stored in the liquid reservoir.
- the evaporator, where the vapour from the liquid reservoir is produced during the discharging phase and absorbed exothermally by the reactor. The evaporator also produces the useful cooling effect in summer.

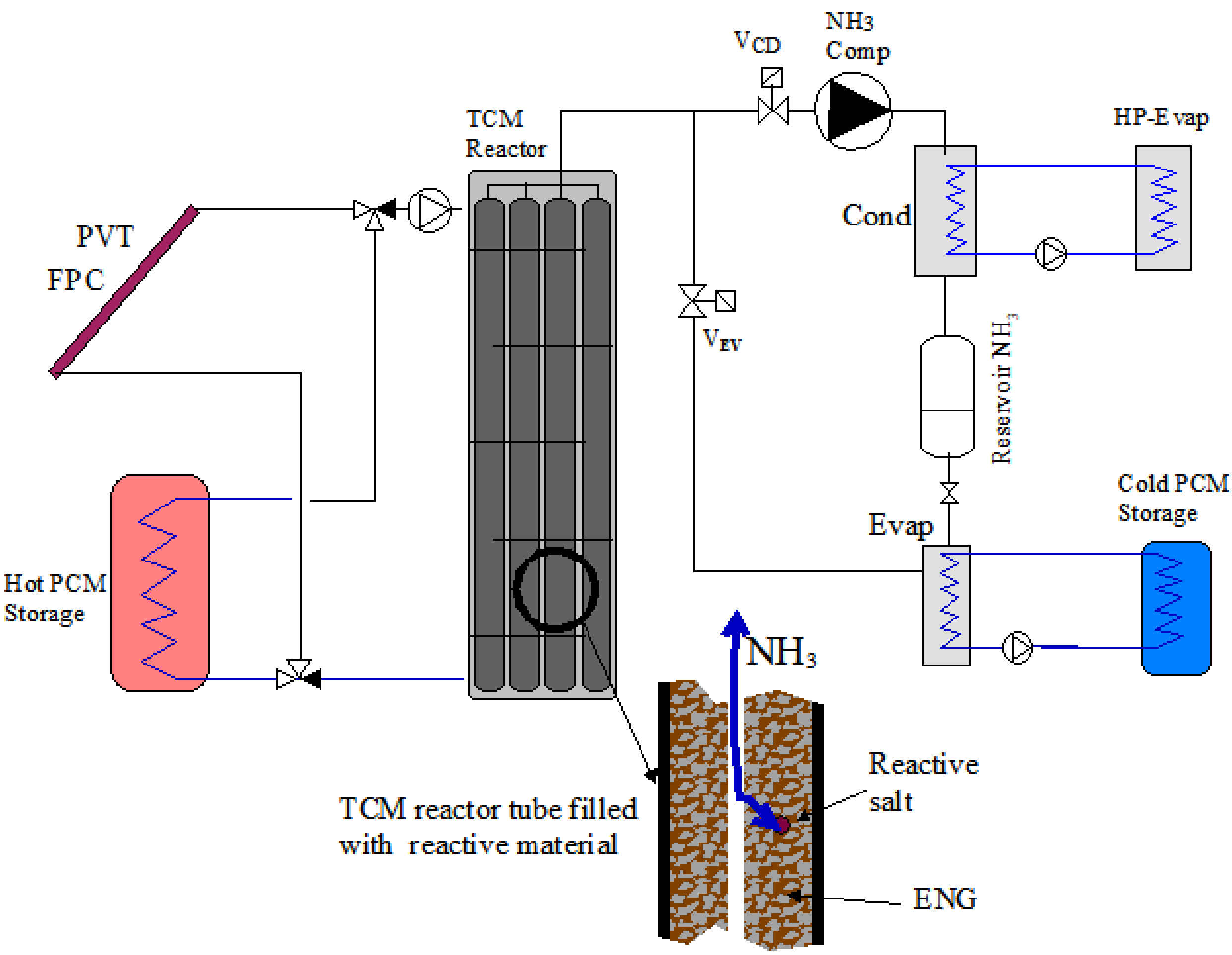

Figure 2: Schema of TCM storage unit implemented in the MiniStor system

The TCM reactor is connected to the condenser during the charging phase and to the evaporator during the discharging phase. The TCM reactor contains the porous reactive material consisting of a recompressed mixture of calcium chloride and a highly conductive material, expanded natural graphite

(ENG). The characteristics of this reactive material have been defined in Task 4.1 of this work package WP4. The reactive material, which contains the ammoniated salt of calcium chloride ($CaCl_2$•n.NH_3), reacts reversibly with ammonia, producing a thermal effect (endothermic or exothermic). To keep the reaction going this thermal effect must be controlled through the operating constraints (pressure and temperature) applied to the TCM reactor. The TCM reactor must first be heated to decompose the fully ammoniated salt according to the following two successive reactions:

1) $CaCl_2 \bullet 8NH_3 \rightarrow CaCl_2 \bullet 4NH_3 + 4NH_3$
2) $CaCl_2 \bullet 4NH_3 \rightarrow CaCl_2 \bullet 2NH_3 + 2\ NH_3$

The ammonia produced is condensed in the condenser and collected in the liquid reservoir. For the reverse reactions during which the TCM reactor exothermally absorbs the ammonia produced by the evaporator, the heat generated by the reaction must be extracted from the reactor by a thermal loop. This heat is either recovered and stored in the hot PCM in winter or released outside by a fan coil in summer. In the MiniStor project the heat of condensation released at 28 °C is also recovered in winter and upgraded by a conventional heat-pump to a higher temperature of 65 °C, which can be also stored in hot PCM storage.

The ammonia compressor, between the reactor and the condenser, operates only during the charging phase and lowers the operating pressure of the TCM reactor and thus the required operating temperature for decomposition of the salt is also decreased. The role of the compressor is to modify the operating conditions of the TCM reactor to exploit the relatively low temperatures provided by the solar collectors in winter. The minimum required temperature for the TCM reactor depends on the compression ratio of the compressor (around 6 with the chosen piston-type compressor) and the melting temperature of the hot PCM storage. To prevent too high discharge temperatures, a cooling device must be implemented at the suction line of the compressor to cool the ammonia vapour produced by the reactor from 50-70 °C to 20-30 °C.

2.2 TCM control devices

Figure 2 shows in more detail the aforementioned elements of the TCM unit and their interconnections during the operating phases. Several sensors and controllers, electrical 2-way valves and needle valves are mandatory to control the operation of the TCM unit and switch between charging and discharging phases. The functionality of this equipment is detailed in Tables 1 and 2.

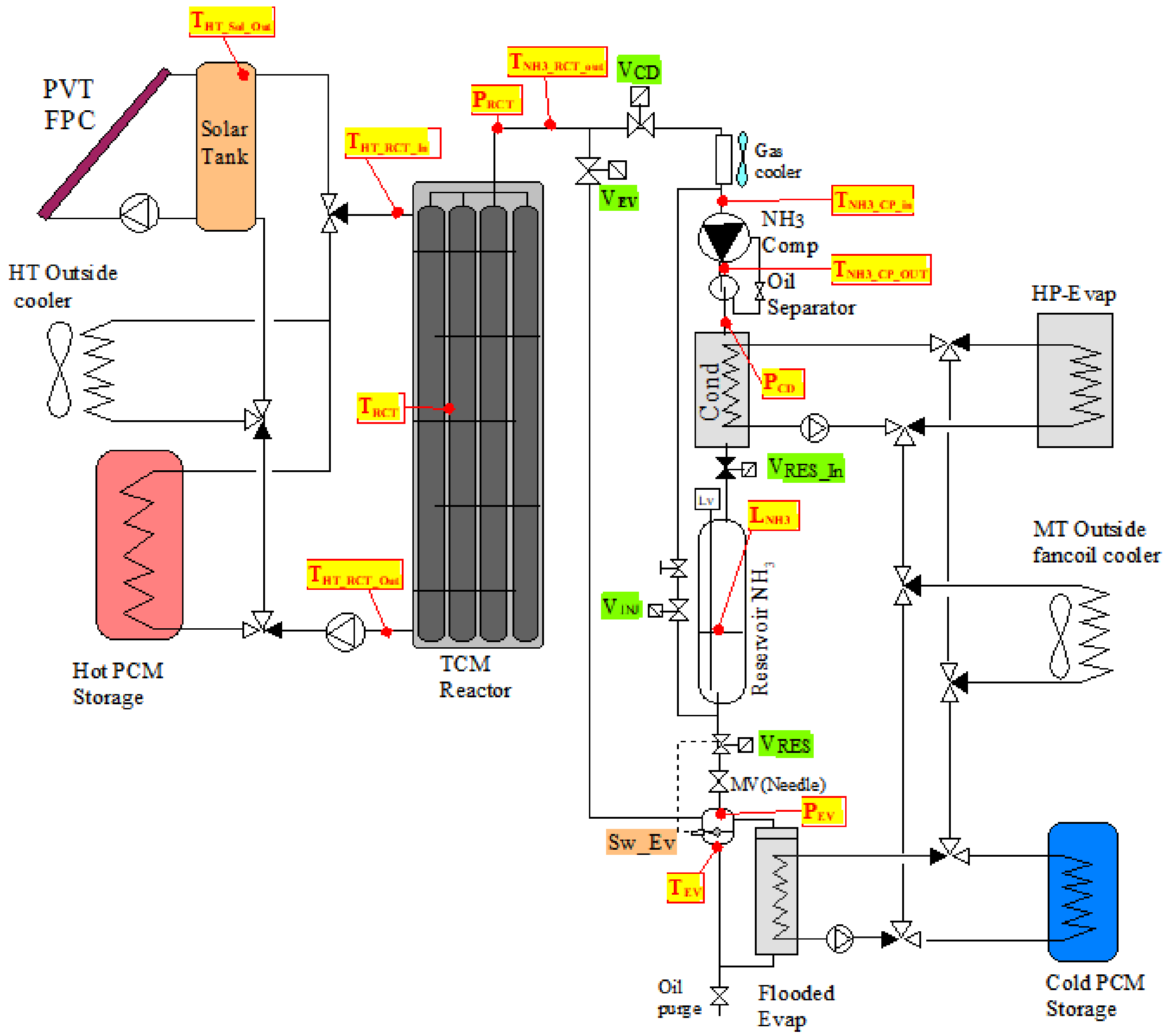

Figure 3: Schematic diagram of the TCM unit showing the interconnections of the different components of the MiniStor system and the required sensors and valves to control operation of the TCM unit

During the charging phase, ammonia vapour produced by the heated reactor at a high temperature (~60 °C) is first cooled by a heat exchanger (gas cooler) and/or by injecting a small quantity of liquid ammonia taken from the outlet of the condenser. This cooling is necessary to avoid a too high discharge temperature that could damage the compressor (max 130 °C). The injection of liquid ammonia is controlled by an electrical on/off valve (Vinj) placed in series with a needle valve, characterised by a small adjustable flow coefficient Cv (minimum 5 turns). The compressor is oil lubricated, so to prevent oil pollution in the TCM reactor an oil separator is used after the compressor to recover at least 99% of the oil in the compressed vapour before it is condensed in the condenser and accumulated in the reservoir.

During the discharge phase, the TCM reactor is cooled as it exothermically absorbs the ammonia vapour generated from a flooded-type evaporator. This absorption lowers level of liquid ammonia in the flooded evaporator. When a low level is detected by a level switch (SW-Ev) located in a small reservoir above the flooded evaporator, the electric valve of the liquid ammonia reservoir outlet is opened, filling the flooded evaporator until a low level is no longer detected by the level switch.

2.2.1 Instrumentation and control sensors of the TCM unit

Different types of sensors must be implemented to decide the start and stop conditions, the different operating phases and to ensure the correct operation of the TCM unit. In particular, the pressure sensors control when the connections between the reactor, condenser, liquid reservoir and evaporator should be activated. A level gauge within the liquid reservoir enables measurement of the state of charge and to confirm when the charging and discharging phases are completed. The temperature sensors are used to maintain correct operation of the unit and advise of any necessary corrective adjustments. Example scenarios that require adjustment are too high discharge temperature at the compressor, the presence of incondensable oil, and too pressure in the reactor. Table 1 summarises the functionality and characteristics of these control components along with other safety sensors that should also be implemented to check for ammonia leakage and protect the compressor.

Table 1: List of control sensors implemented in the TCM unit and their functionalities

Sensor	Abbreviation	Function
Pressures		
Reactor pressure	PRCT	- connection with condenser and evaporator - regulation of the speed rotation of the compressor
Condenser pressure	PCOND	- connection to reactor during charging phase
Evaporator pressure	PEVAP	- connection to reactor during discharging phase
Level		
Liquid NH_3 level	LNH3	- measure of the state of charge of the TCM unit - control of the end of charging/discharging phases
Evaporator switch level	SW_Ev	- liquid ammonia feeding of the flooded evaporator
Temperatures		
Reactor temperature	TRCT	- reactor temperature - control of the TCM pump
HTF inlet reactor	THT_RCT_in	- heat transfer fluid temperature at the reactor inlet
HTF outlet reactor	THT_RCT_out	- heat transfer fluid temperature at the reactor outlet
Inertia tank	THT_Sol_out	- inertia tank temperature – top zone - control of TCM pump - control of the solar loop pump

NH_3 outlet reactor	TNH3_RCT_out	- ammonia vapour temperature at the reactor outlet
NH_3 inlet compressor	TNH3_RCT_out	- ammonia vapour temperature at the compressor inlet
NH_3 outlet compressor	TNH3_RCT_out	- ammonia vapour temperature at the compressor outlet
Evaporation temperature	TEvap	- evaporating temperature - control of the cold PCM storage pump
Condenser temperature	TCond gaz TCond liq	- condensing temperature - control of the on/off HP pump - control of incondensable gaz
Safety sensor		
Compressor differential pressure	ΔP_comp	- pressure differential at compressor - rotation speed control
Compressor oil temperature	T_oil_comp	- overheating of the compressor
NH_3 leakage detector	LL_NH3_conc	- detection of low levels of NH_3 concentration (0-500 ppm)
NH_3 leakage detector	HL_NH3conc	- detection high levels of NH_3 concentration (0-0.2%)

2.2.2 Control valves

The control valves are electrically actuated (24V AC or DC) by the TCM control system to connect the TCM unit components during the different operating phases. They are the on/off 2-way type. Furthermore, needle valves are implemented after two specific on/off 2-way valves to more precisely control the flow rate of liquid ammonia injected into the suction line of the compressor and into the evaporator.

Table 2: List of control valves implemented in the TCM unit and their functionalities

Valve type	Abbreviation	Function
Electric Control Valves		
Evaporator to reactor valve	Vev	Connection of the evaporator to the reactor
Reactor to condenser valve	Vcd	Connection of the reactor to the compressor/ condenser
Condenser to liquid reservoir valve	Vres_in	Connection of the condenser to the liquid reservoir
Reservoir to evaporator valve	Vres_out	Connection of the liquid reservoir to the evaporator
Compressor liquid injection valve	Vinj	Control of liquid injection at the suction line of the compressor to prevent high discharge temperatures of the compressed vapour
Manual Control Valves		
Evaporator control liquid injection valve	Needle MV_Ev	Needle valve to precisely control the liquid ammonia flow feeding the evaporator
Compressor control liquid injection valve	Needle MV_cp	Needle valve to precisely control the liquid ammonia flow that is evaporated at the suction line of the compressor

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869821

2.3 TCM unit operating phases

This section describes in detail the different TCM unit operating phases and the control of the connections between the TCM unit components.

2.3.1 Charging phase

2.3.1.1 Operating conditions of the TCM unit during the charging phase

During winter (graph (a) of figure 4) , the solar collectors should provide heat at a minimum temperature of 60 °C to allow the ammonia compressor to operate with an acceptable compression ratio (here a maximum of 6). Indeed, if solar heat is supplied at a lower temperature, the TCM operating pressure is then lower. Furthermore, the TCM condenser pressure is imposed during winter at 28°C by the mechanical heat pump, which requires a minimum temperature of 20 °C on its evaporator side to operate. During summer (graph (b)), the TCM condenser pressure is imposed by outside ambient conditions. Therefore, when the solar heat is supplied at a lower temperature, the ammonia compressor must operate with higher compression ratios due to lower operating pressure in the TCM reactor or higher condensing pressure in summer. Operating with high ratio can potentially damage the compressor and reduce its performance.

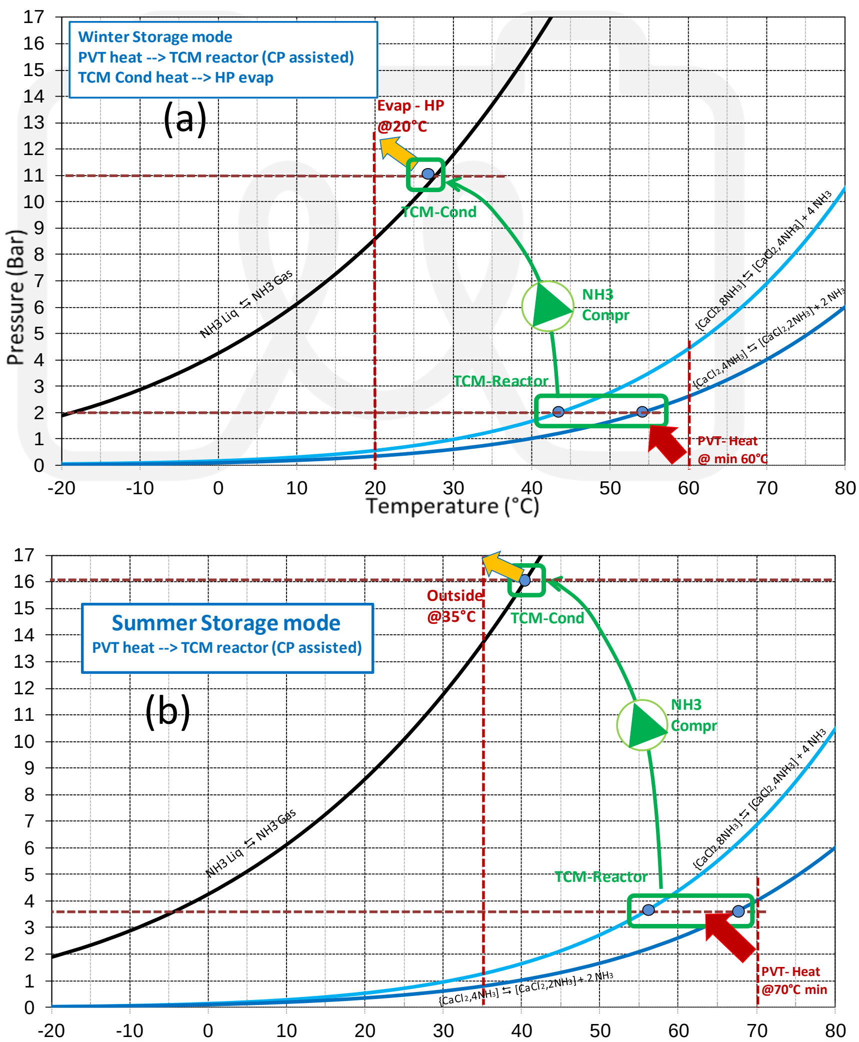

Figure 4: Operating conditions of the TCM unit during the charging phase in winter (a) and summer (b)

The charging phase consists of two steps: firstly establishing the temperature and pressure in the TCM reactor (pre-conditioning) followed by the decomposition of the ammoniated salt in the TCM reactor using the compressor (compressor-assisted charging).

2.3.1.2 Pre-conditioning of the TCM reactor while being isolated

When the temperature of the solar loop is high enough, the hot heat transfer fluid is pumped through the TCM reactor while it is isolated and disconnected from the other components (i.e., all valves are closed). This heats the ammoniated salt in the TCM reactor and starts the decomposition reaction, causing an increase in pressure in the reactor as ammonia vapour builds up.

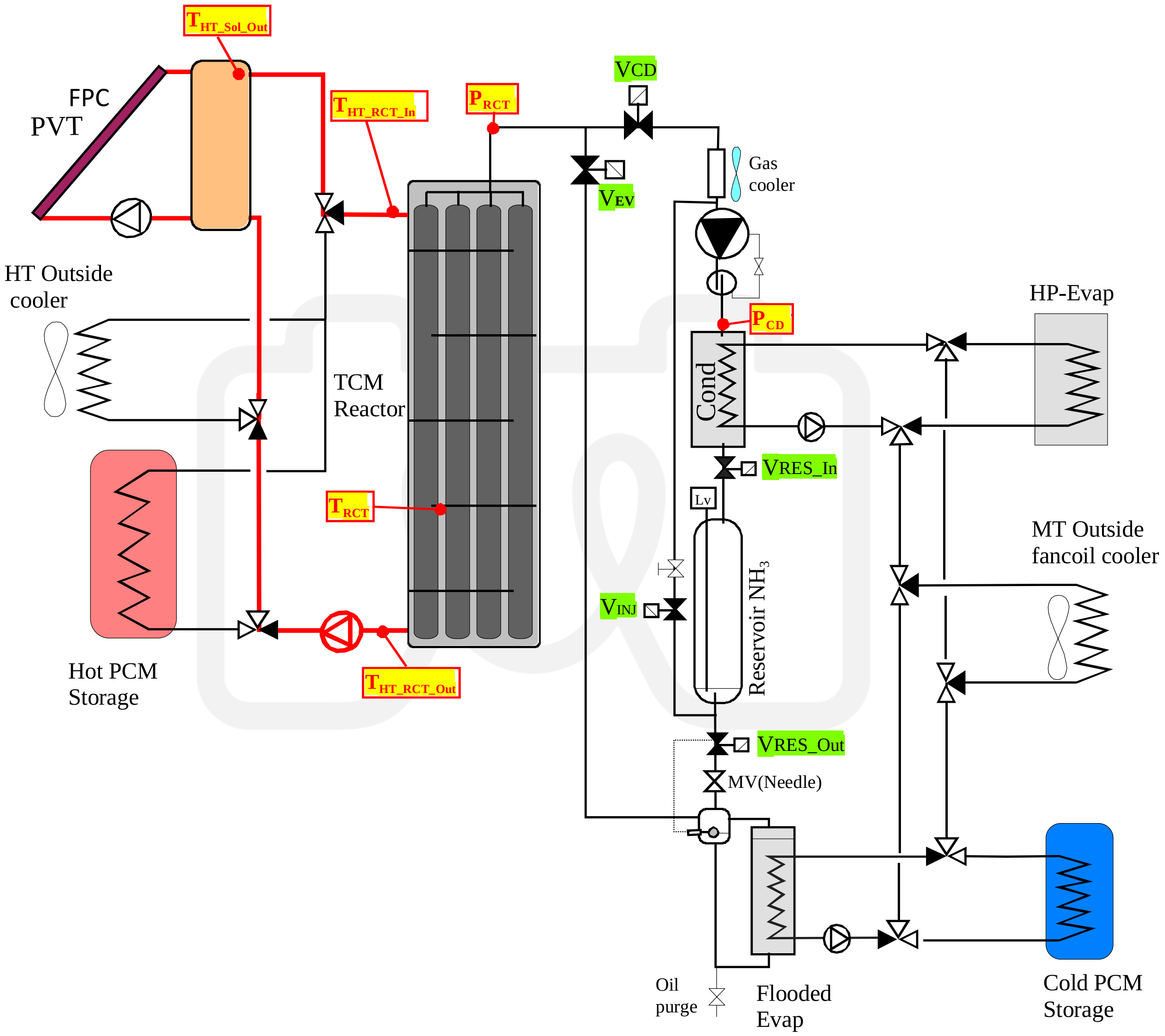

Figure 5: TCM charging phase – pre-conditioning of the TCM reactor

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2.3.1.3 Compressor-assisted charging phase

When the reactor pressure is high enough in comparison to that at the condenser, i.e., when the pressure ratio (P_{RCT}/P_{CD}) decreases below the permitted compression ratio τ for starting the compressor, then the second step commences. The reactor is then connected to the compressor by opening the valve (V_{CD}) and switching on the compressor. The gas cooler fan is also switched on to cool the vapour before it enters the compressor. If the discharged NH_3 vapour temperature is still too high (>130°C) then further cooling is required. This additional cooling is realised by injecting a small amount of liquid ammonia that vaporizes at the suction of the compressor by opening the valve (Vinj); the needle valve precisely controls the required low liquid flow rate. The compressed ammonia vapour is then condensed and the liquefied ammonia is stored in the liquid reservoir as the valve (Vres_in) is opened. The heat of condensation can be either recovered and upgraded by the mechanical HP (in winter) or released outside (in summer). The circulation pump of the condenser loop is started when the condensing temperature has reached a threshold value of 28 °C in winter (or Toutside+5 °C in summer).

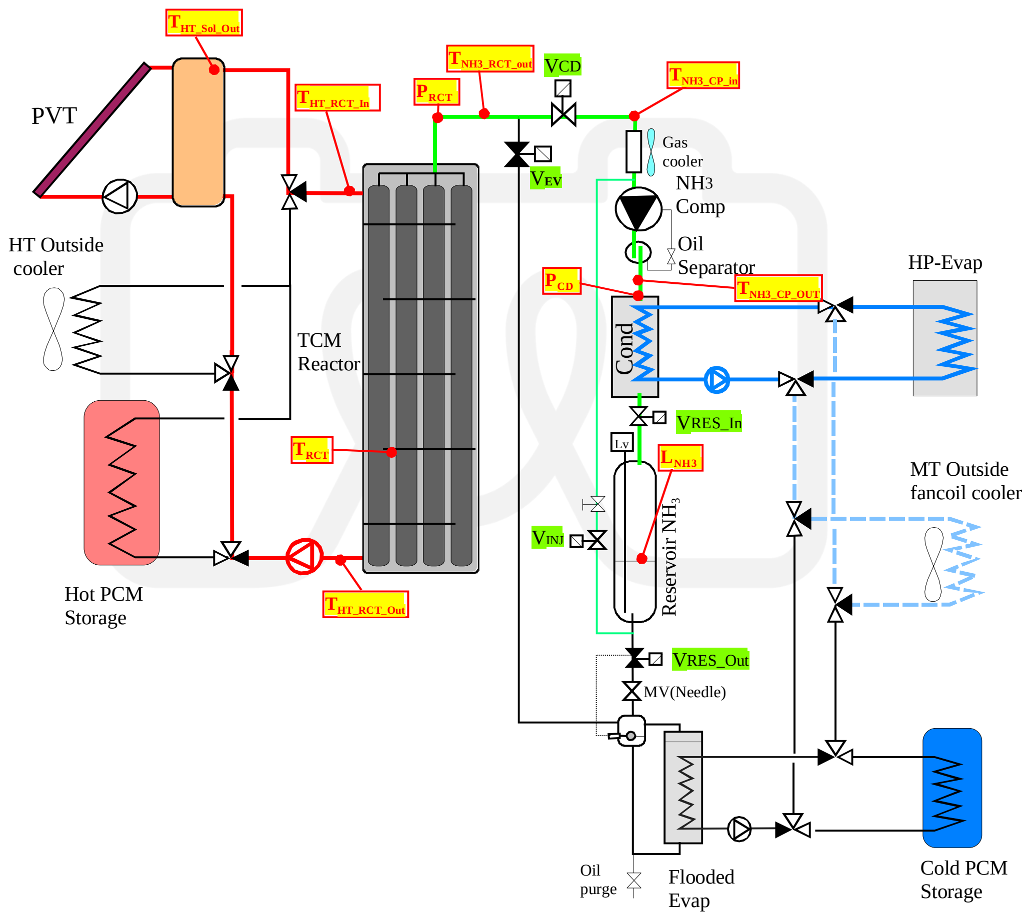

Figure 6: TCM unit charging phase in winter (bold lines) and in summer (dotted lines)

This charging phase can be carried out sequentially over 1, 2 or 3 days depending on the solar resource. The charging phase is completed when the liquid ammonia level in the reservoir has reached a high switching value corresponding to an ammonia mass of 43.7 kg corresponding to the advancement of ΔX_1=0.95 and ΔX_2=0.32 (nominal operation of the TCM unit to reach the targeted energy density of 200 kWh/m3). The TCM unit is then ready for the discharge phase.

2.3.2 TCM unit discharging phase

2.3.2.1 Operating conditions during the discharging phase in winter and in summer

During winter, the heat produced by the exothermic reaction of absorption of ammonia by the reactive salt is recovered at least at 63 °C for storage in the hot PCM unit. This temperature is the minimum required one for melting the hot PCM (SU58 from Sunamp) that occurs at 58 °C. The heat necessary to evaporate the ammonia in the evaporator at a suitable pressure for the TCM reactor (4.5 bar), has to be taken from outside at a temperature of at least 5 °C. If the outside ambient temperature is lower than 5 °C during a winter night, then the heat generated by the TCM unit will be at a lower temperature and the hot PCM may not be melted. To solve this issue, the cold PCM can be used to provide the evaporator with low temperature heat at 5 °C, or a PCM with a lower melting temperature of around 50 °C may be required.

During summer, the reactor can be efficiently cooled by the fan coil which releases heat to ambient (35 °C). The evaporator can produce a cooling temperature below 0 °C, down to -15 °C, allowing the cold PCM to solidify at 5 °C to provide air-conditioning of the building.

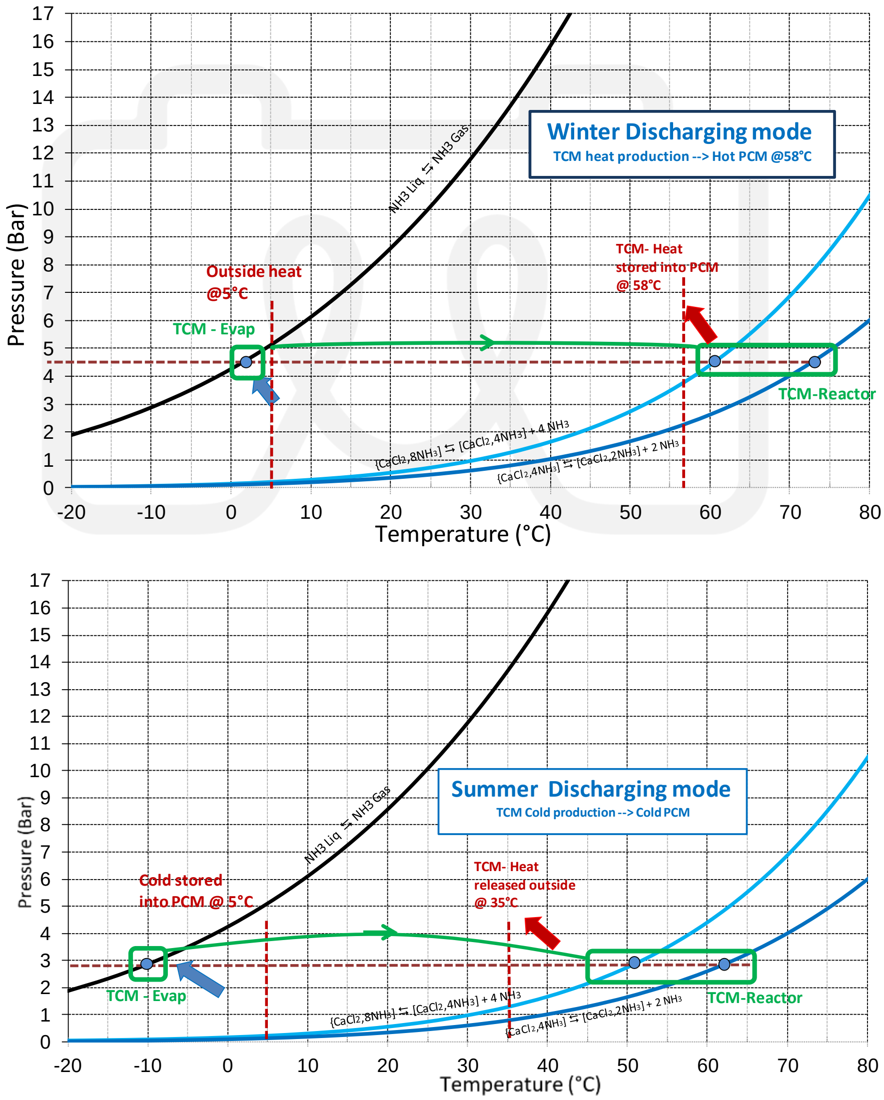

Figure 7: Operating conditions of the TCM unit during the discharge phase in winter (top) and summer (bottom)

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The discharging phase consists of two steps: firstly, if needed, depressurising and establishing the temperature of the TCM unit, followed by the absorption of ammonia vapour by the salt in the TCM reactor that is produced by the evaporator.

2.3.2.2 Preliminary step of TCM reactor depressurisation, if required

Before starting the discharge phase, the reactor pressure must be lower than the evaporator pressure before connecting the TCM reactor to the evaporator. Therefore, the reactor may need to be depressurised, to reduce its pressure to a little lower than that of the evaporator. This is achieved by pumping cold heat transfer fluid through the TCM reactor while it is isolated from the other components. Cooling of the isolated reactor lowers its pressure. The thermal energy extracted from the reactor is then either recovered to heat the hot PCM in winter or released outside via a fan coil in summer. When the reactor pressure becomes lower than that of the evaporator, the discharging phase can commence.

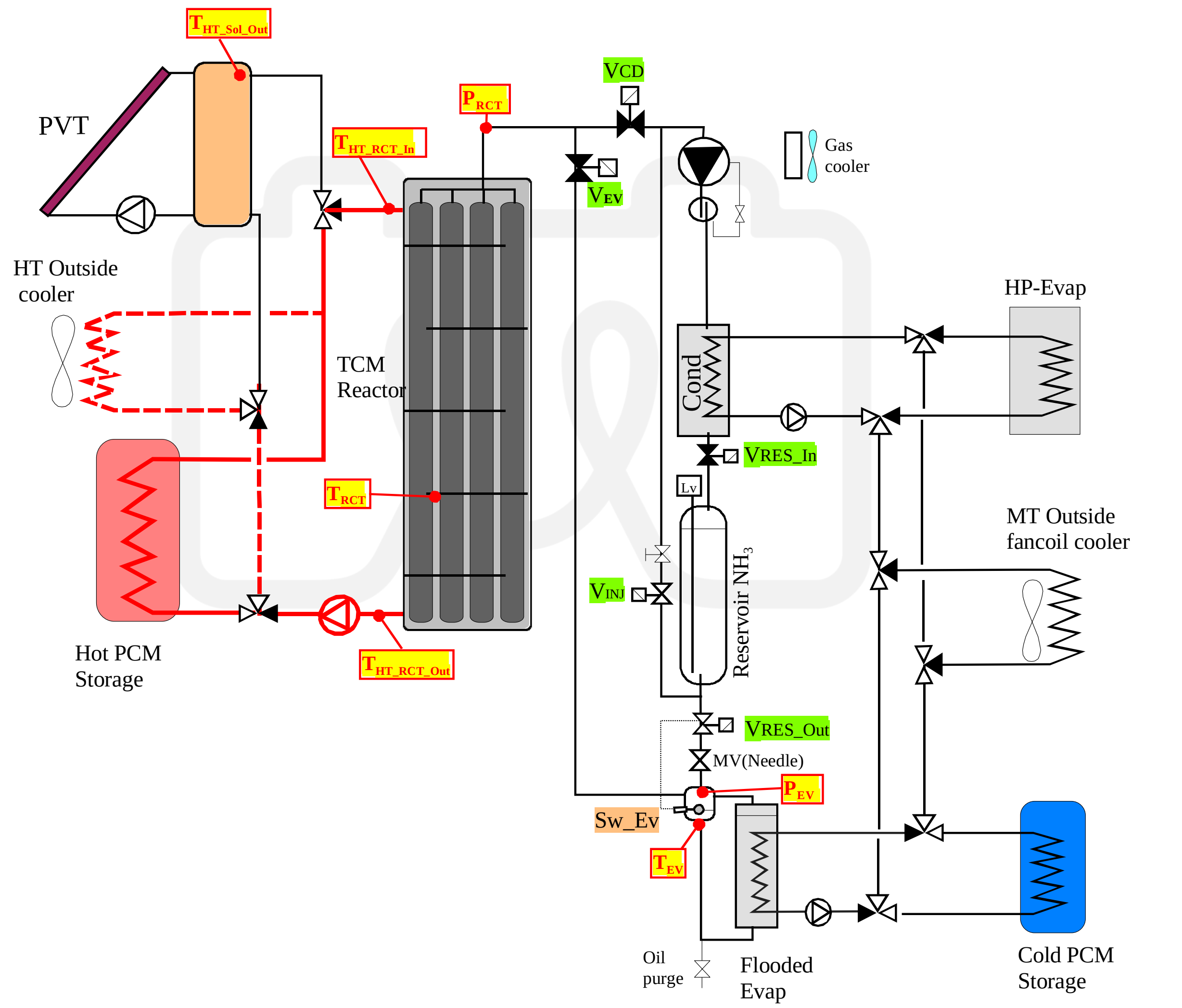

Figure 8: Discharging phase – preliminary pressure establishment of the TCM reactor

2.3.2.3 Discharging phase: heat and cold production

If the TCM reactor pressure is lower than that of the evaporator, then the reactor is connected to the evaporator by opening the valve (Vev). As the salt in the reactor absorbs the ammonia, the liquid level of the evaporator decreases. If the level switch (Sw_ev) in the small liquid reservoir placed just above the flooded evaporator is low, then the valve (Vres_out) is automatically opened to refill the evaporator. The ammonia level in the main reservoir therefore slowly decreases as a function of reactor cooling.

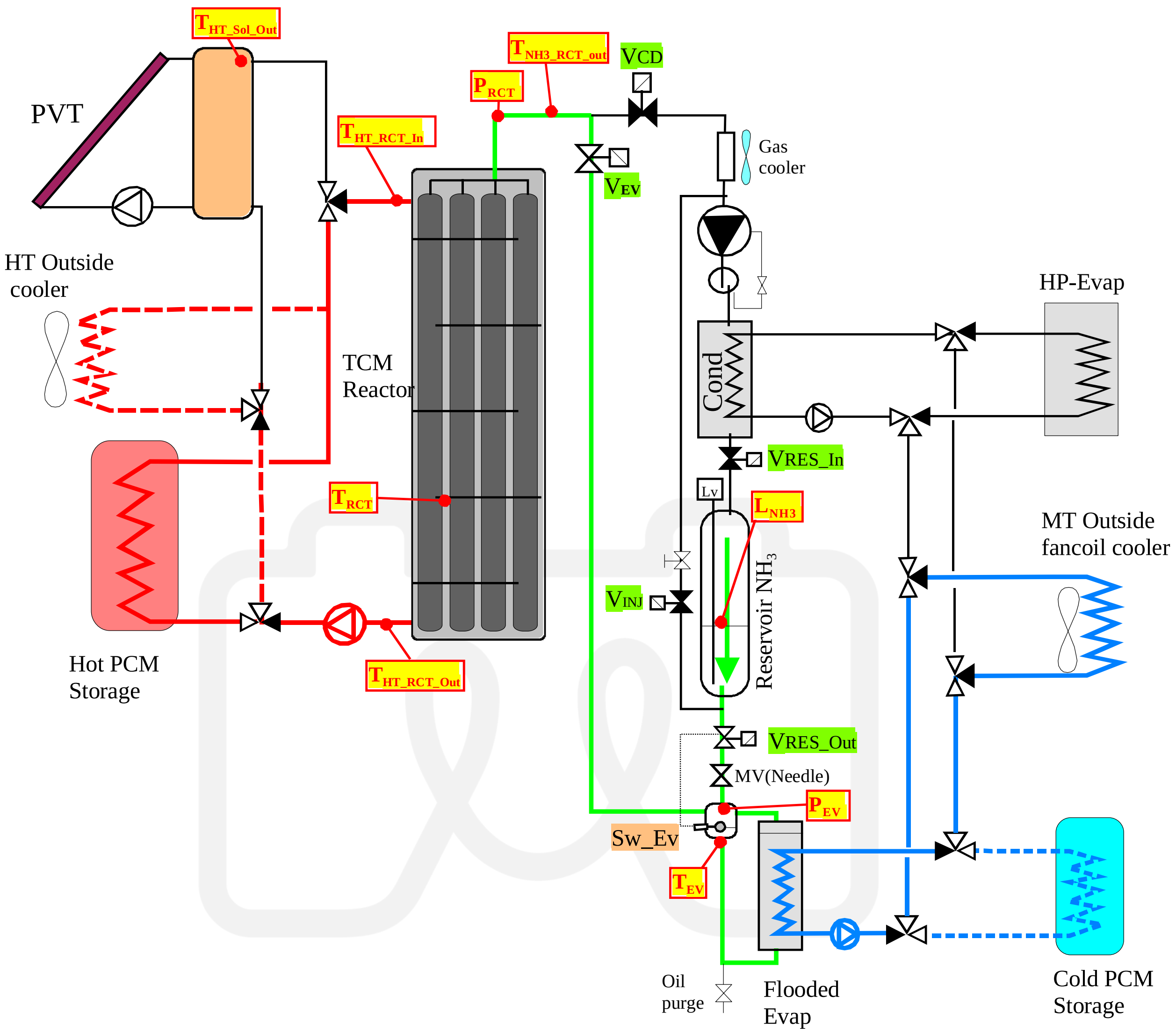

Figure 9: Discharging phase – TCM reactor connected to the evaporator in winter (bold lines) or in summer (dotted lines)

3 Design of the TCM unit components

This section describes the design of each TCM unit component and their required main characteristics to fulfil the TCM storage requirements (energy, power, temperatures, pressures, etc.).

3.1 Operating specifications for the design of the TCM components

The TCM unit components are designed by considering the worst solar conditions in winter and summer available at the demo sites. According to the discussions held between the relevant MiniStor partners, it was decided to implement the same TCM storage unit for all demonstration sites, with a maximum storage capacity of 30 kWh. The following data have been considered for the TCM unit design:

Table 3: Operating specification for the TCM unit

	Winter conditions	Summer conditions
TCM unit storage capacity	30 kWh of heat @ 60 °C	14 kWh of cold @ -5 °C
Solar loop heating power	Heating power : Qh=1000 W → 4000 kW Mass flow rate : mfr = 480 kg/h Minimum Tstart = 60 °C / Tstop = 55 °C	
TCM condenser temperature	28 °C	45 °C
TCM evaporator temperature	0 °C	0 °C

3.2 TCM reactor design

The heat transfer fluid that supplies or removes the heat of reaction from the TCM reactor is characterised by a constant mass flow rate of 480 kg/h. A minimum reactor outlet temperature has been set at 55 °C to maintain an acceptable reactor pressure for the operation of the ammonia compressor (which has a maximum compression ratio of 6). Thus, when the temperature of the inertia tank reaches 60 °C, the TCM pump is activated. This pump is stopped when the inertia tank temperature become lower than 55°C. The compressor speed must then be modulated according to the thermal power supplied to the TCM reactor.

The design methodology of the TCM reactor has been previously described in Deliverable 4.1. To achieve the chosen storage capacity (30kWh) under the specified advancements of reaction ΔX_1=0.95 and ΔX_2=0.32 corresponding to the nominal operating of the TCM unit to reach the targeted energy density of 200 kWh/m^3, the required TCM reactive composite material is then 77.2 kg, composed of 65.9 kg of anhydrous $CaCl_2$ salt and 11.3 kg of expanded graphite. The corresponding volume of the TCM material, considering its bulk density of 500 kg/m3, is 151.1 Litres. In nominal operating of the TCM, the total ammonia mass that is cycled is 43.7 kg, which corresponds to conversion rates ΔX1 =0.95 and ΔX2 = 0.32.

However, it should be pointed out that if the solar resource is higher than expected, then more implemented ammoniated salt should be decomposed into $CaCl_2.2NH_3$, producing thus more ammonia gas. This results in a higher conversion rate ΔX_2 of the second reaction. In the extreme case that all of the implemented salt is decomposed into $CaCl_2.2NH_3$, the total amount of ammonia that is produced should be 59.1 kg. In this case, the TCM unit stores more energy (around 39 kWh) and its achieved energy density is higher (256 kWh/m^3). Moreover, it should also be pointed out that during the first commissioning phase, the initial state of the salt is in anhydrous form ($CaCl_2$). In order to put in operation, the TCM unit, the salt has then to be first fully ammoniated into $CaCl_2$,$8NH_3$, and the required ammonia to fully ammoniate the 64.3 kg of anhydrous salt is 78.7 kg of ammonia.

As a result, the TCM reactor will be composed of 13 reactor tubes assembled together in a shell where the solar heat transfer fluid (HTF) circulates. Each reactor tube has an external diameter of 114.3 mm, a thickness of 2 mm and a total length of approximately 1.33 m, and contains 5.97 kg of reactive composite (corresponding to a length of 1.26 m). All reactor tubes are connected together at one end by a spider-shaped distributor, allowing the correct flow of the ammonia gas from each reactor tube in desorption phase (storage mode) or to each reactor tube in absorption phase (heat/cold production mode). The flow from/to each reactor tube is achieved independently and as needed to equalize the pressure in all reactor tubes. In fact, each reactor tube when heated (storage mode) or cooled (production phase) produces or absorbs ammonia independently and according to its needs resulting from the thermal equilibrium deviation that is imposed on it. Such a spider-shaped distributor is therefore the most appropriate means of connecting and ensuring the proper flow of ammonia from/to each reactor tube that constitutes an independent source or sink of ammonia.

Five equally spaced baffles (about 25 cm apart) maintain the position of the bundle of reactor tubes so that the HTF circulates perpendicularly to the reactor tubes. The reactor tubes are spaced 5 mm apart to enable circulation of the heat transfer fluid. In this way, the shell should have a diameter of 540 mm and a total length of approximately 1.5 m. The water content of the TCM unit should be approximately 120 litres.

In order to avoid corrosion of the reactor tube by the chloride salt and ammonia, the salt is strongly in situ dehydrated and always kept in a solid state (salt). Indeed, corrosion phenomena mainly occur when the salt is solubilised in liquid ammonia or water and in the presence of oxygen. These situations never occur because the reactor tube is first evacuated while filled with salt (no oxygen remains) and the solubilisation of the salt is avoided by controlling the pressure of the reactor during operation: this pressure must be kept lower than the pressure of the saturated solution, about the half that of the liquid/vapour phase change of ammonia). Furthermore, the material of the reactor tube is made of stainless steel, the **grade 316L (EN 1.4435)**, which is one of the most cost-effective and corrosion-resistant stainless steel. The significant presence of molybdenum (about 3%) in the 1.4435 stainless steel is well known to increase the corrosion resistance to chlorides, strong acids and bases.

Such a choice of material for the reactor tube has been tested for many years in the various experiments carried out in CNRS-PROMES laboratory without any problems, while taking care to operate under conditions that avoid the formation of saline solutions. Furthermore, 316L stainless steel (grade EN 1.4435) is used since many years by Coldway Technologies for the manufacture of its thermochemical reactors implementing Manganese chlorides and with which it equips its cold storage devices which are marketed since 2006 for cold chain applications. The company has had very few customer returns for corrosion defects.

Table 4: Summary of the design data of the TCM unit

	13 tubes design
Heat Storage Capacity @ 60°C	30.3 kWh
Cold Storage Capacity @ 5°C	14.1 kWh
Total Volume of TCM material	151.1 litre
Mass of the TCM material	77.2 kg
Mass of anhydrous $CaCl_2$ salt	65.9 kg

Mass of Expanded Natural Graphite (ENG)	11.3 kg
Total mass of ammonia required to fully charge the TCM material from initial anhydrous salt $CaCl_2$ to fully ammoniated salt $CaCl_2.8NH_3$. ***This step is realized only once, during the commissioning phase. Note that <u>NOT all of this ammonia amount</u> is cycled and some remains always fixed in the $CaCl_2.2NH_3$ salt***	78.7 kg
Maximum ammonia that can be cycled when fully discharged TCM material from $CaCl_2 \bullet 8NH_3$ to $CaCl_2 \bullet 8NH_3$ → **corresponds to advancements of reaction of $\Delta X1 = 1$ and $\Delta X2 = 1$**	59.1 kg
Cycled Ammonia mass that is cycled in nominal operation to meet the 200 kWh/m^3 of energy density → **corresponds to advancements of reactions of $\Delta X1 = 0.95$ and $\Delta X2 = 0.32$**	43.7 kg
Total length of required reactive material	16.4 m
Number of reactor tubes	13 tubes
Length of unitary reactor tube (4"OD Sch5S) Length of reactive material in each tube	1.33 m 1.26 m
Size of shell of the TCM storage unit (diameter / length)	540 mm x 1.45m
Total mass of stainless steel (Shell + 6 baffles + reactor tubes)	25+ 4 + 111=140 kg
Volume content of heat transfer fluid in TCM shell	122 litres
Total mass of shell and tube reactor when salt is fully charged (@ $CaCl_2 \bullet 8NH_3$) and filled with water	420 kg (approx.)

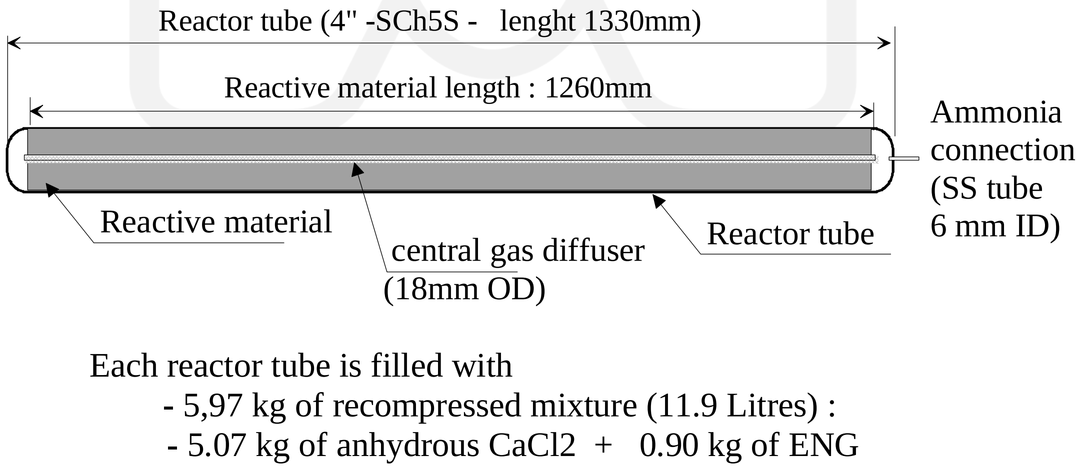

Figure 10: Schematic view of a reactor tube placed in the shell-type TCM reactor

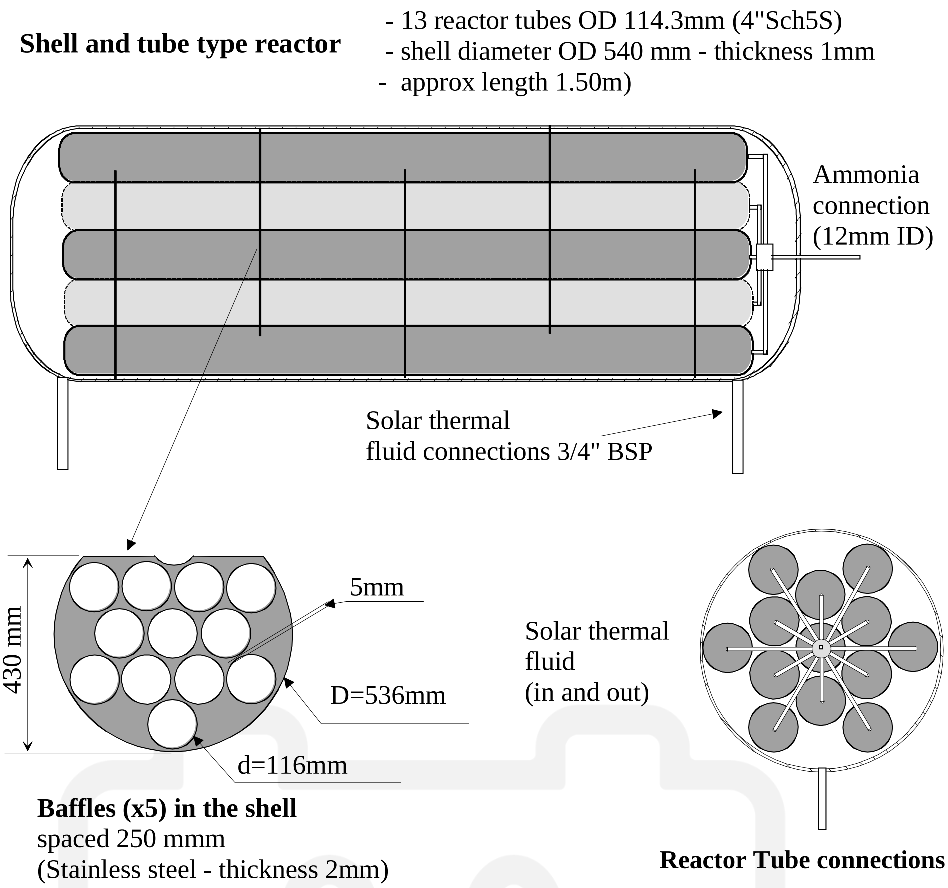

Figure 11: Schematic view of the shell and tube TCM reactor composed of 13 reactor tubes

3.3 Ammonia Compressor

The compressor compresses the ammonia vapour that is released from the TCM reactor when it is heated during the charging phase. The vapour is compressed to a pressure where it can be subsequently liquefied in the TCM condenser, and thereafter stored in the liquid reservoir. The compressor enables operation of the TCM reactor at the low driving temperature delivered by the solar collectors (55-60 °C). Without a compressor the operating pressure of the TCM reactor would be the same as the condensing pressure – 11 bar if the TCM condensing temperature is 28 °C in winter. The reactor would therefore need to be heated to 100 °C, whereas the use of a compressor lowers this temperature to 60 °C.

A limitation of the PVT solar thermal system, related to the climate analysis, is that it can only supply a thermal power of 1-5 kW, depending on the inertia tank temperature. The heat transfer fluid that supplies or removes the heat of reaction from the reactor has a constant mass flow rate of 480 kg/h. When the temperature of the inertia tank increases above 60 °C, the TCM pump is activated. The pump is switched off when the tank temperature decreases below 55 °C. The minimum reactor outlet temperature has been set at 55 °C in order to keep an acceptable pressure in the TCM reactor for the operation of the ammonia compressor (which has a maximum compression ratio of 6). The compressor speed must be varied to track the thermal power supplied to the TCM reactor.

The thermal power absorbed by the TCM reactor is related to the ability of the compressor to compress a given mass flow rate of ammonia (depending on the swept volume Qv_{swept} at a given rotation speed and the compression ratio). It also depends on the ability of the reactor to absorb the thermal power $\dot{Q}_{PVT}$ provided by the solar collectors , in particular the quality of the heat exchanged between the HTF and the wall ($\dot{Q}_{TCM}^{Exch\_ext}$) of the reactor and the wall with the reactive medium ($\dot{Q}_{TCM}^{Exch\_int}$) (see deliverable D4.1 for more details). The different thermal powers involved at the TCM reactor level are governed by the following equations, and of course have to be equal to each other:

$$\dot{Q}_{PVT} = \dot{m}_{PVT}.Cp_{PVT}.\left(T_{PVT\_in} - T_{PVT\_out}\right)$$

$$\dot{Q}_{TCM}^{Exch\_ext} = U_{W\_ext}.A_{W\_TCM}\left(\tilde{T}_{PVT} - T_{W\_TCM}\right)$$

$$\dot{Q}_{TCM}^{Exch\_int} = U_{W\_int}.A_{W\_TCM}\left(T_{W\_TCM} - T_{Eq1}(P_{TCM})\right) + U_{W\_int}.A_{W\_TCM}\left(T_{W\_TCM} - T_{Eq2}(P_{TCM})\right)$$

$$\dot{Q}_{TCM}^{reaction} = \frac{\dot{m}_{NH3}}{Mm_{NH3}}.\Delta H_R^o$$

The volumetric flow rate at the compressor inlet can be expressed as:

$$Qv_{NH3} = \alpha_{swept}.Qv_{swept}.\eta_v = \frac{\dot{m}_{NH3}}{\rho_{NH3\_vap}(T_{suct.}, P_{TCM})}$$

with $$\dot{m}_{NH3} = \left(\frac{U_{W\_int}.A_{W\_TCM}}{\nu_1.\Delta H_{R1}^o}\left(T_{W\_TCM} - T_{Eq1}(P_{TCM})\right) + \frac{U_{W\_int}.A_{W\_TCM}}{\nu_2.\Delta H_{R2}^o}\left(T_{W\_TCM} - T_{Eq2}(P_{TCM})\right)\right)Mm_{NH3}$$

Figure 12 shows how the HTF temperatures at the reactor inlet and outlet change as a function of the TCM thermal power:

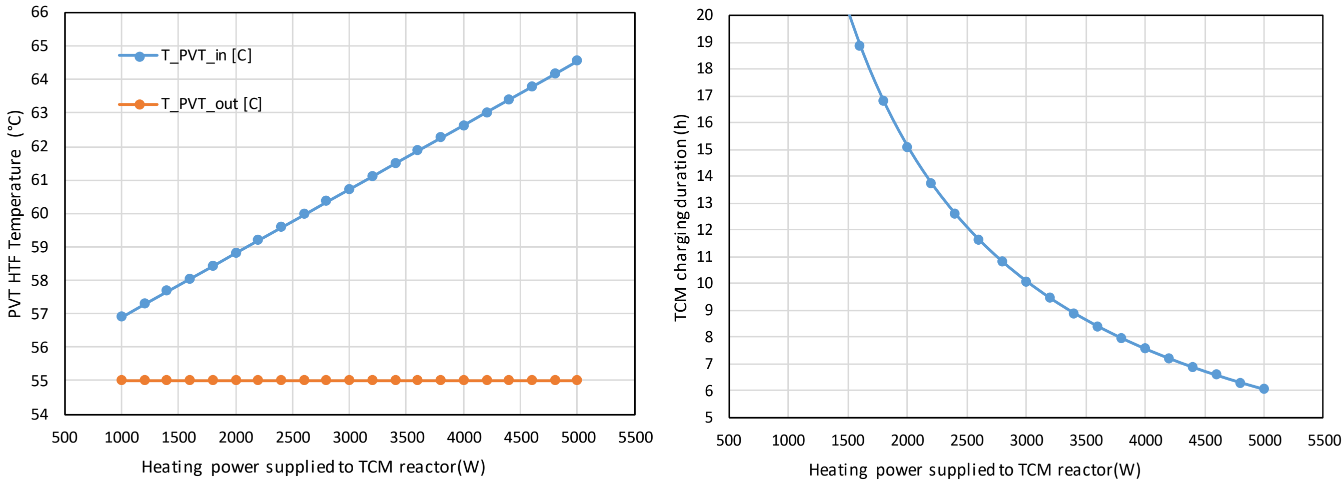

Figure 12: Change in HTF inlet and outlet temperatures (left) and the charging time of the TCM unit (right) as a function of the thermal power supplied

The thermal power supplied to the TCM reactor causes the desorption of ammonia from the reactive salt. This heating power enables the TCM reactor to produce an ammonia mass flow rate ranging from 2 to 7 kg/h as the power increases from 1 kW to 5 kW. As introduced in section 2.3.1.3, to protect the compressor, the supplier indicates that the temperature of the compressed vapour must not exceed a maximum temperature of 130 °C. The ammonia must then be cooled at suction line of the compressor. Taking into account the compression ratio and the isentropic efficiency of the compressor, the ammonia vapour produced by the TCM reactor at approximately 55 °C must be cooled to at least -15 °C, which is a slightly higher temperature than the saturation temperature (-20 °C) at the TCM reactor operating pressure (and also the suction pressure of the compressor), approximately 2 bar. This cooling can be efficiently carried out by injecting a small amount of liquid ammonia taken from the liquid reservoir by opening the valve (Vinj). This liquid ammonia is then evaporated at the suction line causing cooling of the ammonia vapour. A first estimation indicates less than 10% of the liquid ammonia produced at the condenser would need to be injected into the suction line over the course of the charging phase. Figure 13 shows the mass flow rates of the ammonia produced in the TCM reactor and the liquid ammonia that should be injected at the suction line in order to cool the vapour to -15 °C.

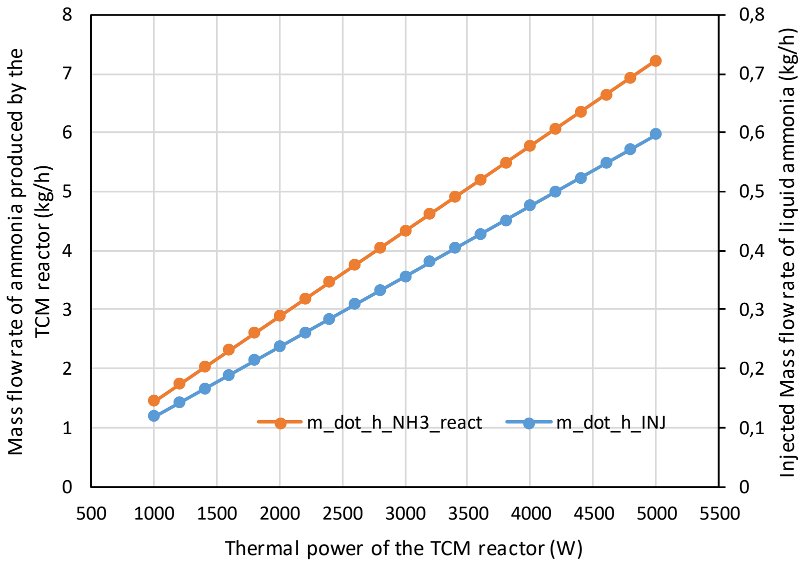

Figure 13: Mass flow rates of the ammonia produced in the reactor and the liquid ammonia injected to cool the vapour at the suction line of the compressor.

Taking into account the volumetric efficiency η_v of the compressor operating between a suction pressure of 2 bar and a condensing pressure of 11 bar, the required swept volume rate of the compressor ranges from 1.5 to 7.4 m^3/h. For a heating power of 2.5 kW, the required swept volume of the compressor is approximately 3.8 m^3/h and the total volumetric flow at the compressor inlet is 2.7 m^3/h. In order to modify the swept volume of the compressor (nominal swept volume of around 7 m^3/h) to respond to the heating power supplied to the TCM unit, the rotation speed of the compressor must be adjusted. The rotation speed of the compressor is set by maintaining the suction pressure at the operating pressure required by the TCM reactor.

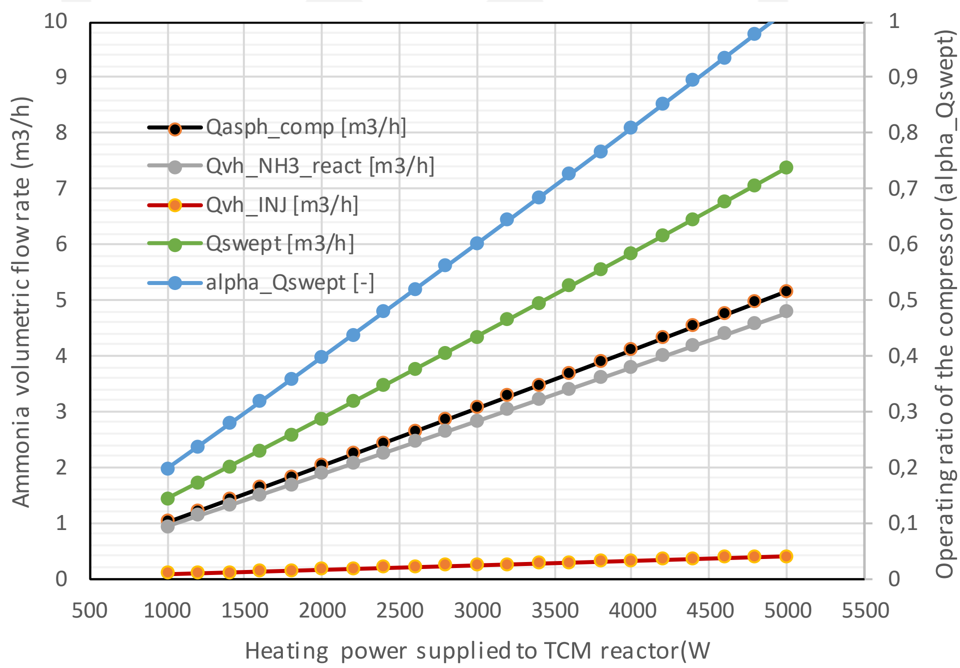

Figure 14: Change in the volumetric flow rates of ammonia (produced by the TCM reactor, injected at the suction line and the compressor inlet), required swept volumetric flow rate and operating speed ratio considering a nominal swept volume of 7.22 m^3/h.

Figure 15: Semi-hermetic ammonia compressor manufactured by Frigopol

The compressor model "Frigopol 7DLY", which is the smallest model manufactured by Frigopol is suitable for the MiniStor application. This compressor is a semi-hermetic type of compressor with a separating hood to reduce ammonia leakage risks. Its nominal swept volumetric flow rate is 7.22 m^3/h @ 1450 rpm (50 Hz) and can operate with a maximum compression ratio of 6.

The compressor motor has a separate control unit also provided by Frigopol. This enables the frequency applied to the motor to be varied between 35 Hz and 75 Hz, enabling the rotation speed to be adjusted from 700 rpm to 2000 rpm. This frequency regulation enables the swept volumetric flow of the compressor to be varied from 3.5 m^3/h to 9.9 m^3/h.

The minimum allowed swept volume rate of 3.5 m^3/h at 35 Hz may be too high, e.g., to simultaneously keep the TCM pressure above 2 bar and the condenser more than 11 bar when the thermal power from the solar loop is less than 2500 W. It may therefore be necessary (but not efficient from an energy point of view) to equip the compressor with a capacity-control circuit to allow an additional reduction of its effective swept volume rate when the available solar thermal power is less than 2500 kW. The capacity-control circuit is composed of a feedback loop that connects the compressor's discharge line with the inlet line. Some of the ammonia vapour from the compressor outlet is returned to the intake, thus reducing the effective vapour flow rate from the reactor. As the mixing increases the inlet vapour temperature, the mixing pipe should be connected before the gas cooler fan on the suction line.

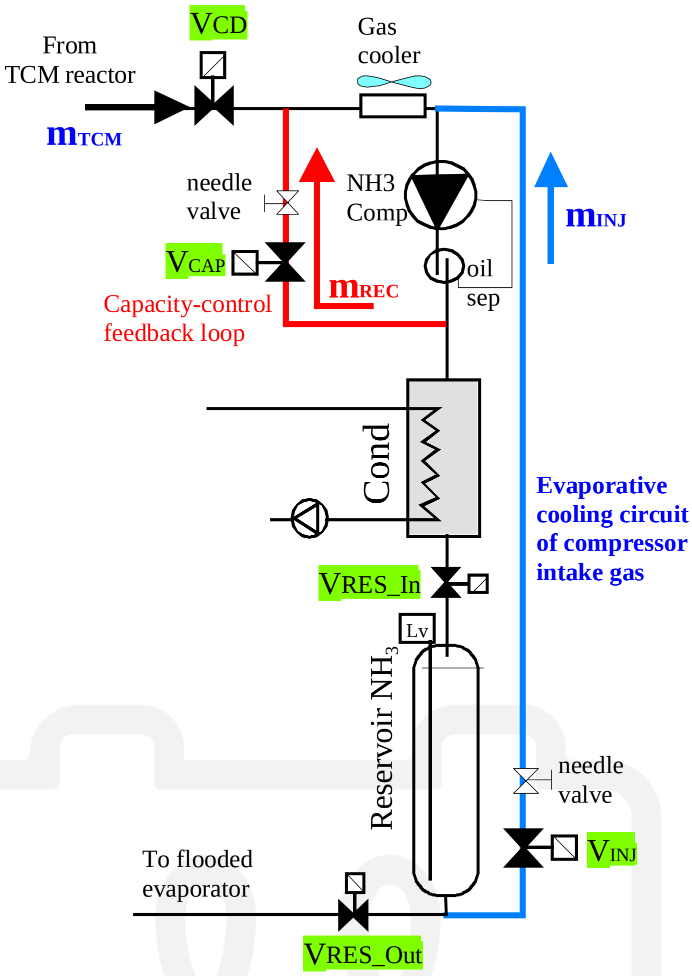

Figure 16: Schematic of the capacity-control feedback loop for reducing the effective volumetric swept volume of the compressor (m_{TCM}) by recirculating some of the hot gas (m_{REC}) from the compressor outlet

3.4 Oil separator

As the ammonia compressor uses a synthetic oil lubricant that is not miscible with ammonia (polyalphaolefin-based oil, such as MOBIL SHC 226), an oil separator must be installed on the discharge line. The purpose is to achieve gravimetric separation of the small droplets of oil that are expelled through the compressor's discharge line. The oil is recovered and accumulates in the oil separator. When a given accumulation volume is reached, an automatic return of the oil is then initiated by opening the oil-return valve, causing the oil to return to the compressor crankcase by pressure difference.

The oil separator is chosen by taking into account the volumetric flow rate of the ammonia (maximum of 10 m^3/h). In order to reach a high efficiency of oil separation an oil separator with double the compressor displacement is recommended.

The ESK Shultze company can provide on request the specific oil separator for our needs (hermetic model OS12-FL1 or OS16-FL1 should suit this application).

Figure 17: Hermetic oil separator manufactured by ESK-Shulze (www.esk-schultze.de)

3.5 Ammonia condenser

The condenser liquefies the compressed ammonia vapour released by the heated TCM reactor. The heat of condensation is either recovered at 25-30 °C by the evaporator of the heat pump (at 20 °C) in winter or released outside at 45-50 °C by a fan coil (maximum outdoor temperature 35 °C). The condensing power is a function of the mass flow rate of the ammonia vapour. This flow rate results from the thermal power supplied to the TCM reactor by the solar loop. Considering that the TCM heating power varies between 1000 and 5000 W, the condenser power should also vary from 600 W to 3100 W.

The heat transfer fluid should have inlet and outlet temperatures of 22 °C and 26 °C, respectively, and a mass flow rate of 500 kg/h to meet the requirements of the mechanical heat pump. Therefore, the required heat exchange surface of the condenser should be approximately 0.5 m² (using an overall heat exchange coefficient of 1000 W/m².K for a typical water-cooled condenser).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869821

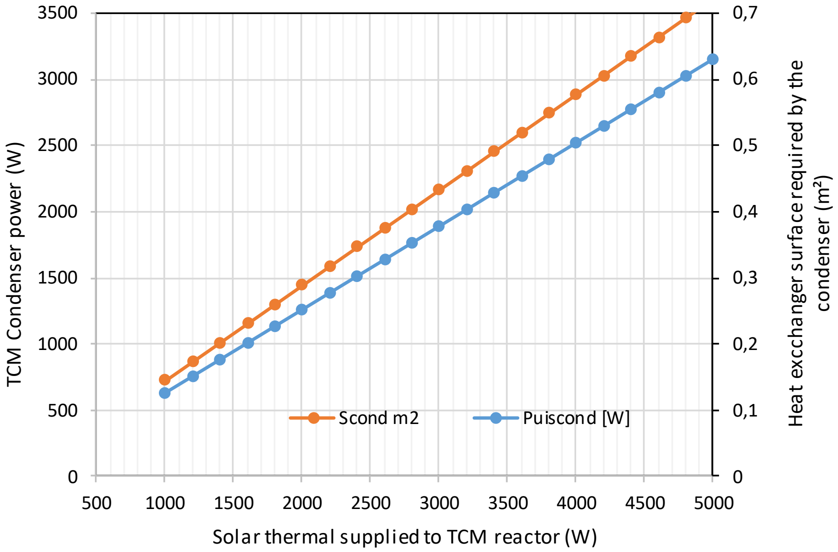

Figure 18: Change in thermal power of the condenser and the required heat exchange surface as a function of the thermal power supplied to the reactor.

After consideration of several different types of condensers, spiral-plate heat exchangers manufactured by Spirec were chosen. Their working principal is shown in Figure 19. The Spirec heat exchangers are based upon a thin baffle that is rolled up and then encapsulated in an enclosure. The **Spirec model EC.07.48** meets the requirements of the TCM units, namely: a heat exchange surface of **0.73 m²,** fully stainless steel 316L construction with Teflon baffles for ammonia resistance, a maximum pressure in the ammonia circuit of 40 bar (circuit B), a maximum pressure in the water cooling circuit of 15 bar (circuit A), a pressure drop of 0.12 bar for a water mass flow rate of 0.54 m^3/h, no liquid ammonia retention when placed vertically, an operating temperature range from –50 °C to +150 °C, compact size, and low cost compared to alternative heat exchangers.

Figure 19: Spiral-plate heat exchanger from Spirec and its working principle

3.6 Liquid ammonia reservoir

After being condensed, the ammonia is stored in the liquid receiver at ambient temperature. During summer periods, the outdoor temperature can reach 35-40 °C, hence the pressure in the receiver may reach pressures in the order of 20 bar. In winter, the ammonia evaporator exploits the outdoor heat, even if the liquid ammonia is at a lower temperature than ambient. This is because the pressure in the liquid reservoir is higher than the evaporator outlet.

For safety reasons, the volume of the reservoir must be slightly larger than the maximum amount of ammonia that the TCM reactor can produce when the ammonia is completely desorbed from the salt. In normal operation, 95% of $CaCl_2•8NH_3$ is expected be converted to $CaCl_2•4NH_3$ and 32% of $CaCl_2•4NH_3$ into $CaCl_2•2NH_3$. These conversion rates enable the energy density target of more than 200 kWh/m^3 required by the MiniStor project at the material level, and lead to a total mass of cycled ammonia of 43.7 kg.

As explained before in Part 3.2, If the implemented fully ammoniated salt $CaCl_2.8NH_3$ is totally decomposed and converted into $CaCl_2•2NH_3$ because of a higher available solar resource, then the total amount of produced ammonia would be 59.1kg. The liquid reservoir must be able to store this maximum amount of ammonia in liquid form at the highest expected outdoor temperature (45 °C). The required volume is therefore 98.3 litres of liquid ammonia at 45 °C, while the expected cycled volume is only 76.3 litres in normal operating (corresponding to 43.7 kg).

Furthermore, the reservoir should never be completely filled with liquid and an additional volume should be retained as gas. This gas volume should represent at least 5% of the total volume of the reservoir. Standard pressure vessel design includes an 80% sizing factor, so the recommended vessel size for installation is at least 120 litres.

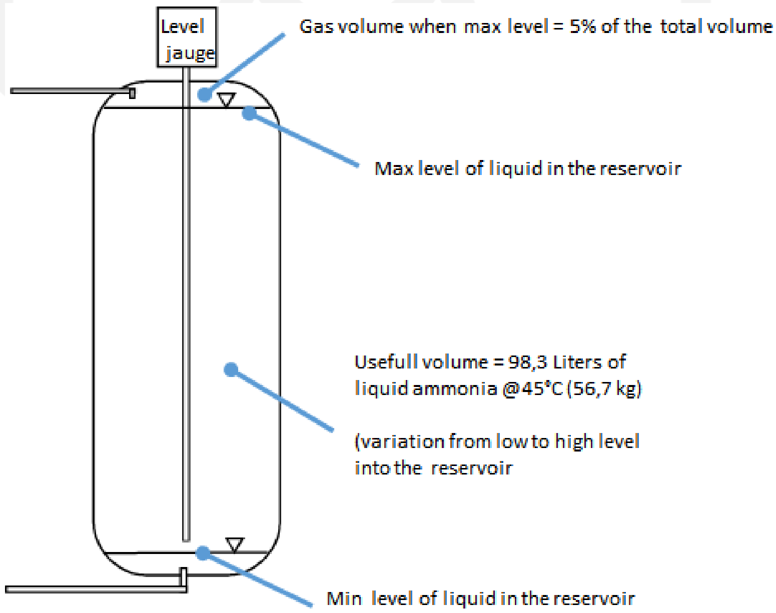

Figure 20: Schematic view of the liquid ammonia reservoir

At the top of the liquid reservoir there is an inlet connection from the condenser and, at the base, an outlet connection to the evaporator via a throttling valve. Each connection pipe has a valve that serves to isolate the liquid ammonia from the rest of the system. The central part of the reservoir is crossed by a capacitive-type liquid level transducer that measures the state of charge of the TCM reactor. The rod of the level sensor reaches the bottom of the reservoir with a margin of about 20 mm (the gap should be as small as possible to limit the amount of unnecessary liquid ammonia in the reservoir). It would be useful to install a visual indicator of the liquid level inside the reservoir, for maintenance purposes or to recalibrate the capacitive liquid level transducer, if needed. The reservoir will be provided by Spirotech Group Ltd (UK).

Table 5: Characteristics of the liquid reservoir

Liquid reservoir	
Brand	Custom designed
Max operating conditions	45 °C / 20 bar
Material	316L stainless steel
Capacity	Volume: ~120 litres; height: ~ 1 m; useful cycling volume 76.3 litres
Dimensions	To be defined
Connections	Liquid inlet: Ø 10 mm OD tube - pipe conn. ¾" BSP
	Liquid outlet: Ø 10 mm OD tube - pipe conn. ¾" BSP
Associated instrumentation	2 thermocouples (in vapour and liquid regions)
	1 liquid level transducer with alarm/switch level
	1 visual level indicator placed in parallel to the reservoir
	1 pressure sensor (condensing pressure)

During discharge of the TCM unit, i.e., to produce useful heat in the TCM reactor during winter or useful cold at the evaporator during summer, liquid ammonia flows out of the reservoir and enters the evaporator with a carefully controlled mass flow rate, where it evaporates by absorbing heat from the heat transfer fluid, which is cooled down. The cooled heat transfer fluid is then heated up either by charging the cold PCM storage or by a fan coil.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869821

3.7 TCM evaporator

The chosen evaporator is a gravity-fed flooded type. The implementation of a direct expansion evaporator was ruled out since there were no commercially available options for an expansion valve suitable for ammonia installations with a low cooling capacity. Secondly, flooded type evaporators are much easier to control. Instead of the conventional vapour superheating control at the outlet of the evaporator, the required filling of such a flooded evaporator can be easily achieved by an on/off switching level placed in a small tank placed just above the evaporator that controls a liquid supply valve.

The evaporator chosen is the same model as the condenser manufactured by Spirec (model EC.07.48). As this model is a little bit oversized for the TCM application (1 to 3 kW cooling power), the operating conditions of the evaporator in winter should be better as it will lead to a smaller difference between the evaporating temperature and outdoor temperature, and thus a higher temperature of heat from the TCM reactor should be obtained.

A gravity-fed flooded evaporator works on the thermo-siphon principle. The liquid ammonia exits the liquid reservoir, it passes through the electric (Vres_out) and needle valves and enters the small evaporator reservoir through the vapour-liquid inlet, which has a 90° elbow downwards to avoid splashing the level switching sensor with the ammonia saturated mixture. The electric valve (Vres_out) that controls the flow of liquid ammonia should have a small shut-off orifice (diameter of around 2 mm, flow coefficient of 0.15 m^3/h). The needle valve (10-turn needle valve), with a smaller orifice (1 mm, flow coefficient of 0.04 m^3/h), allows for fine regulation of the throttling process of the liquid ammonia into the evaporator reservoir.

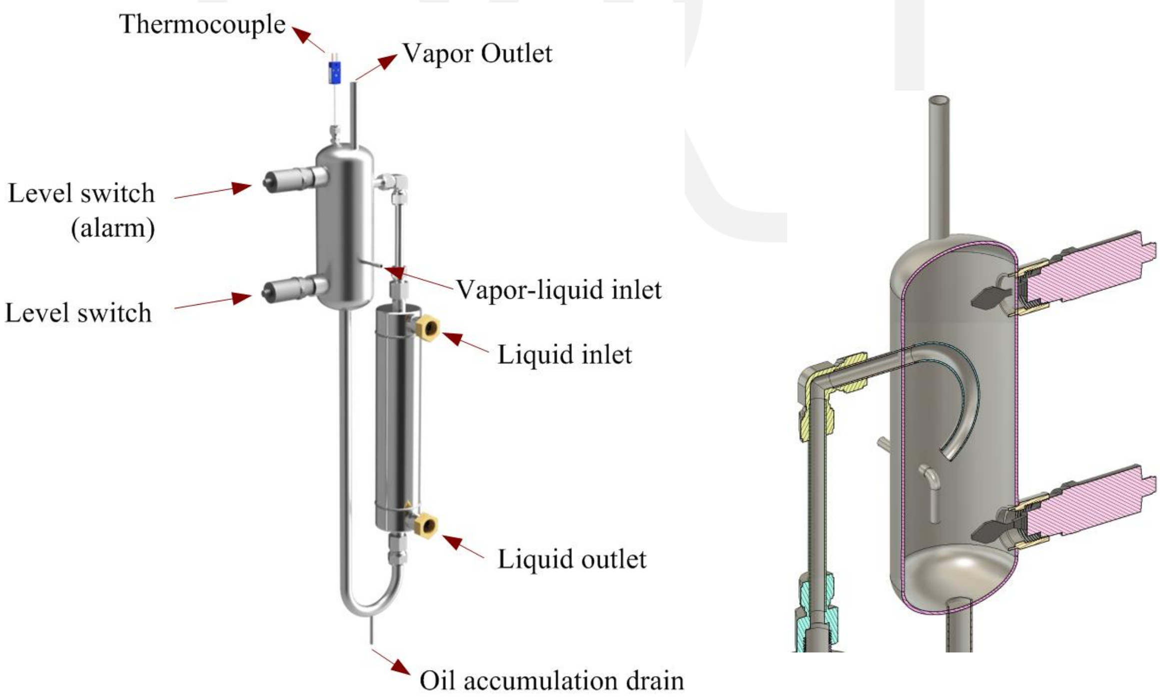

Figure 21: Working principles of a flooded evaporator (diagram not to scale)

The evaporator reservoir also acts as a liquid/gas separator avoiding the entrainment of liquid ammonia in the TCM reactor. The standard design rules for such a liquid/gas separator lead to a diameter, D, of 65 mm, a total height of around 130 mm (2D) and the ammonia inlet connections placed such that the ammonia outlet is 65 mm (1D) from the bottom. The connecting pipes to the evaporator should have an internal diameter of 12 mm. The level switch should be placed 40 mm (0.5D) from the bottom of the evaporator reservoir. Furthermore, for the same reason as above (liquid entrainment in the TCM reactor), an additional level switch sensor should be implemented in the upper part of the evaporator reservoir to avoid over-flooding in case of malfunction of the first sensor. This security level sensor will enable the closing of the connection between the evaporator and the TCM reactor, if needed.

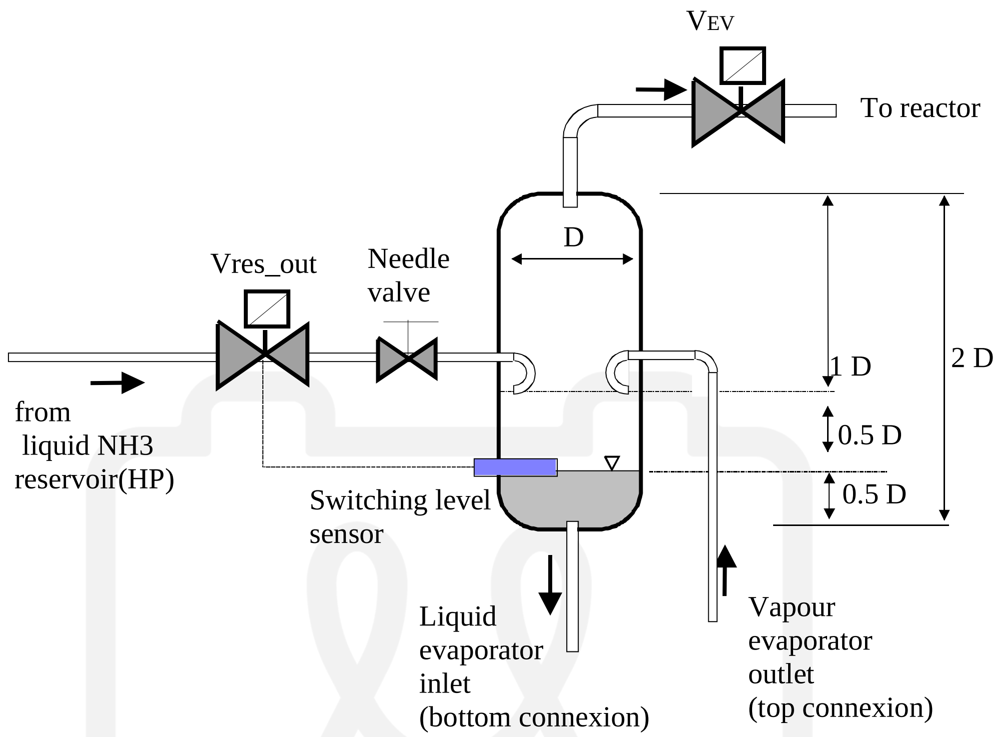

Table 6: Schematic view of the flooded evaporator and its small upper reservoir for controlling the ammonia level.

3.8 Valves and piping of the TCM unit

Table 7 describes the electric 2-way valves and needle valves that should be implemented in the TCM unit. In order to avoid pressure loss, valves installed on ammonia vapour pipes should have the highest possible orifice flow.

The ammonia pipe diameters are calculated from the maximum achievable volumetric flow rate (5 m^3/h for NH_3 vapour at the suction line of the compressor and 10 L/h for liquid ammonia) and the maximum admissible flow velocity of 10 m/s for ammonia vapour and 1 m/s for liquid ammonia. As a result, ammonia vapour pipes (reactor to compressor to reservoir and reactor to evaporator) should have a diameter of 12 mm ID and the liquid ammonia pipes (reservoir to evaporator, injection line) should have a diameter of 6 mm ID.

Furthermore, ¼-turn ball valve (1/2" BSP, specific for ammonia) should be installed so that the different components of the TCM units can be isolated from each other. This is necessary for preliminary testing, commissioning and maintenance of the TCM storage unit.

Table 7: Characteristics of valves implemented in the TCM unit

Valve type	Valves	Roles	Characteristics
NH_3 gas valves	VCD VEV VCAP Vres_in	• Connection of reactor to condenser (vapour) • Connection of evaporator to reactor (vapour) • Compressor capacity control (vapour bypass) • Connection of condenser to liquid reservoir (L/V)	- 2-way valve - Direct acting / normally closed - Orifice diameter = 5-6 mm - Connection 1/2" BSPT or NPT - Stainless steel / EPDM - Max service conditions: 100 °C/ 25 bar - 24 V (DC or AC, to be decided)
NH_3 liquid Valves	Vres_out VINJ	• Connection of liquid reservoir to evaporator (L) • Connection of liquid reservoir to compressor (L)	- Direct acting / normally closed - Orifice diameter = 2-3 mm - Connection 1/4" BSPT or NPT - Stainless steel / EPDM - Max service conditions: 100 °C/ 25 bar - 24 V (DC or AC, to be decided)
Manual needle valves Liquid pipes	MV evap MV Inj	• Control of the liquid flow rate of evaporator Valve suggestion : micromite 2300 Hoke 1° stem – orifice 0.062" • Liquid injection control at compressor intake: Valve suggestion : micromite 1600 Hoke 1° stem – orifice 0.047"	- Metering valve 20 turns - Stem tip (1°) - Orifice diameter = 1-1.5 mm - Max Cv = 0.0025 or 0.0005 - Connection 1/4" BSPT or NPT - Stainless steel / EPDM or PTFE - Max service conditions: 100 °C/ 25 bar

The flow rate coefficient of the needle valves for fine liquid ammonia flow control have been estimated as follows:

1- ***Liquid injection at compressor intake (evaporative gas cooling)***:

- maximum mass flow rate: 0.6 kg/h @ 20°C → 1 L/h of liquid ammonia
- compressor pressure difference: 9 bar in winter to 13 bar in summer
- maximum Kv value: 0.004 L/min (or Cv = 0.0005 GPM)
- the metering valve Micromite 1600 (model 1° stem 0.047" orifice) from Hoke manufacturer fits the requirements (to be confirmed by Sunamp)

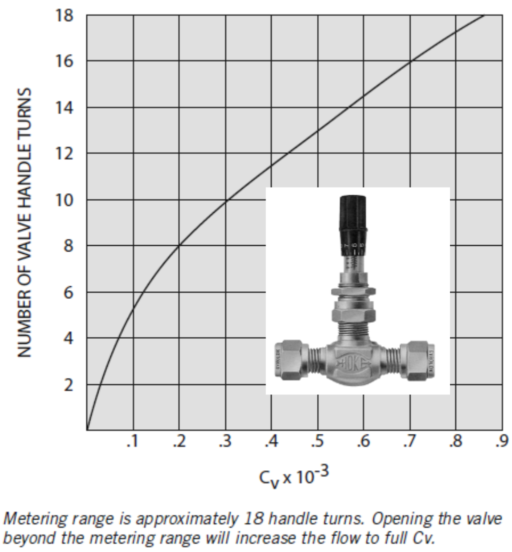

Figure 22: Characteristics of the needle valve for liquid injection at the compressor intake (evaporative gas cooling)

2- Liquid injection at evaporator:

- maximum mass flow rate: 7 kg/h @ 20°C → 10 L/h of liquid ammonia
- Reservoir/evaporator pressure difference: 1 bar in winter to 13 bar in summer
- maximum Kv value: 0.03 L/min (or Cv = 0.0025 GPM) in winter to 0.09 L/min (or Cv = 0.005 GPM) in summer .
- the metering valve Micromite 2300 (model 2355): 1° stem - 0.062" orifice - from Hoke manufacturer fits the requirements (to be confirmed by Sunamp)

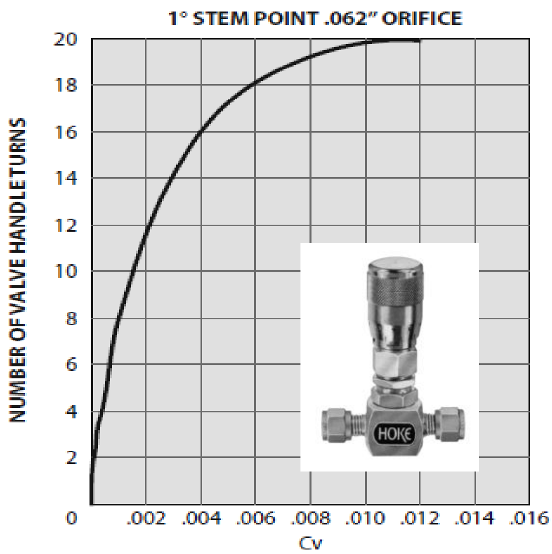

Figure 23: Characteristics of the needle valve for liquid injection at the evaporator (liquid throttling)

4. Procedure for charging the TCM unit with ammonia at demo sites

The TCM reactor is to be shipped already filled with the salt being pre-ammoniated to the octa-ammoniate. This procedure describes the filling of the rest of the system at the demo sites prior to commissioning. In particular, it describes the filling of ammonia into the liquid reservoir (partial filling) and the flooded evaporator using a vacuum pump (minimum pressure below 0.1 mbar (10 Pa) in order to remove all water) and a liquid ammonia bottle (pressure of 9-10 bar at ambient temperature).

The system includes two additional connections for commissioning and maintenance purposes: one for draining the condenser of any incondensable gas that may accumulate in the condenser during normal operation and the other for vacuuming and filling of ammonia when the system is started for the first time and put into operation.

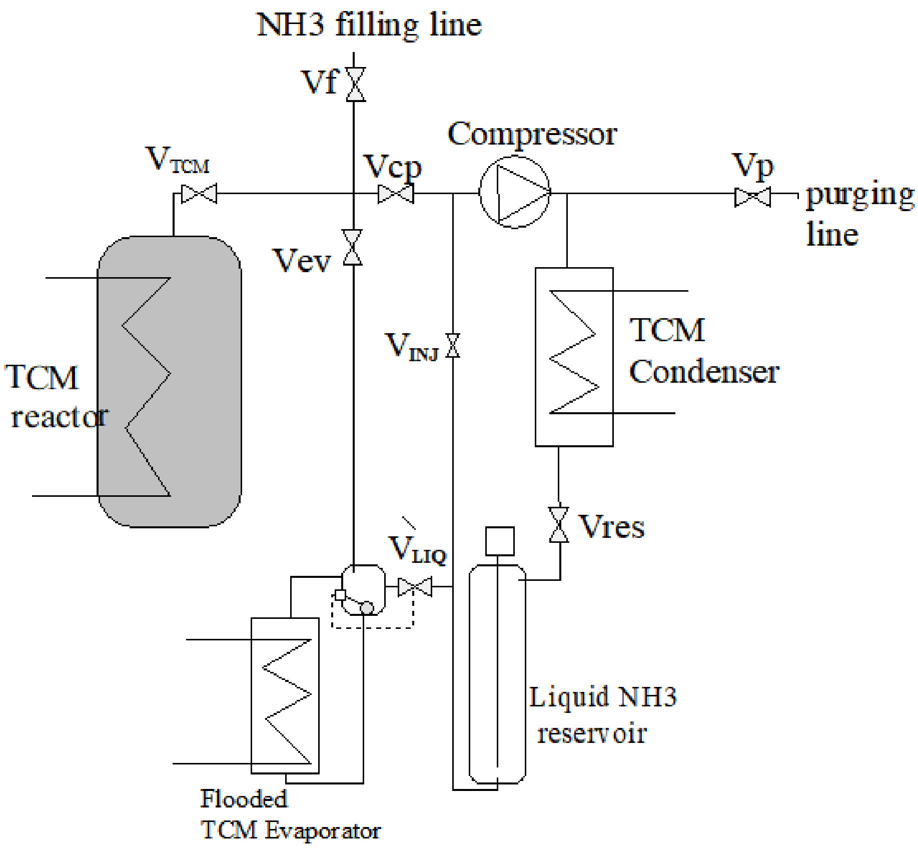

Figure 24: Schematic view of the TCM unit for the ammonia filling procedure at demo sites

The procedure of filling the system with ammonia consists of two steps:

Vacuuming of the installation

1- Connect the ammonia bottle to the filling pipe (ensuring the bottle is closed).

2- Connect the vacuum pump to the purging line.

3- Open all valves except the one to the TCM reactor (V_{TCM}).

4- Run the vacuum pump until the pressure has been stable below 0.1 mbar for at least one hour (if the pressure increases when the valve at the purging line is closed, then there is a leak and the tightness of the connections should be verified). No leakage is allowed. When no leakage is detectable, the system can be filled with ammonia. Close the filling and purging valves (Vf) and (Vp).

Filling of the system with ammonia

1- Open the ammonia bottle and the filling valve (Vf)

2- Wait until the pressure in the system has equalized to that of the bottle. Close the valves (Vev) and (Vinj) in order to isolate the evaporator from the ammonia compressor

3- Run the condenser circulating pump to enable cooling via the fan coil or with an external water loop. The cooling of the condenser should be achieved by circulating water at as low a temperature as possible (i.e., 15-20 °C).

4- Run the NH_3 compressor in order to pull the ammonia from the bottle. The bottle temperature may decrease considerably (it may be below 0 °C) through evaporation of ammonia. It may be necessary to heat it through trace heating or a hot air blower.

5- The ammonia, pulled out from the bottle and compressed by the compressor, condenses and progressively fills the liquid reservoir.

6- When the ammonia level has reached a minimal value of around 2-3% (measured by the level sensor or a visual level), then close the filling valve (Vf) and open the evaporator valve (Vev) in order to fill the evaporator from the liquid reservoir. It is not necessary to circulate water in the evaporator.

7- Liquid ammonia will progressively fill the evaporator and its associated small reservoir, making the level decrease in the liquid ammonia reservoir.

8- Wait for the liquid level to reach the lowest readable level by the level sensor (0.1 to 0.5% in the liquid reservoir).

9- If the evaporator is not completely filled and the ammonia level is under 0.1% then close the valve (Vev) again and open the filling valve (Vf).

10- Repeat the steps from 6 to 9 until the evaporator is filled. The evaporator is completely filled when the valve (V_{LIQ}) closes itself by detecting the switching level in the small reservoir of the flooded evaporator. Then close the valve (Vev) and let the compressor operate

11- When the level of ammonia in the liquid reservoir has reached 2% then stop the compressor

12- Close all valves.

13- The TCM unit is now ready for commissioning.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869821

5. Hot and cold PCM storage

The hot and cold PCM storage will use components based on the UniQ range of Sunamp's commercially available Heat Batteries. Each model in the UniQ range has the same footprint but different heights. The MiniStor system will implement a UniQ 6 heat battery for space heating and a UniQ 9 for domestic hot water and one UniQ 12 battery for the cold PCM storage (6 kWh storage capacity).

In Sunamp's UniQ range of Heat Batteries, the heat exchanger is submerged in PCM and encapsulated in a polypropylene case for the hot PCM and a polyethylene case for the cold PCM. The case is surrounded by insulation and finally an outer aluminium case. The heat exchanger consists of two separate but interleaved circuits with the high power circuit (A-D) comprising 66% of the heat exchanger volume and the low power circuit (B-C) comprising 33% of the heat exchanger volume. This allows two different heat transfer fluids to be used, for example, a technical fluid can be used to charge the hot PCM via the low power circuit and water can be used to discharge the hot PCM, providing domestic hot water or space heating. A vertical string of three temperature sensors is placed in a sensor pocket running through the centre of the heat exchanger for control of charging and state of charge approximations.

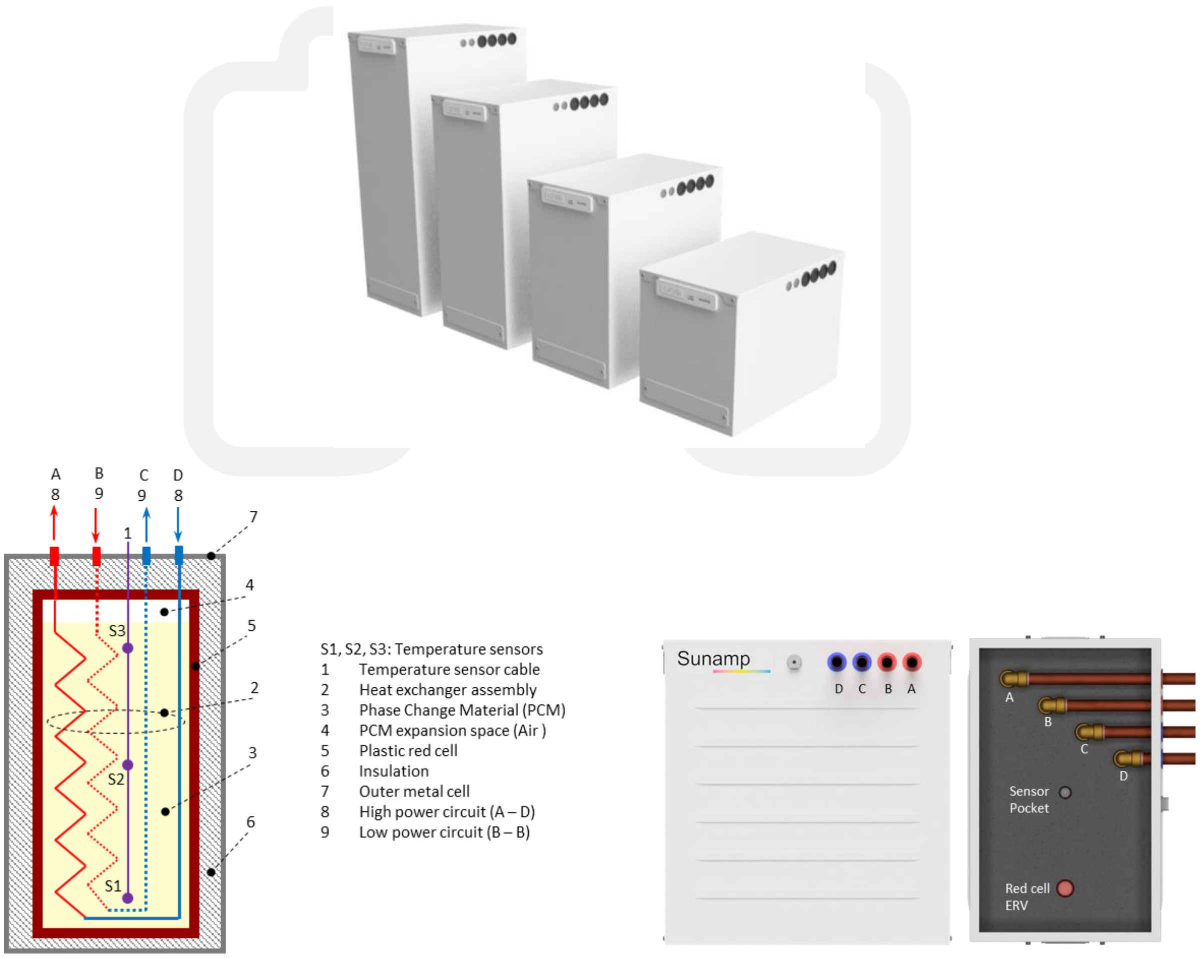

Figure 25: Views and schematics of Sunamp's UniQ range of Heat Batteries

The hot PCM storage will contain Sunamp's SU58 PCM and, as defined in Deliverable 4.2, **a minimum heat source temperature of 63 °C** is required for complete melting of the PCM. The PCM will provide heat at 50-55 °C for building heating needs. The minimum flow temperature required to charge the SU58 Heat

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Batteries is 63 °C, and the maximum flow rate ranges from 6-25 L/min depending on the size of the Heat Battery.

The hot PCM is charged under the following conditions:

1. during the TCM charging phase the temperature in the TCM condenser cooling loop is at least 28 °C – this is then uplifted to 65 °C by the mechanical heat pump.
2. during the TCM discharging phase when the temperature on the reactor cooling loop is more than 63 °C .

The PCM is charged by flowing hot heat transfer fluid through the low power circuit until the return temperature reaches a minimum of 62 °C (4K above the melting temperature, 1K HTF temperature difference). When there is a need for hot water or space heating, water flows through the high power circuit of the heat exchanger, transferring the heat from the PCM to the water and into the property.

The cold PCM storage is connected to the evaporator of the TCM system and is used for space cooling in summer or in winter to provide heat to the evaporator of the TCM unit at a higher temperature than the outside temperature. The cold storage is filled with Sunamp's SU5 (storage density 35.8 kWh/m^3 for a ΔT of 20 °C, melting temperature 5 °C) or SU11 PCM (storage density of 44.7 kWh/m^3 for a ΔT of 20 °C; melting temperature 11 °C) as defined in Deliverable 4.2. The cold storage is charged (i.e., frozen) during the discharging phase of the TCM. **The maximum flow temperature required to charge (i.e., solidify) or discharged (i.e., melting) the Cold Battery is 3 °C below or above the phase transition temperature**. The maximum flow rate ranges from 6 to 25 L/min .

Item	Description
1	Earth Clamp (supplied) - to be clamped to Ø22mm copper tube
2	Hot Water Outlet – 'A' – Ø22mm elbow – rotatable 360 degree
3	Cold Water Inlet – 'D' - Ø22mm elbow – rotatable 360 degrees
4	External heating source Flow – "B" – Ø 22mm elbow – rotatable 360 degrees
5	External heating source Return – "C" – Ø22mm elbow – rotatable 360 degrees
6	Cable Entry via Gland - supplied but not fitted
7	Ø22mm Copper Tube to BSEN1057 - Suitable for installation (not supplied).
	Tube and cable entries are used depending on installation location

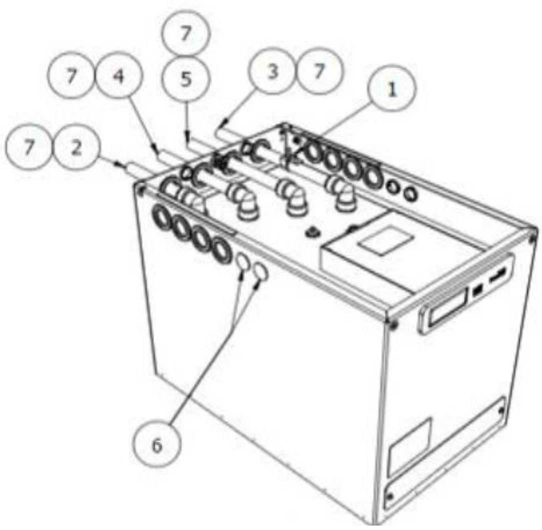

Figure 26: External connections to a UniQ Heat Battery

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Specification	Size 12
Heat storage capacity (kWh)	14
Water Content (L)	13.7
Equivalent Hot Water Cylinder Size (L)	284
V_{40}, Volume of Hot water available at 40°C (L)	370
Standby heat loss rate (kWh / 24h | (W))	0.84 / (35)
Energy efficiency rating class	C
Recommended maximum HW flow rate (L/Min)	25
Minimum mains supply pressure at inlet of Heat Battery (MPa | (Bar))	0.15 | (1.5)
Maximum working pressure (MPa | (Bar))	1.0 | (10)
Pressure loss characteristics K_V Values	Figure 6.1 (Section 2.6)
Hot water outlet temperature at design flow rate (˚C)	45-55
Connected load at ~ 230 V, 50Hz (W)	2,800
Power supply | Standby consumption (W)	1 PH ~ 230 V | 7
Electrical efficiency (ηelecwh) (%)	93.3
Annual electricity consumption (AEC) (kWh/annum)	2,701
Tapping cycle	L

Figure 27: Specification of Sunamp's UniQ 12 SU58 Heat Battery

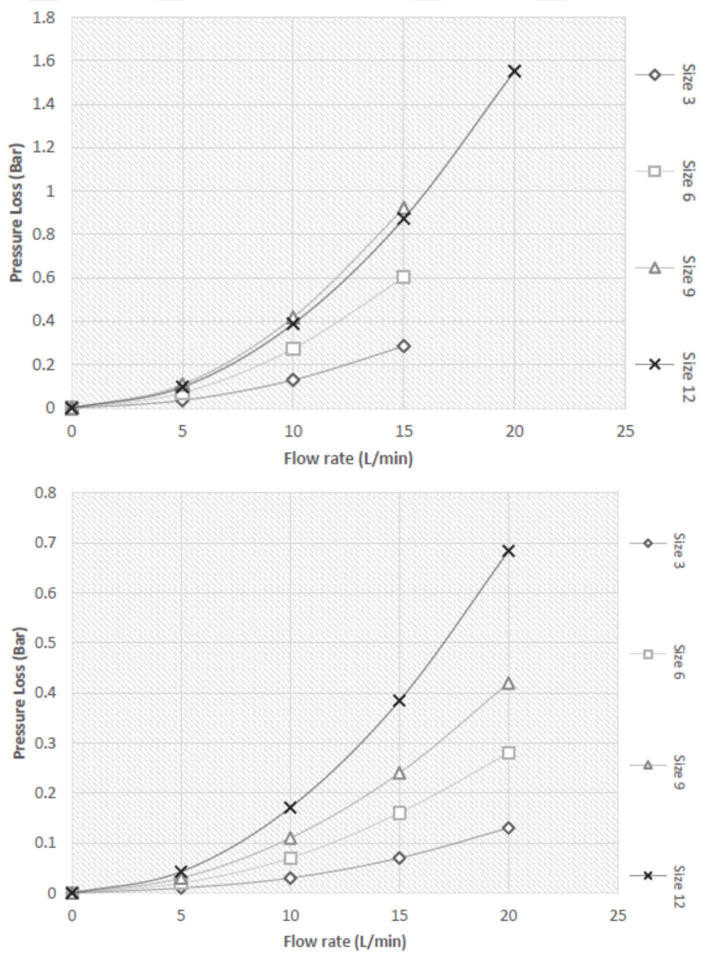

Figure 28: Pressure loss characteristics for the high power (left) and low power (right) circuits of UniQ Heat Batteries

6. Conclusions

This Deliverable discusses the design specifications of the main components of the TCM storage unit and the PCM storage. The storage has been designed by taking into account the solar heat resource available and the solar system installed at each demo site. The consortium has decided that the same design is to be used for all demo sites in order to avoid the additional time and cost that would be involved in building bespoke systems for each site.

A 30 kWh heat storage capacity in winter and a 15 kWh cold storage capacity in summer was the target for the design of these units. Based on these specifications and the operating conditions in winter and summer, a shell and tube reactor design has first been defined. Such a reactor containing 77.2 kg of TCM material (151 litres) will enable an energy storage density of over 200 kWh/m^3 of reactive material as required by the project proposal. The ancillary equipment of the TCM storage unit (compressor, evaporator, condenser, liquid reservoir, valves, etc.) have also been defined and suitable available commercial models are proposed. Secondly, additional mandatory devices for monitoring the operation of the TCM unit are defined: pressure sensors, temperature sensors, level sensors, switches, metering valves, etc.) and a control strategy is described.

Moreover, the hot and cold PCM storage units have been chosen to be those already manufactured by Sunamp. The hot PCM unit should have a storage capacity of around 3.6 kWh to achieve a material energy storage density of over 200 kWh/m^3 for space heating. The hot water PCM store will have a capacity of around 10 kWh, while the cold PCM a storage capacity of around 6 kWh.

The outcomes of this Deliverable will lead to a simpler choice of thermal and hydraulic components for the building of the TCM unit according to the energy/power requirements and operating conditions, as well as for the implementation of a relevant control strategy.