SFERA-III

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IRES 2022 Conference - SFERA III Workshop

Towards a fair evaluation of Thermal Energy Storage prototypes - Guidelines for CSP applications

Case study on latent heat storage

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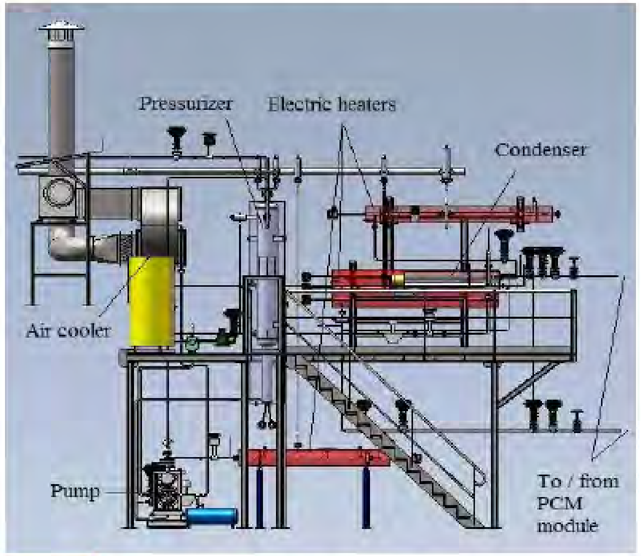
JOINT RESEARCH ACTIVITIES

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO **823802**

Latent heat storage for for steam processes

- Thermal Storage is a critical issue for industrial processes using steam as HTF
  - Latent Heat Thermal Energy Storage **(LHTES)** may be required
  - Shell-and-tubes storage with Phase Change Material **(PCM)**
    - Low thermal conductivity → Need of heat transfer enhancement methods on the PCM side

- LHASSA experimental facility at the CEA Grenoble
  - High pressure water-steam closed loop
  - Operating conditions similar to those of CSP DSG plants (145 bar, 350 °C)

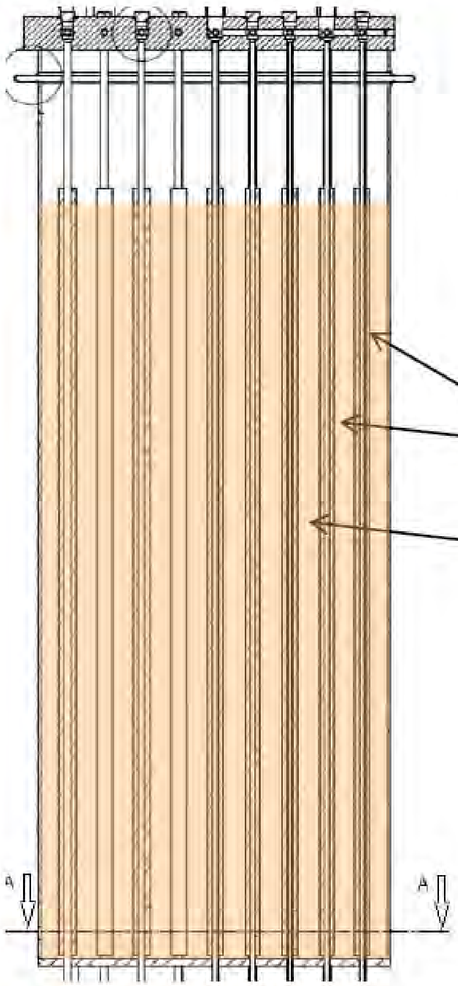


LHASSA test facility

PCM module (6,3 tons of $NaNO_3$)

PCM tubes & inserts

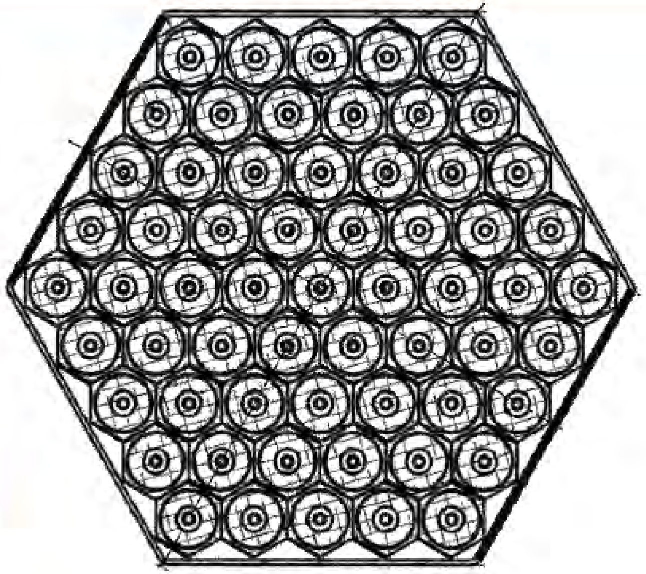
Prototype – General Scheme



Vertical bundle of parallel tubes with high pressure steam/water inside and a static PCM volume outside

Finned tubes

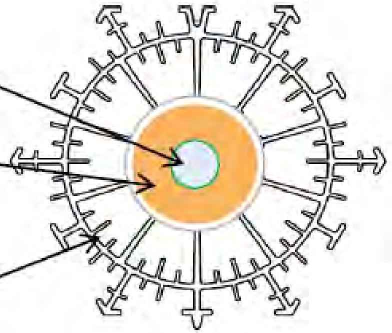
PCM volume



A-A section

Tubes

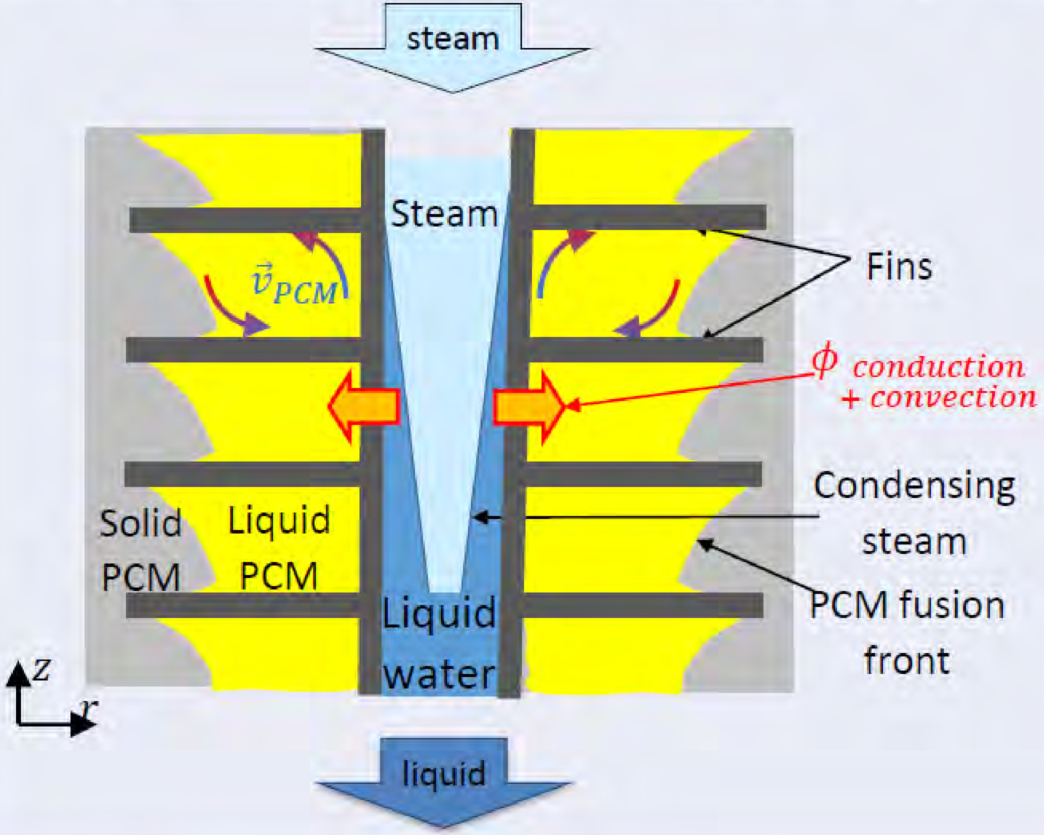
Aluminum fins

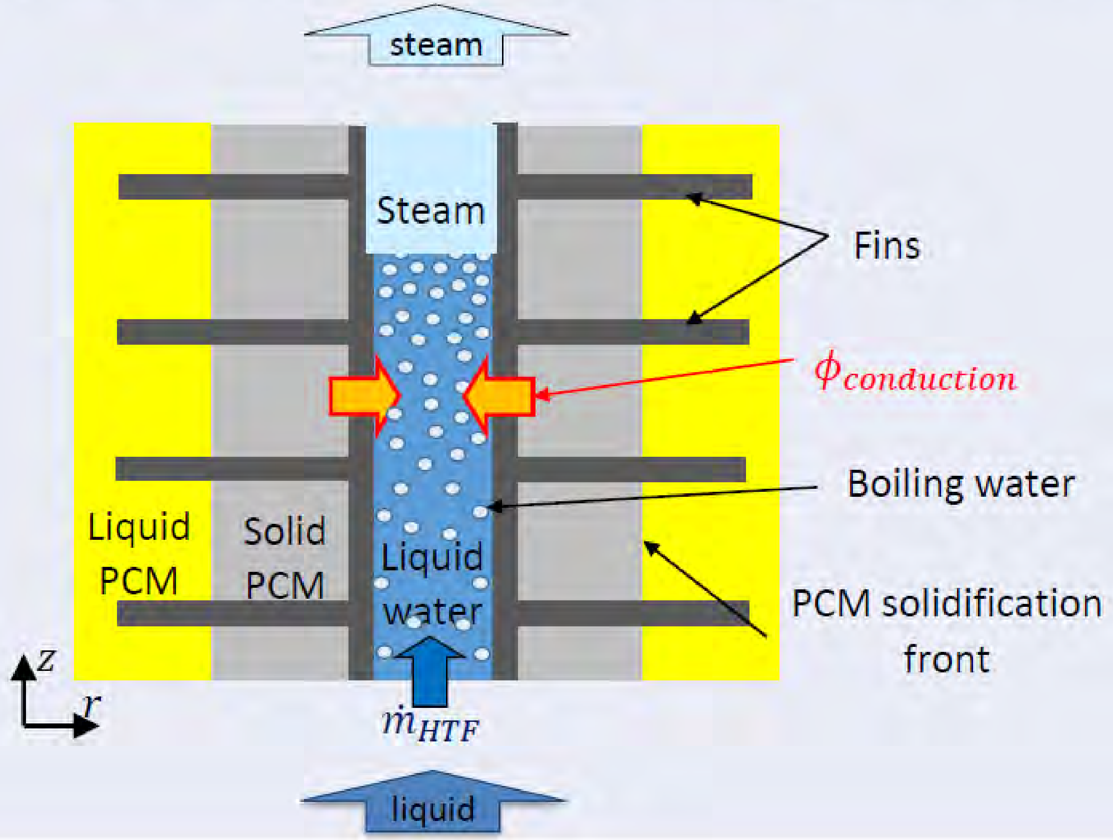


Heat transfer enhancement by aluminum inserts around the vertical finned tubes

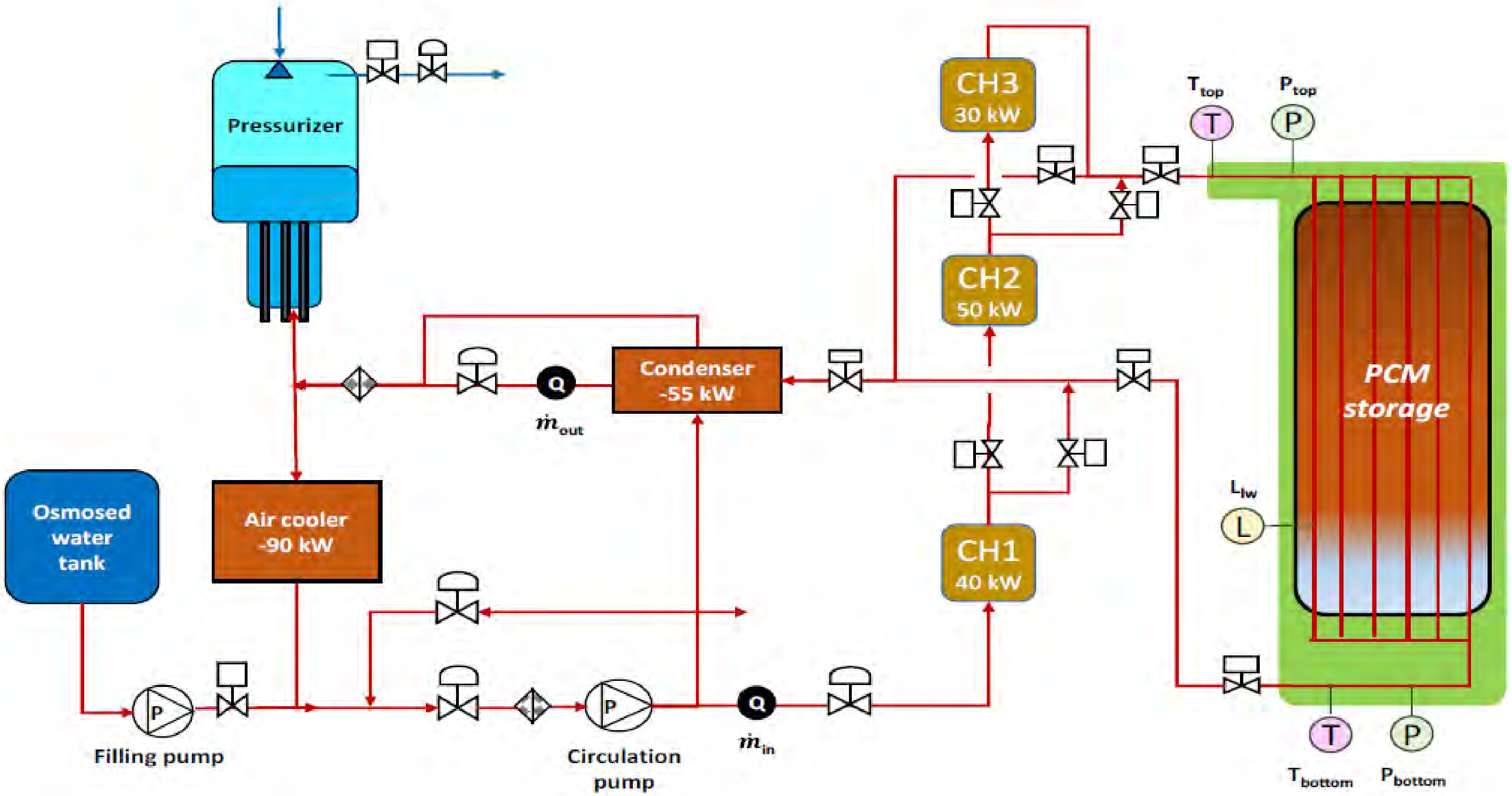
How does it works

Charge	Discharge
Steam condenses causing the melting of the PCM	Liquid PCM solidifies causing the evaporation of the liquid water





Considered system	Tank = storage system, including shell and collectors



Enthalpy calculations

- *Bottom - liquid water*

$h_{in} = enthalpy(T_{in}, P_{in})$

- *Top - steam*
  - *If* $T_{out} > T_{sat} + 2°C$, $h_{out} = enthalpy(T_{out}, P_{out})$
  - *Else,* h_{out} *is calculated from an energy balance at the condenser boundaries*

- *In charge,* $h_{out} = h_{bottom}$ *and* $h_{in} = h_{top}$
- *In discharge* $h_{out} = h_{top}$ *and* $h_{in} = h_{bottom}$

System definition
Theoretical storage capacity

Theoretical storage capacity (SC_{th}) Includes PCM and metallic parts (tubes, shell, inserts)
Water volume and thermal insulation are neglected

$$SC_{th} = m_{PCM}\, H_f + \left(m_{PCM}\, {c_p}_{PCM} + m_{alu}\, {c_p}_{alu} + m_{steel}\, {c_p}_{steel}\right) \cdot \left(T_{rated,charge} - T_{rated,discharge}\right)$$

Depends on temperature references

Rated conditions	Temperature (°C)	Pressure (bara)	Specific enthalpy (kJ/kg)
Inlet conditions in charge	320	100	2783
Outlet conditions in charge	300	100	1343
Inlet conditions in discharge	280	80	1236
Outlet conditions in discharge	300	80	2786

$T_{rated,c}$ = 310°C $T_{rated,d}$ = 290°C

Metallic parts	Metal	Steel	Aluminum
	Total mass (kg)	3795 kg	1725 kg
	Density (kg/m³)	7900	2700
	Specific heat (J/kg/K)	490	900
PCM (sodium nitrate)	PCM mass (kg)	6330 kg	
	Phase change temperature (°C)	306 °C	
	Heat of fusion (J/kg)	172000 J/kg	
	Mean specific heat (>300 °C) (J/kg/K)	1655 J/kg/K	
	Density (kg/m³)	ρ(T) [Bauer 2012]	

Total latent heat	302 kWh_t
Total sensible heat (PCM)	58 kWh_t
Total sensible heat (metal)	19 kWh_t
Theoretical storage capacity	**380 kWh_t**
% sensible heat	*20%*

Full charge and discharge test
Operating conditions

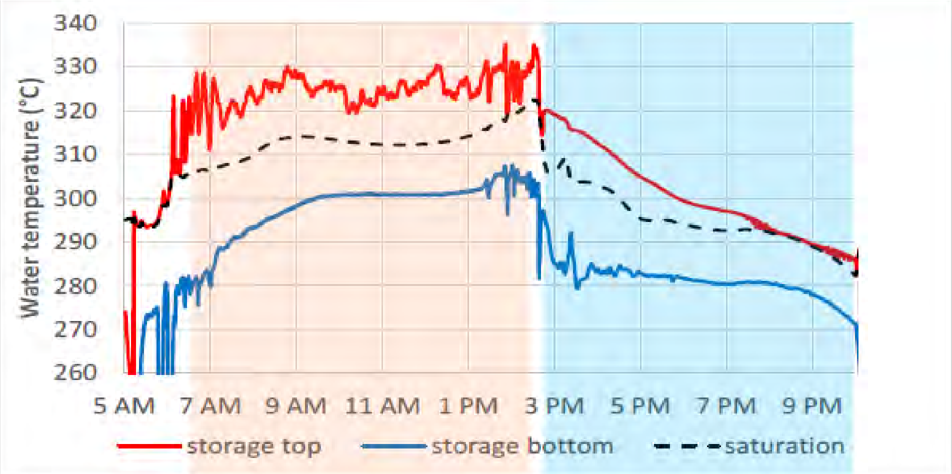
- **Complete charge and discharge close to rated conditions**
  - 17-hour duration
  - Sliding pressure
- Initial conditions: first cycle

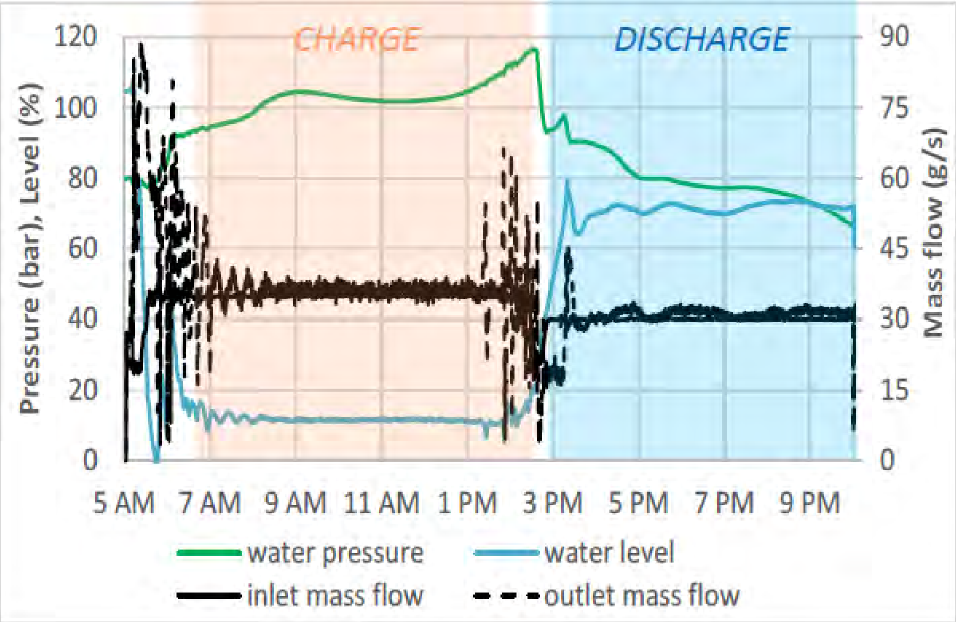
HTF flow rate charge	35 g/s
HTF flow rate discharge	30 g/s
Ambient temperature	15°C

- Operating conditions:

	Criterion	Threshold value	Time
Start of charge	Inlet steam temperature	$T_{sat} > T_{pc}$ (306 °C)	6:37 AM
End of charge	PCM temperature	All temperatures in PCM > 306 °C	2:37 PM
Start of discharge	Inlet water temperature	$T_{sat} < T_{pc}$ (306 °C)	2:50 PM
End of discharge	PCM temperature	$T_{mean} = T_{mean}(t_{start\_charge})$	9:26 PM

- Start / End criteria: **PCM** mean temperature threshold
  - Temperature on HSM side: inside the tank!
  - To approach cycled conditions

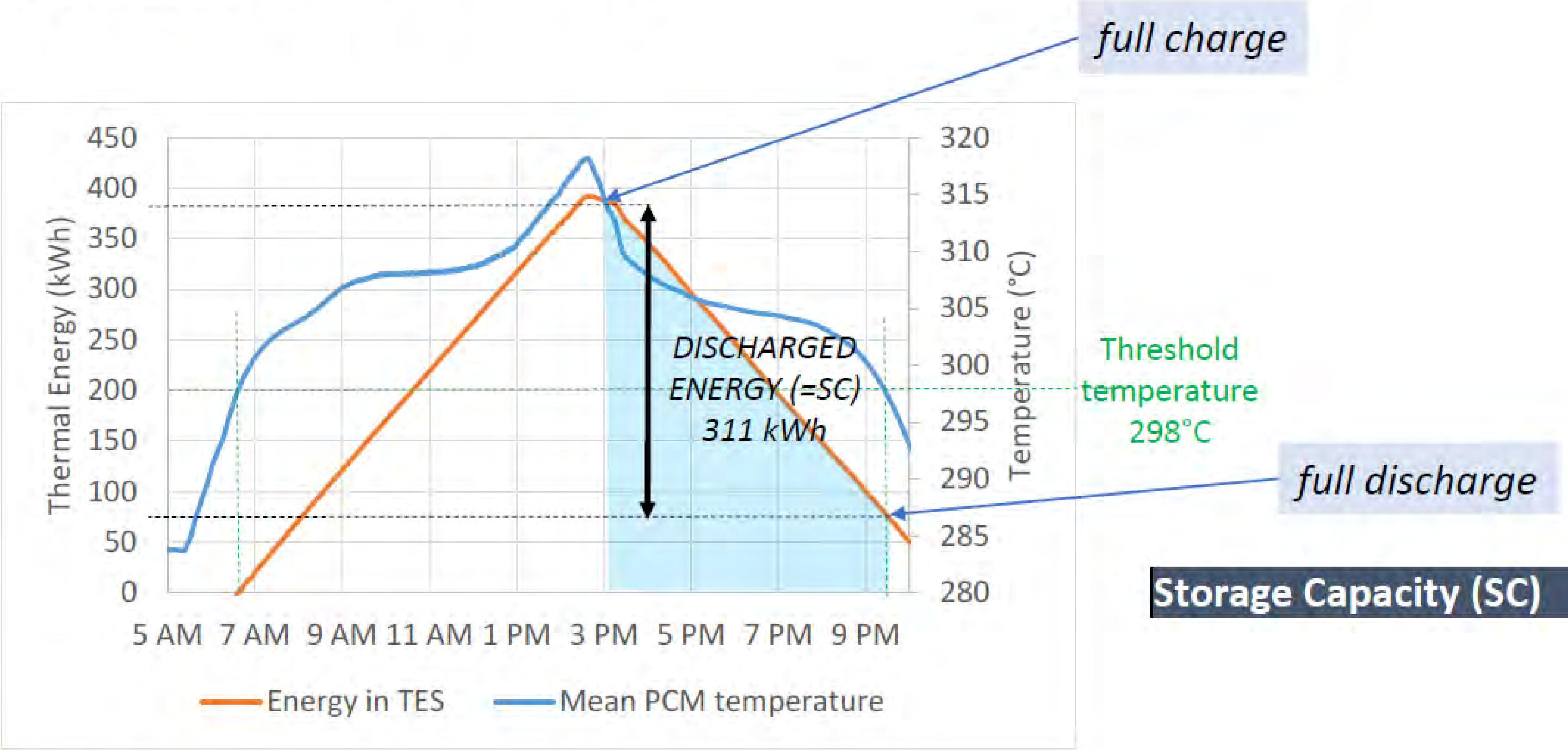




Full charge and discharge test
KPI - Storage Capacity

Amount of thermal energy that the TES system can supply by full discharge.

- Calculated on HTF side
  - $SC = \int_{full\ charge\ conditions}^{full\ discharge\ conditions} [\dot{m}_{out} h_{out} - \dot{m}_{in} h_{in}] dt$

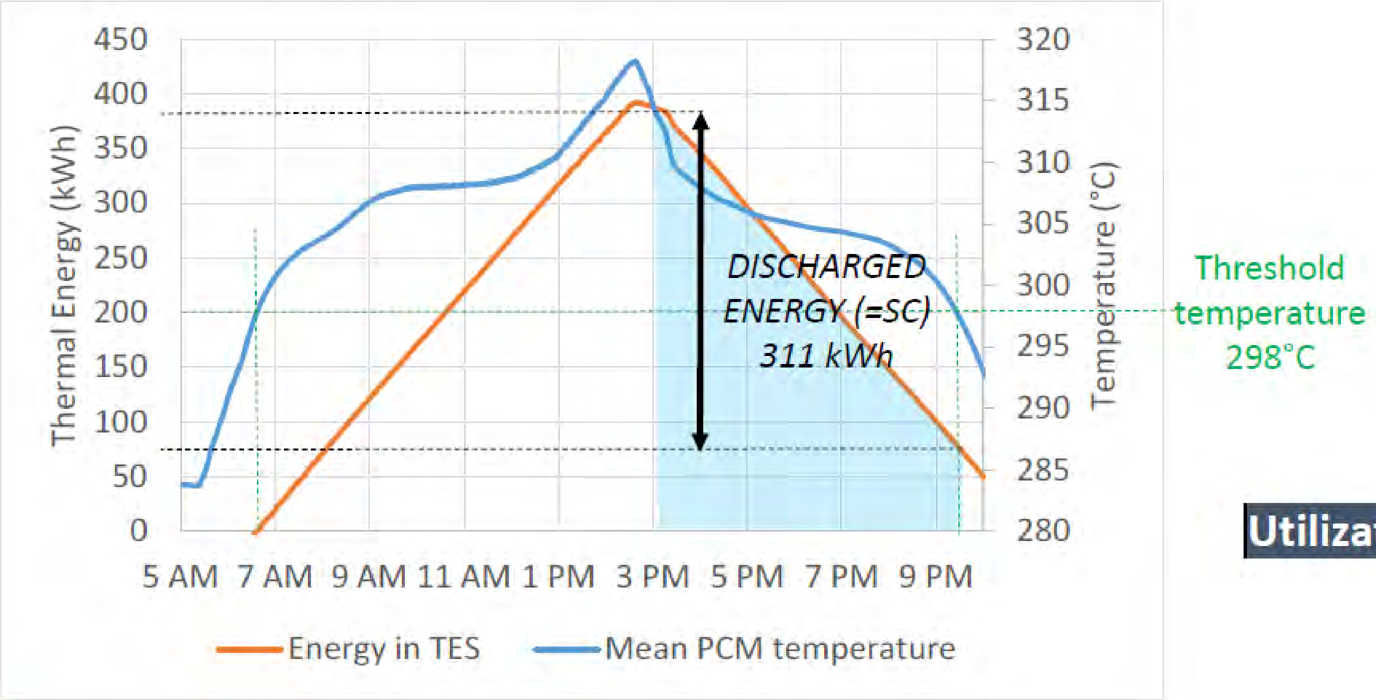


Storage Capacity (SC)	311 kWh$_t$

Full charge and discharge test
KPI - Utilization rate

Ratio of the storage capacity to the theoretical storage capacity of the TES system in rated conditions

- $UR = \frac{SC}{Sc_{th}}$
- With SC calculated on HTF side
- With SC_{th} calculated on storage materials side

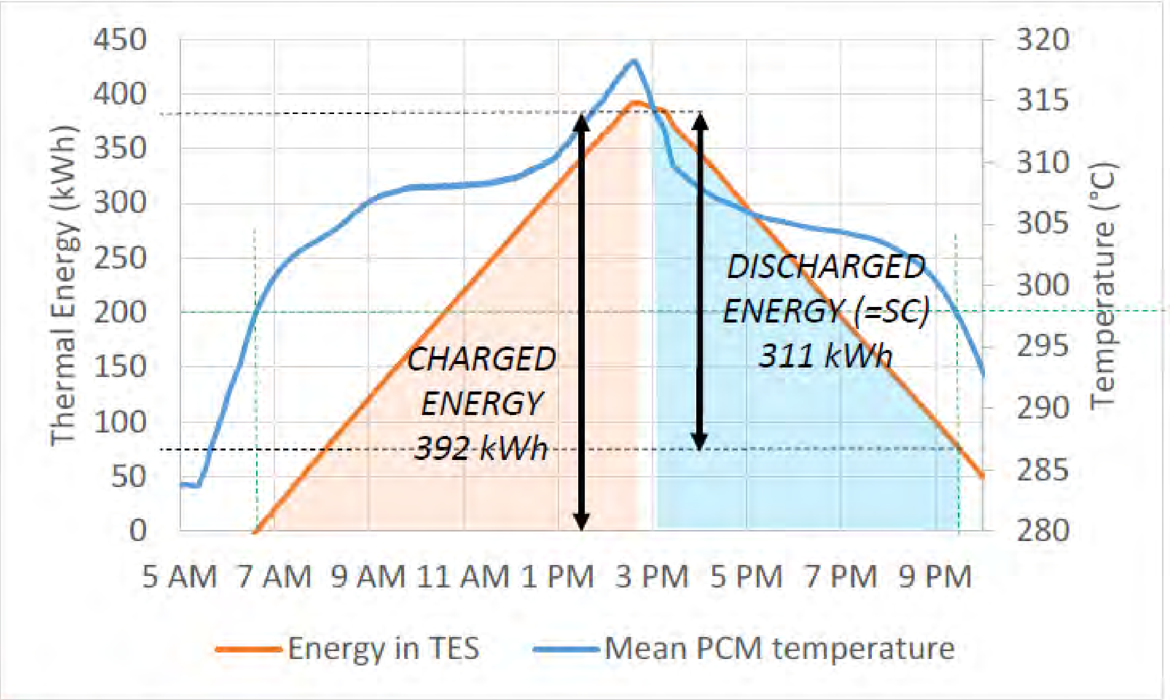


Utilization rate (UR)	82%

Full charge and discharge test
KPI - Storage efficiency

Ratio of energy gained by the HTF from the storage system during discharge to the energy delivered by the HTF during charge

- $\eta_{TES} = \frac{Q_{discharge}}{Q_{charge}} = \frac{Q_{HTF\_out}}{Q_{HTF\_in}}$ (In consecutive charge and discharge)
- η_{TES} should be estimated in « cycling conditions »
  - With storage conditions at the end of discharge equal to those at the beginning of charge



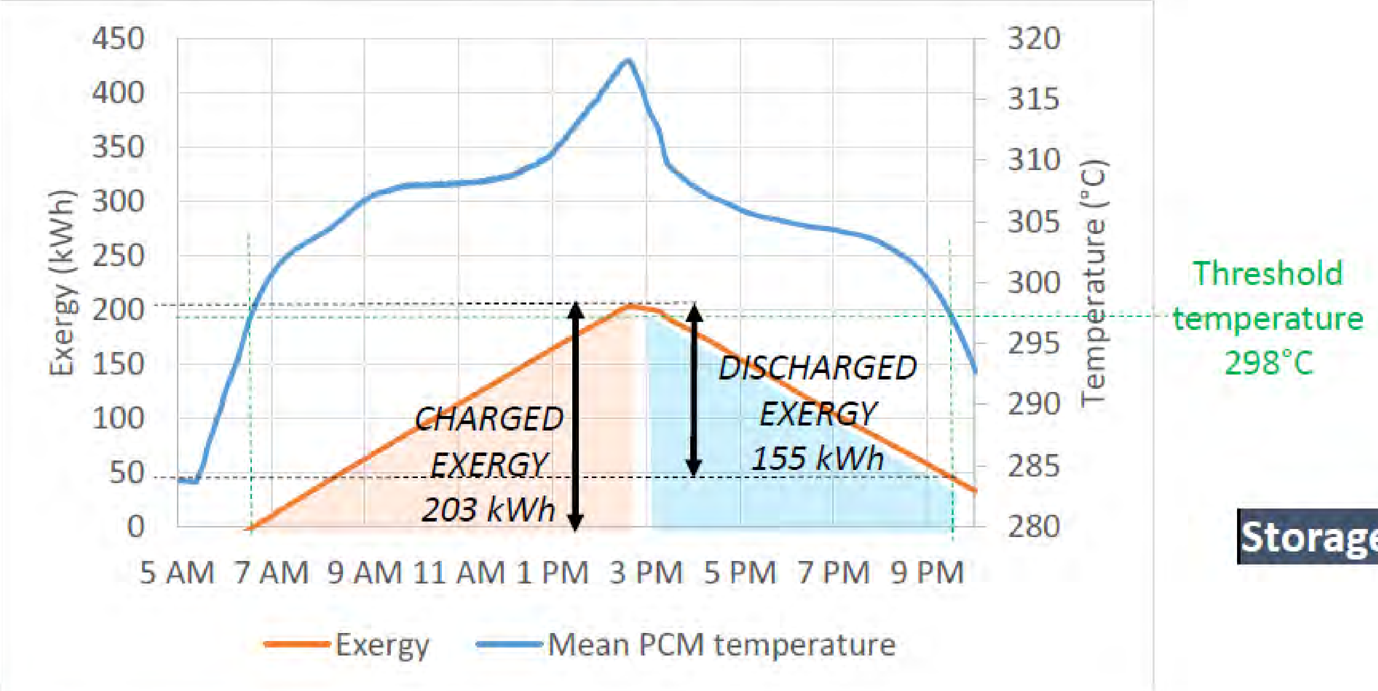
Threshold temperature 298°C

Storage efficiency (η_{TES})	79%

Full charge and discharge test
KPI - Storage exergy efficiency

Ratio of exergy gained by the HTF from the storage system during discharge to the energy delivered by the HTF during charge

- $\eta_{ex} = \frac{\epsilon_{discharge}}{\epsilon_{charge}} = \frac{\int_{discharge}\left(1-\frac{T_0}{T_{discharge,out}}\right)dQ}{\int_{charge}\left(1-\frac{T_0}{T_{charge,in}}\right)dQ}$ (In consecutive charge and discharge)
- $T_{charge,in}$ and $T_{discharge,out}$ are usually measured by the same sensor



Storage exergy efficiency (η_{TES})	76%

Some conclusions

- **On the initial state**
  - Many KPIs vary depending on the initial state of the TES system
    - e.g. for thermocline TES, the initial state depends on previous charge-discharge cycles until stable initial conditions are reached
    - Less critical for LHTES (almost isothermal temperature at initial conditions)
  - To estimate storage efficiency in a fair way, “cycled initial conditions” are preferred
    - To have $E_{start,charge} = E_{end,discharge}$ inside the tank
    - For latent heat storage , this criterion can be approached by looking at mean PCM temperature

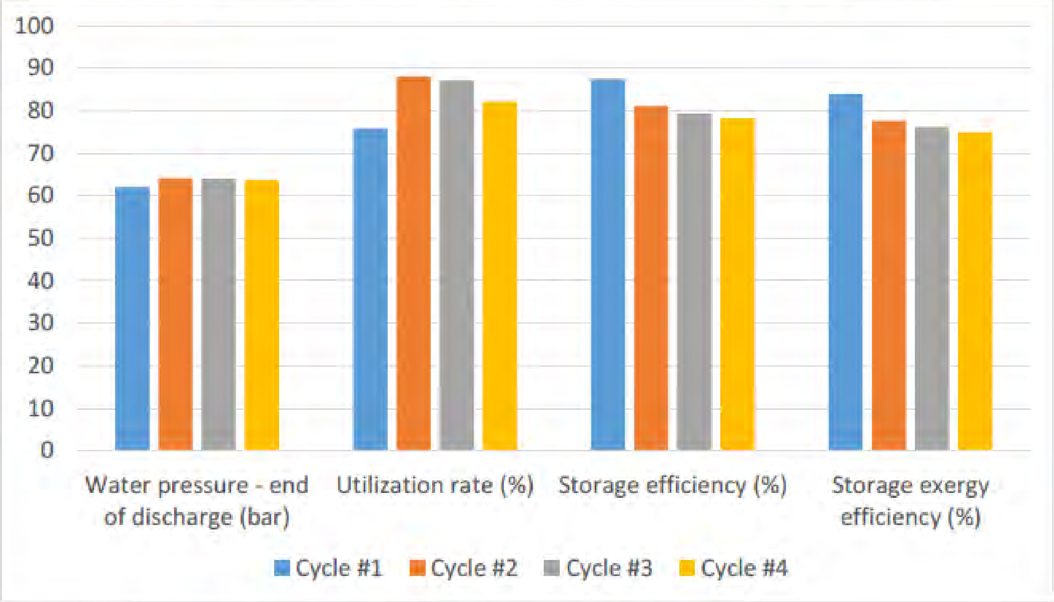
- **On the start / end criteria**
  - KPI are evaluated on the HTF side, but you sometimes need information from inside the tanks…
    - Concept of storage level
  - For an operator in an industrial plant, end of charge/discharge criteria will be system-related
    - e.g. temperature threshold, pressure threshold, discharge duration,…

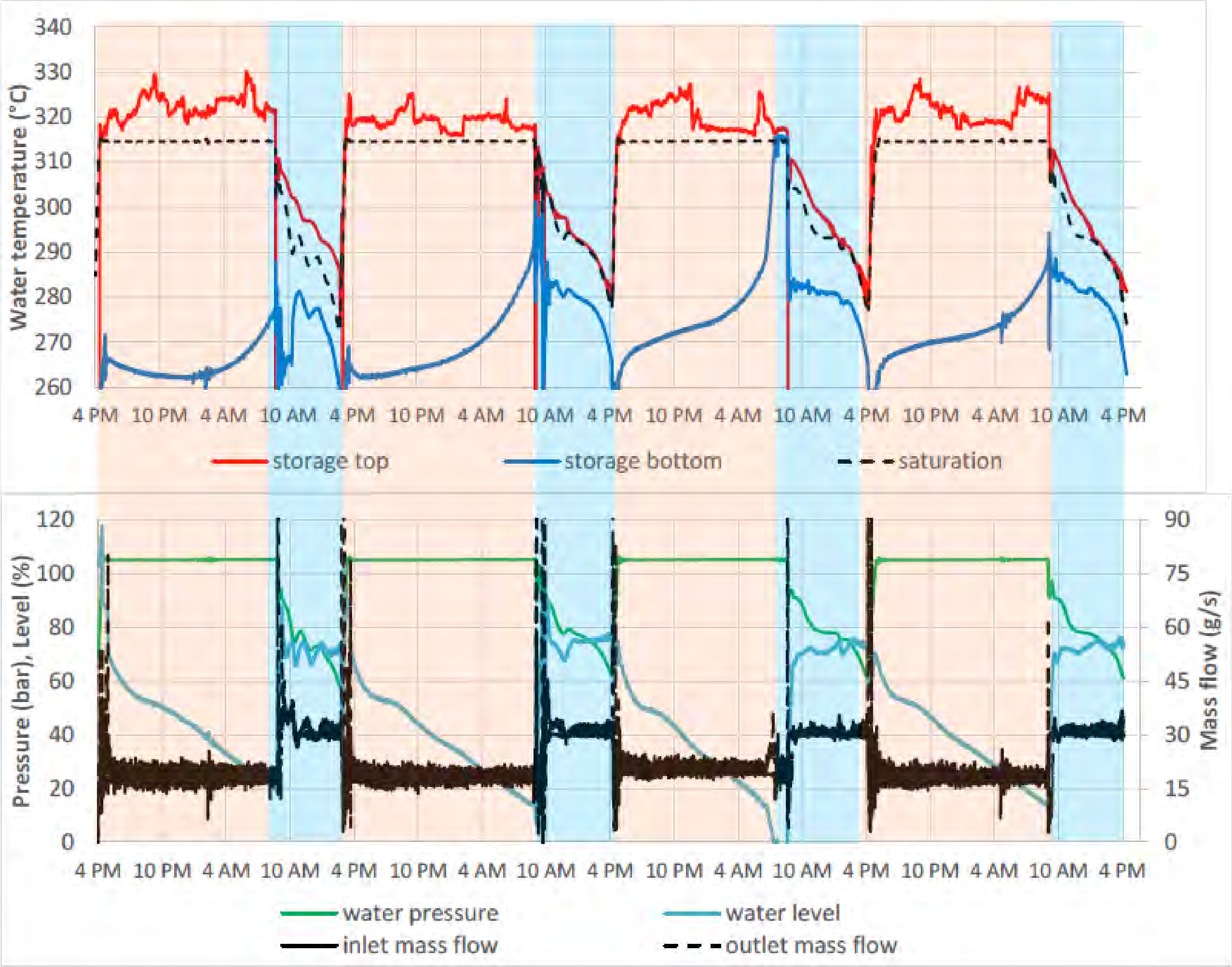
- **For one TES prototype, there is not a unique value for each KPI (≠ industrial standard)**
  - These guidelines mainly aims at pointing what should be clearly described for a fair and reproducible KPI evaluation

Durability tests
Repetitive cycles

- Fixed pressure in charge, automated control during night
  - Thermal power: 25 kW_{th} in charge, 50 kW_{th} in discharge
  - 4 consecutive cycles

	Criterion	Threshold value
Start of charge	PCM temperature	T_{mean} > 290 °C
End of charge	Water level in tubes	L_{lw} < 17%
Start of discharge	Water flow direction	Valve positions in discharge configuration
End of discharge	PCM temperature	T_{mean} < 290 °C





THANK YOU FOR YOUR ATTENTION!
ANY QUESTIONS?