SFERA-III

Solar Facilities for the European Research Area

D6.3: Protocol for testing sensible and latent storage prototypes

Towards the Standardization of testing prototypes for storage systems

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DOCUMENT HISTORY

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1	15-05-2019	Initial version
2	26-09-2019	Draft version for milestone MS15
3	07-02-2020	Addition of inputs needed for the test definitions
4	10-04-2020	Inputs from ENEA and CEA
5	12-05-2020	Inputs from CIEMAT, Fraunhofer, and METU
6	19-10-2020	New release of the draft version
7	04-10-2022	New release after experimental cross-comparisons
8	09-12-2022	Final release
9	07-06-2023	New release to fullfill to PO’s request
10	22-08-2023	New release adding the state of the art prior SFERA-III project

VALIDATION

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Disclaimer

Table of Contents

1. Nomenclature

Symbols

Q	Energy, J
ϵ	Exergy, J
$\dot{Q}$	Power, W
T	Temperature, K
t	time, s
m	mass, kg
$\dot{m}$	HTF mass flow rate, kg/s
k	Thermal conductivity of the material, W/(m·K)
Cp	Specific heat, J/(kg·K)
h	Specific enthalpy, J/kg
V	Volume, m^3
ρ	density, kg/m^3
η	efficiency, kg/m^3

Subscripts

inlet, in	at inlet
outlet, out	at outlet
start	start
end	end
charge	charge
discharge	discharge
loss	losses
ex	exergy
A	state A
B	state B

Abbreviations

CSP	Concentrating Solar Power
HSM	Heat Storage Medium
HTF	Heat Transfer Fluid
LHTES	Latent Heat Thermal Energy Storage
PCM	Phase Change Material
SC	Storage Capacity
TES	Thermal Energy Storage

2. Basic principles

Measurable performance indicators are required everywhere, for example in research calls for proposal and in CSP plants invitations to tender. They can be defined at various scales, from process level (e.g. a CSP plant) to material level (e.g. a storage medium). This document deals with performance indicators at system levels, that is to say including not only storage tank(s) but also HSM/HTF heat exchanger, storage piping and storage pumps when needed, as shown, only as simplified concept examples, in Figure 1.

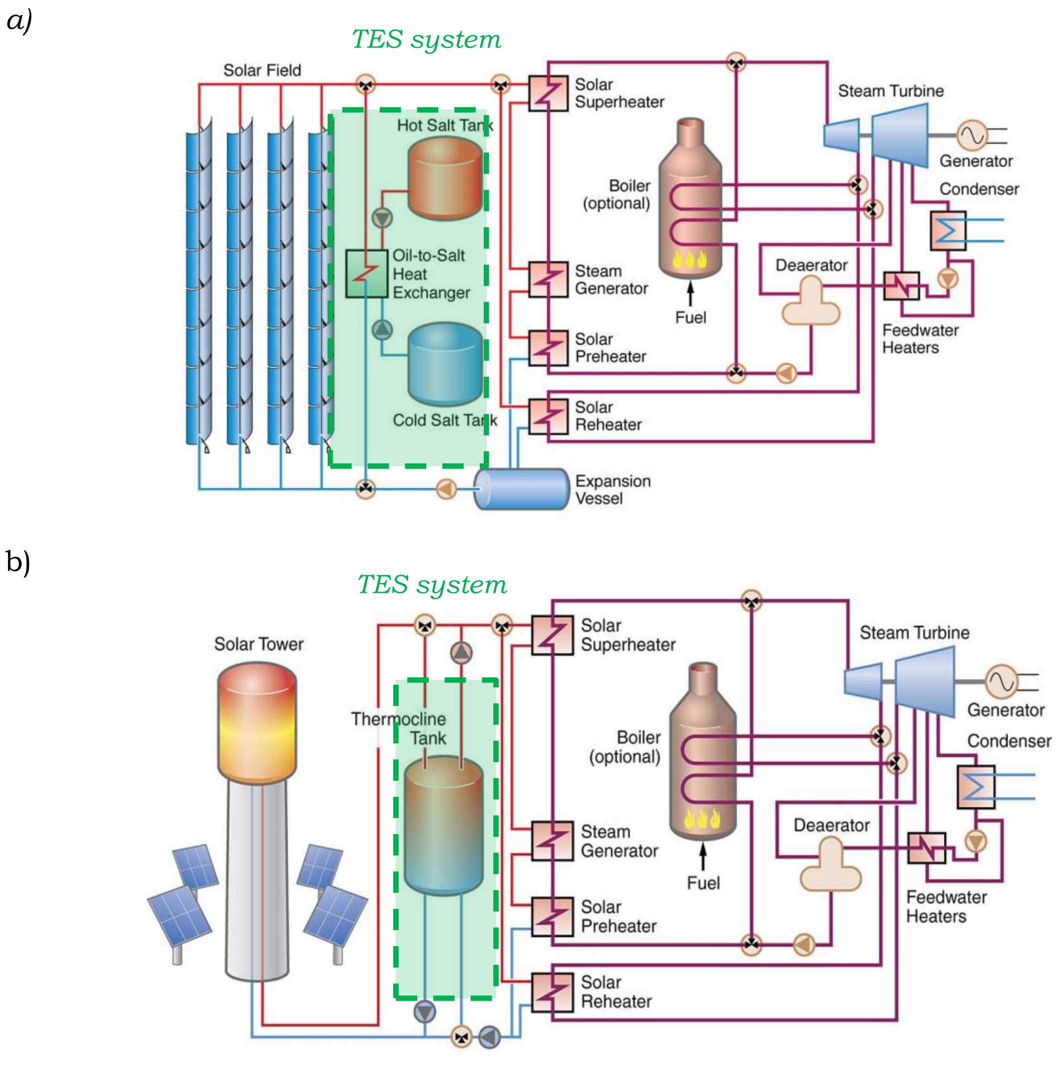

Figure 1. Definition of the TES boundary as applied to two examples of storage integration in a CSP plant: a) indirect two-tank storage in parabolic trough system, b) direct thermocline storage in power tower system (source Libby et al., 2010)

The following paragraphs gain only the activity done during Task 6.3 of SFERA-III project since January 2019 till the end of 2022, mainly by online discussions (a total of 26 in these four years). The main purpose of the activity is not to propose normalized tests, but to give definitions of indicators and guidelines on the protocols to quantify these indicators. Various kinds of protocols can be followed, maybe leading to different values for the indicators. Our point is not to certify the performances of a TES component, but rather to ensure that the indicators are estimated in a systematic and reproducible way. Consequently, the main target audience of this document is scientists, not plant operators which would be probably more interested in standards.

The following basic principles are used in the document:

- Most of the measurements are made in the Heat Transfer Fluid (HTF) side, thus outside of the storage device. This approach could have the drawback of being only partially representative of Thermal Energy Storage (TES) behaviour (as storage material is not specifically considered) but allows easy measurements and is consistent with TES operating control.
- To correctly estimate latent heat, specific enthalpy (in J/kg) is considered instead of temperature. However, for sensible heat storage systems, temperatures may be used instead of specific enthalpy.
- Many features described in this document may vary depending on the initial state of the TES system. It is particularly significant for thermocline TES, where the initial state can depend on previous charge-discharge cycles.

2.1. Scope of this work

This document is mainly focused on TES systems that are currently at prototype or demonstration level. In particular, the following technologies will be considered:

- Single media thermocline tank (with molten salts or thermal oil as HTF),
- Concrete storage module,
- Dual media thermocline tank (with molten salts or thermal oil or air as HTF; and rocks, sand, or slags as filler material),

- Solid particles tank in fluidized bed,
- Latent heat storage with Phase Change Material (PCM) in a shell-and-tubes design.

There is also a lack of proposals for standardized testing procedures to identify and quantify varying storage performance over time due to aging of storage materials or components, but durability aspects are not in the scope of this work.

2.2. Testing procedures status prior SFERA-III project

As pointed out in the WP6 description, there is not standardized methods for testing thermal storage prototypes, either sensible or latent, of interest for the STE industry.

The ANSI/ASHARE standards 94.3-2010 (*"Methods of Testing Active Sensible Thermal Energy Devices Based on Thermal Performance"*) and 94.1-2010 (*"Methods of Testing Active Latent –Heat Storage Devices Based on Thermal Performance*") deal with determining the thermal performance of sensible and latent energy storage devices, respectively, but to be used in heating, air conditioning and service hot water systems, so some of the assumptions and coefficient of certain formulas cannot be applied to thermal storage prototypes for CSP. Additionally, these standards consider that the storage device starts/ends from/to a nearly uniform temperature established by a small variability in the outlet-inlet temperature difference. According to the experts participating in this SFERA-III task, this may not be the case and a nearly constant difference in the outlet-inlet temperature may occur when having an important temperature gradient along the storage device.

A first attempt to improve the protocols these ANSI/ASHRAE standards propose was done in the first of the EU funded projects SFERA (GA. 228296). There, both sensible and latent storage prototypes were considered. The deliverable 15.2 "*Definition of standardised procedures for testing thermal storage prototypes for concentrating solar thermal plants*", dealt with the specific features of working at higher temperature than in water storage system devices. Although based on the participants' experience, all the work done in that deliverable was paper work, so some definitions support each other, leading to unclear descriptions of some concepts. For example, it claims that "when the prototype is in such a state that it may be able to provide the maximum useful energy has 100% storage level and it is said that the prototype is fully charged" but not a definition of what by maximum useful energy is intended for is given.

In between SFERA and SFERA-III projects, the activity on defining testing protocols for thermal storage prototypes has been kept on through the Thermal Energy Storage Working Group (TES WG) of the SolarPACES TCP, which published a report on "Definition of common procedures for testing thermal storage prototypes for STE plants" in 2016, which starts dealing with the problems faced in relation of not having an uniform initial temperature in the device when charging/discharging processes. Nevertheless, since this activity was not funded, no mayor advantage was achieved but highlighting the necessity of including this research in a funded project.

Deliverable 15.2 of SFERA project and the report of the TES WG were quite useful for the Spanish standard UNE206012:2017 "Caracterización del sistema de almacenamiento térmico para aplicaciones de concentración solar con captadores cilindroparabólicos" and the international specification IEC TS 62862-2-1:2021 "Solar thermal electric plant – Part 2-1: Thermal energy storage systems – characterization of active, sensible systems for direct and indirect configurations". These standards deal with thermal storage systems at power plant level, which implies a much larger size than prototypes and certain limitations for testing since the energy source is a large solar field-. Features and limitations that have to be considered when defining the testing protocols.

In this SFERA-III deliverable the proposed definitions and procedures have been checked with real experimental data of different types of thermal storage prototypes, -those listed in 2.1 Scope of this work paragraph- and resumed in paragraph 10 of this deliverable. Specific attention has been paid to particle thermal storage devices, which were not specifically considered in the mentioned previous documents. Working with experimental data reveals problems and situations that were not foreseen previously. Thus is why, for example, a steady state end of charge is claimed not to mean that the storage device is at uniform temperature but a thermal gradient may occur, so it proposes to talk on stable conditions more than on steady state conditions; different starting process conditions are considered (steady-state, first cycle, cycled TES), etc. Two additional methods for evaluating thermal losses are proposed: Energy balance method and Test comparison method. Two new Key Performance Indicators (KPI) are considered as relevant so included here: Utilization rate and Storage exergy efficiency. A sequence to follow when testing thermal storage prototypes is proposed in paragraph 6, giving the required steps to obtain the five KPIs proposed in this deliverable. Since experimental results for prototypes and their evaluation is most of the times a critical tool to validate simulation models of their thermohydraulic behaviour, a paragraph is included here with suggestions and recommendation on how to apply the KPIs found with these experimental procedures in such simulation models.

2.3. Glossary

Theoretical conditions: Characteristic conditions associated with materials specifications (including HTF, filler material, PCM shells, baskets, heat exchangers, resistors, etc.), and to the HTF volume and flow rate and both the inlet and outlet specific enthalpies, all at design time.
It is worth noting that, with this definition, any change in these specifications will define new theoretical conditions although the equipment can be the same.

Rated conditions: Also known as design conditions or nominal conditions. Characteristic conditions established when a thermal storage system is designed. These conditions are associated with the HTF flow rate and its inlet and outlet specific enthalpy during charge and discharge. These rated conditions may be the same or different from charging and discharging, and maybe the same or different from maximal and minimal operating conditions.

In particular:

- Rated inlet specific enthalpy (or temperature) in charge: set point fixed by the operator that may correspond to the maximal operating temperature of the thermal storage (fixed by the limitations of the HTF and storage materials) or to a design set point linked to the integration of the storage into a specific system.
- Rated inlet specific enthalpy (or temperature) in discharge: set point fixed by the operator that may correspond to the minimal operating temperature of the thermal storage (fixed by the limitations of the HTF and storage materials) or to a design set point linked to the integration of the storage into a specific system.

Initial conditions: State of the considered system at the beginning of the considered experimental process. For a reproducible and accurate assessment of the device performance, it is recommended that the initial conditions are clearly stated as one of the following ones:

Considered process	Charge	Discharge
A) Steady-state	First charge from *steady-state end of discharge* state	First discharge from *steady-state end of charge* state
B) First cycle	First charge from *steady-state end of discharge* state	First discharge after one full charge at defined operating conditions. [This previous charge is done starting from *steady-state end of discharge* state]
C) Cycled TES	Charge after *n* successive full cycles, where *n* is reached when there is only a defined small difference in the storage outlet temperature profile (converged profile) between two consecutive discharge cycles.	Discharge after *n* successive full cycles, where *n* is reached when there is only a defined small difference in the storage outlet temperature profile (converged profile) between two consecutive discharge cycles.

Operating conditions: Conditions defined by an operator at a given moment, considering an aimed operating strategy. It is expected that the operating conditions defined by the operator can fit within the rated conditions, thus considering maximum and minimum rated temperatures, mass flow rates, etc.

Theoretical storage capacity: storage capacity at theoretical conditions; the maximum amount of energy that can be accumulated by the storage medium from the thermodynamic point of view. It is an ideal parameter and no heat loss or stratification is included. It will depend of the kind of thermal process that the storage medium undergoes: latent heat, sensible heat or chemical reaction.

$$\begin{aligned}
&\mathit{Theoretical\ storage\ capacity} \\
&\quad = \sum_{storage\ materials} m_{charged,rated}\, h_{charged,rated} \\
&\quad - m_{discharged,rated} h_{discharged,rated} \\
&\quad = \sum_{storage\ materials} \rho_{charged,rated} V \cdot\ h_{charged,rated} \\
&\quad - \rho_{discharged,rated} V \cdot h_{discharged,rated}
\end{aligned}$$

Where $h_{\text{charged, rated}}$ and $h_{\text{discharged, rated}}$ are calculated on the storage material's side. The authors should clearly state what is considered as storage materials or not in the theoretical storage capacity: HTF, storage fluid, filler, walls, baskets, integrated heat exchangers, thermal insulation… It is recommended to take into account walls and internal structures of the storage tank (baskets, integrated heat exchangers). Thermal insulation can be excluded, except if it accounts for a significant share of the storage capacity (for example higher than 5%).

For latent heat storage, the authors should specify if sensible heat is taken into account, or even better distinguish sensible and latent heat shares. If the share of sensible heat is significant (for example higher than 5%), it is recommended to include it.

Charge: Process during which the energy is transferred or supplied to the storage system by the HTF. Depending on the final conditions reached, the process is:

- Full charge: a full charge is obtained when the HTF is entering the TES system at the rated charge HTF inlet specific enthalpy. Various initial conditions may be considered, although they must be clearly defined. End of full charge must be defined in a consistent way, the following criteria can be used (non-exhaustive list):

  - ☐ when the outlet HTF specific enthalpy is equal or larger than the threshold charge HTF outlet specific enthalpy. Maximum charge HTF outlet specific enthalpy value is often not only storage-dependent, it can be defined based on the global system needs (for example inlet temperature of the heat production system).

  - ☐ when the HTF specific enthalpy difference between inlet and outlet becomes constant and close to zero for constant mass flow rate ("*steady-state end of charge*"). However, in the case of latent heat storages, the outlet specific enthalpy maybe constant while a *steady-state end of charge* is not reached, when phase change occurs (fusion at constant temperature). One must be sure that no phase change is ongoing when defining end of full charge.

- ■ Part charge: part charge is defined as a % in energy of a full charge

Remarks:

1) Having a given value of the HTF outlet specific enthalpy does not ensure to have the same energy stored in the TES system after a full charge (temperature distribution may vary).

2) "Steady-state end of charge" does not necessarily means that all the storage volume is at uniform temperature. A thermal gradient may persist.

3) The end of charge can also be detected by calcultating the thermal power of the TES system: end of charge occurs when the thermal power becomes lower than a certain value (for example 110% of the thermal losses estimated by the "Energy balance at constant temperature" method, see Section 4.4).

4) The inlet mass flow rate may variate due to the aimed temperature and to the resource availability.

Discharge: Process during which energy is transferred from the storage system. Depending on the final conditions reached, the process is:

- ■ Full discharge: a full discharge is obtained when the HTF is entering the TES system at the rated discharge HTF inlet specific enthalpy. Various initial conditions may be considered, although they must be clearly defined. End of full discharge must be defined in a consistent way, the following criteria can be used (non-exhaustive list):

- ☐ when the outlet HTF specific enthalpy is equal or lower than the threshold discharge HTF outlet specific enthalpy. Minimum discharge HTF outlet specific enthalpy value is often not only storage-dependent, it can be defined based on the global system needs (for example inlet temperature of the user system).
- ☐ when the HTF specific enthalpy difference between inlet and outlet becomes constant for constant mass flow rate (a steady state is observed in the TES). However, in the case of latent heat storages, the outlet specific enthalpy maybe constant while a *steady-state end of discharge* is not reached, when phase change occurs (solidification at constant temperature). One must be sure that no phase change is ongoing when defining end of full discharge.

- ■ Part discharge: part discharge is defined as a % in energy of a full discharge

Remarks:

1) Having a given value of the HTF outlet specific enthalpy does not ensure to have the same energy released in the TES system after a full discharge (*temperature distribution may vary).*

2) *“Steady-state end of discharge” does not necessarily means that all the storage volume is at uniform temperature. A thermal gradient may persist.*

3) Unlike the Charge process, this process is expected to occur at "constant" mass flow rate.

Full Cycle: A full cycle is considered when a full charge and a full discharge are performed consecutively following its definitions.

Partial cycle: A partial cycle is defined as a cycle that contains a discharge after a charge without being one or both of them fully completed.

Storage level: Ratio of the useful thermal energy that can be supplied by the thermal storage system from the present state until full discharge and the rated storage capacity.

Remarks:

- *The storage level is said to be 0% when the amount of useful energy that can be supplied by the thermal storage system is zero, and where applicable, at rated specific enthalpies and pressures. Storage is said to be at 100% when the amount of useful energy from the system is maximum at rated temperatures and pressures, where applicable.*
- *The storage level at an instant t cannot be estimated at this instant t: one must wait the end of the discharge. Another definition using measurements on storage media's side might be needed to solve this issue. Regarding latent heat storage, and since the temperature values are not indicative of the media energy, one of these measurements could be the use of pressure sensors or material level sensors (since volumetric densities of the PCM are usually distinct in solid and liquid state for instance, which could provide information on the liquid fraction, and hence translating into a storage level indicator). Another option, applicable for thermocline TES devices only, could be to measure the axial temperature profile of the HTF in the tank, to estimate the position of the thermocline, thus the amount of available energy stored.*
- *It is often impossible to "foresee" a correct storage level. With regard to a thermocline tank, the useful energy to be supplied depends, among other things, on the discharge mass flow rate and on the threshold outlet temperature for the discharge process. Therefore, either it is acceptable to deal with an inaccurate storage level or the storage level relates with the thermal energy inside the tank instead of the useful energy that will be supplied.*

Inlet temperature in charge: Measurement of temperature at the top (or high temperature) flow boundary. In rated or nominal conditions, it is the maximum inlet temperature for the TES (depending on the considered condition). In operating conditions, the operator can define a different value within the rated limits and according to the operating strategy.

Outlet temperature in charge: Measurement of temperature at the bottom (or low temperature) flow boundary. This measurement can be monitored to define the end of the charge process if the end-of-charge criterion used is a temperature threshold (maximum outlet temperature for the TES) defined by the operator within the rated limits and according to the operating strategy.

Inlet temperature in discharge: Measurement of temperature at the bottom (or low temperature) flow boundary. In rated conditions, it is the minimum inlet temperature for the TES (depending on the considered condition). In operating conditions, the operator can define a different value within the rated limits and according to the operating strategy.

Outlet temperature in discharge: Measurement of temperature at the top (or high temperature) flow boundary. This measurement can be monitored to define the end of the discharge process if the end-of-discharge criterion used is a temperature threshold (minimum outlet temperature for the TES) defined by the operator within the rated limits and according to the operating strategy.

Stable conditions: A measurement can be considered stable when the measured value T at the system inlet does not vary more than a defined deviation ΔT during a defined period of time Δt. The criteria ΔT and Δt should be defined by the authors. As examples, one of the two the following criteria can be used:

- ΔT can be absolute values taken equal to 1 to 5 K for temperature measurements and some g/s for mass flow measurements (or a fraction of the rated mass flow), or derivatives values such as 1 to 5 K/min for temperature measurements and some g/s/min for mass flow measurements. These values must be compatible with the accuracy of the measurement devices. The authors may refer to existing standards defining such concepts, like UNI 4546[1] or ISO9806[2].

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[1] UNI 4546:1984, Italian Language, MEASURES AND MEASUREMENTS. FUNDAMENTAL TERMS AND DEFINITIONS

[2] ISO 9806:2017, English version, Solar energy — Solar thermal collectors — Test methods

- Δt can correspond to a fraction (typically 1 to 5%) of the real or theoretical charge/discharge time.

A similar yet different concept is the one of “constant conditions”: definitions of constant inlet temperature and constant flow rate can be found in EN 12977-3[3].

Steady-state conditions: Overall system status in which no parameters vary upon time. Nevertheless, in an experimental facility some (minor) variations are expected to be found in given measuments. However, these variations must comply with described **Stable conditions**.

2.4. Thermal power calculations

Many performance indicators described in the following sections are derived from instantaneous thermal power (Q) at the storage system boundaries. Thermal power can be calculated as follows:

$$\dot{Q} = \frac{dQ}{dt} = \dot{\boldsymbol{m}}_{\boldsymbol{out}}\boldsymbol{h}_{\boldsymbol{out}} - \dot{\boldsymbol{m}}_{\boldsymbol{in}}\boldsymbol{h}_{\boldsymbol{in}}$$

With $h = \int_{T_0}^{T} \boldsymbol{c}_{\boldsymbol{p}}(\boldsymbol{T})\boldsymbol{dT}$

C_p is expressed as a function of the temperature. For large temperature variations, a second-degree polynomial function is recommended.

$$\dot{Q} = \dot{\boldsymbol{m}}_{\boldsymbol{out}} \int_{T_0}^{T_{out}} \boldsymbol{c}_{\boldsymbol{p}}(\boldsymbol{T})\boldsymbol{dT} - \dot{\boldsymbol{m}}_{\boldsymbol{in}} \int_{T_0}^{T_{in}} \boldsymbol{c}_{\boldsymbol{p}}(\boldsymbol{T})\boldsymbol{dT}$$

Inlet and outlet mass flows rates may be different because of density variations according to the temperature, or liquid level variations in the case of LHTES. In practice, mass flow rate is not always measured at both locations. Some hypotheses can be applied to simplify this calculation:

1) With hypothesis $\dot{\boldsymbol{m}}_{\boldsymbol{out}} = \dot{\boldsymbol{m}}_{\boldsymbol{in}} = \dot{\boldsymbol{m}}$

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[3] EN 12977-3:2018,Thermal solar systems and components - Custom built systems - Part 3: Performance test methods for solar water heater stores

$$Q = \dot{\boldsymbol{m}} \int_{T_{in}}^{T_{out}} \boldsymbol{c_p(T)dT}$$

2) Or with an average C$_p$ hypothesis:

$$\overline{c_p} = \frac{\boldsymbol{c_p(T_{in}) + c_p(T_{out})}}{2}$$

$$Q = \dot{\boldsymbol{m}}_{\boldsymbol{out}}\overline{c_p}(\boldsymbol{T_{out}} - \boldsymbol{T_0}) - \dot{\boldsymbol{m}}_{\boldsymbol{in}}\overline{c_p}(\boldsymbol{T_{in}} - \boldsymbol{T_0})$$

Thus with T_0 = 0 °C: $Q = \dot{\boldsymbol{m}}_{\boldsymbol{out}}\overline{c_p}\boldsymbol{T_{out}} - \dot{\boldsymbol{m}}_{\boldsymbol{in}}\overline{c_p}\boldsymbol{T_{in}}$

And with $\dot{\boldsymbol{m}}_{\boldsymbol{out}} = \dot{\boldsymbol{m}}_{\boldsymbol{in}} = \dot{\boldsymbol{m}}$: $Q = \dot{\boldsymbol{m}}.\overline{c_p}(\boldsymbol{T_{out}} - \boldsymbol{T_{in}})$

Note: Average c$_p$ hypothesis and enthalpy expression $h = \overline{c_p}(T - \boldsymbol{T_0})$ *are not recommended for liquids with large temperature variations as they may lead to large enthalpy values deviations.*

3. Testing conditions

The procedures defined in this section are adapted to thermocline and sensible packed bed TES systems. The procedures might be different to calculate the performance indicators of other systems like Phase Change Material (PCM) or two-tank TES systems.

The rated conditions define the rated operation of the TES system and must be given previously to any experimental study. They can be defined as:

- Charge process:
    - Rated charge HTF mass flow rate in stable conditions
    - Rated charge HTF inlet specific enthalpy in stable conditions
    - Full charge conditions (as defined in Section 2.2)
- Discharge process:
    - Rated discharge HTF mass flow rate in stable conditions
    - Rated discharge HTF inlet specific enthalpy in stable conditions
    - Rated discharge HTF outlet specific enthalpy
    - Full discharge conditions (as defined in Section 2.2)
- Data acquisition frequency: acquisition frequency should be high enough to appreciate the trend of the measured variable, typically at least 50 time values for each charge or discharge process.
- Instrumentation accuracy must be specified, along with the type of instruments that can be used (with their advantages and drawbacks). This accuracy should include not only the accuracy of the sensor, but of the overall measuring device (transmitters, signal converters, acquisition system,...). Interesting recommendations about instrumentation can be found in the standard EN 12977-3[3] and in the Guide to the expression of uncertainty in

Measurement[4].

The following basic storage parameters should be given for every test decribed in the following sections:

- Tank (or other storage device) geometry: useable volume, with or without convex ends;
- Heat transfer fluid properties (density, specific heat) expressed as functions of the temperature.

The way of the temperature dependent properties are calculated affects resulting KPI values. The method to compute the thermal power shoud be clearly explained (see recommendations in Section 2.3). Some additional specific storage parameters might be necessary for some indicators (for example storage media properties), in this case they are clearly mentioned in the dedicated sections. The accuracy of temperature dependent inlet and outlet properties directly affects the accuracy of the results, therefore an accurate property table or polynomial expressions for temperature dependent properties either should be obtained from HTF supplier specification sheets for off-the-shelf HTF or should be supplied by the TES system supplier together with the data for non-standard HTF.

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[4] Joint Committee for Guides in Metrology/WG 1, Evaluation of measurement data: Guide to the expression of uncertainty in measurement, 2008

4. Key performance indicators: definitions and procedures

By default, all the performance indicators in this document are defined for rated conditions. For any other operating conditions, non-rated mass flow rates, inlet and outlet specific enthalpies should be specified.

4.1. Storage capacity

4.1.1. Definition

Amount of thermal energy measured in $\mathrm{Wh_{th}}$ that the thermal storage system can supply by full discharge under well-defined starting and ending conditions.

$$SC = \int_{t_{fully\ charged\ state}}^{t_{fully\ discharged\ state}} (\dot{\boldsymbol{m}}_{\boldsymbol{out}}\boldsymbol{h}_{\boldsymbol{out}} - \dot{\boldsymbol{m}}_{\boldsymbol{in}}\boldsymbol{h}_{\boldsymbol{in}})\boldsymbol{dt}$$

Precise location of inlet and outlet should be clearly stated. Heat exchangers (for indirect TES systems), convex ends and collector plates should be included: if they are not taken into account it must be clearly mentioned.

$$\boldsymbol{Q}_{\boldsymbol{charge}} = \int_{t_{fully\ discharged\ state}}^{t_{fully\ charged\ state}} \dot{\boldsymbol{m}}_{\boldsymbol{in}} \cdot \boldsymbol{h}_{\boldsymbol{in}}\,\boldsymbol{dt}$$

$$\boldsymbol{Q}_{\boldsymbol{discharge}} = \int_{t_{fully\ charged\ state}}^{t_{fully\ discharged\ state}} \dot{\boldsymbol{m}}_{\boldsymbol{out}} \cdot \boldsymbol{h}_{\boldsymbol{out}}\,\boldsymbol{dt}$$

In general, storage capacity is estimated from experimental measurements. However, when the discharge is operated at rated discharge mass flow rate, it is defined as **rated storage capacity**. Rated storage capacity calculation is useful for modelling activities, for example for prototype sizing. It is different from theoretical storage capacity, where ideal heat transfers are considered.

Remarks

- *A **charge capacity** can also be defined, different from the storage/discharge capacity.*
- *The storage capacity depends on the initial and operating conditions in the storage. For one set of initial and operating conditions, only one value of storage capacity can be estimated. However, for different initial or operating conditions, different values of storage capacity can be obtained for the same storage device.*
- *Mass flow rate and temperature measurements are needed to define storage capacity. When the HTF is a monophasic fluid operated close to atmospheric pressure, there is no need for pressure measurements. Reversely, for two-phase HTF (e.g. liquid water / steam), pressure measurement are required to estimate specific enthalpy levels.*
- *This comes down to say that storage level can also be defined as the ratio of the storage capacity at present conditions and the rated storage capacity.*

$$\boldsymbol{S}torage\ level = \frac{SC_{present\ conditions}}{SC_{rated}}$$

4.1.2. Evaluation

4.1.2.1. Inputs needed

Initial conditions (as defined in the Glossary section, choose one option)

- A) Steady-state full charge state,
- B) First cycle,
- C) Cycled TES.

Operating conditions

- Rated discharge inlet temperature
- Rated discharge mass flow rate (for rated storage capacity evaluation only)
- End of discharge when full discharge conditions are reached

Instrumentation

- Inlet temperature measurement (type, location, accuracy)
- Outlet temperature measurement (type, location, accuracy)
- Mass flow measurement (type, location, accuracy)

4.1.2.2. Procedure

Storage capacity is estimated using inlet and outlet temperature measurements and mass flow measurements from a full discharge state under initial, operating, and ending conditions defined above. To compare TES systems, fixed initial and full discharge state (final conditions) temperatures may be defined. These values may differ from one type of storage to the other.

From experimental or simulated time series, SC can be obtained by integrating thermal power Q with a trapezoidal rule:

$$SC = \sum_{i=1}^{n} (t_i - t_{i-1}) \frac{(Q_i + Q_{i-1})}{2}$$

4.2. Utilization rate

4.2.1. Definition

Ratio in percentage of the storage capacity to the theoretical storage capacity of the TES system in the rated conditions. Rated utilization rate is obtained when full discharge is considered.

$$\text{Utilization rate} = \frac{\text{Storage capacity}}{\text{Theoretical storage capacity}}$$

The authors should clearly state what is considered or not in the theoretical storage capacity: fluid, filler, walls, baskets, integrated heat exchangers, thermal insulation…

Remark: Like storage capacity, utilization rate depends on TES initial state and may *evolve from cycle to cycle in case of repetitive cycles.*

4.2.2. Evaluation

4.2.2.1. Inputs needed

Specific storage parameters

- Storage media properties: density, specific heat
- Thermal properties (density and specific heat) of walls, fillers, thermal insulation

Initial conditions (as defined in the Glossary section, choose one option)

- A) Steady-state full charge state,
- B) First cycle,
- C) Cycled TES.

Operating conditions

- Rated discharge inlet temperature
- Rated discharge mass flow (for rated utilization rate evaluation only)
- End of discharge when full discharge conditions are reached

Instrumentation

- Inlet temperature measurement (type, location, accuracy)
- Outlet temperature measurement (type, location, accuracy)
- Mass flow rate measurement (type, location, accuracy)

4.2.2.2. Procedure

Theoretical storage capacity is calculated either from literature material characteristics, or from material properties measurements. Afterwards the utilization rate can be evaluated from any storage capacity test as defined in Section 3.1.

4.3. Discharging time

4.3.1. Definition

The **discharging time** between two storage states B and A is the time the thermal storage system takes to discharge from a higher storage level B to another lower storage level A under rated discharge conditions. Rated discharging time is obtained when full discharge is performed.

Remarks:

- *The **charging time** between two storage states A and B is the time needed for the thermal storage system to reach a higher level of storage B by charging at rated charge conditions, starting from a lower storage level A. Rated charging time is obtained when full charge is performed following its rated conditions. It may be different from rated discharging time.*
- *For one set of initial and operating conditions, only one value of charging/discharging time can be estimated. However, for different initial or operating conditions, different values of charging/discharging time can be obtained for the same storage device.*
- *The **mean thermal power (P_{mean})** is the mean thermal power of the discharge. It is is a mean value all over the discharge process, directly linked to the rated discharging time ($t_{discharge}$).*

  $$\mathrm{P}_{mean} = \frac{\text{Storage capacity}}{t_{discharge}}$$

  If relevant for the TES system, the mean power of the charge ($P_{mean,\ ch}$) can be indicated next to the discharge value, clearly stating which belongs to charge and which to discharge. P_{mean} can be limited by:

  - *The maximum mass flow rate of the storage pumps,*
  - *The maximum allowable pressure drop in the TES system,*
  - *The heat transfer rate between the HTF and the storage material (ex*

PCM).

4.3.2. Evaluation

4.3.2.1. Inputs needed

Initial conditions (as defined in the Glossary section, choose one option)

- A) Steady-state full charge state,
- B) First cycle,
- C) Cycled TES.

The initial point is when the flow of HTF starts.

Operating conditions

- Rated charge (discharge) inlet conditions: temperature, HTF mass flow rate
- Minimum outlet temperature set-point (end of discharge criterion)
- Maximum outlet temperature set-point (end of charge criterion)

Instrumentation

- Inlet temperature measurement (type, location, accuracy)
- Outlet temperature measurement (type, location, accuracy)
- Mass flow measurement (type, location, accuracy)

4.3.2.2. Procedure

Full discharge (charge) time: starting from fully charged (discharged) tank, the discharge (charge) time is the period from which the initial HTF starts to enter the storage tank (or heat exchanger for indirect storage) up to the instant when full discharge (charge) conditions are reached.

4.4. Thermal losses

4.4.1. Definition

Thermal power lost by the storage system during period "Δt" from the instant at which it is at storage state A (at $t=t_A$) to the instant at which it is at storage state B (at $t=t_B$).

$$\dot{Q}_{loss} = \frac{Q_A(t_A) - Q_B(t_B) + Q_{in}(t_B - t_A) - Q_{out}(t_B - t_A)}{\Delta t}$$

One can distinguish idle or stationary thermal losses, estimated during idle periods (when $Q_{in} = 0$ and $Q_{out} = 0$), and dynamic thermal losses estimated when the storage system is operated (in charge or discharge). Thermal losses must be given at a specified temperature level.

Remarks:

- *Thermal losses can hardly be extrapolated from small to large systems.*
- *Some orders of magnitude for TES temperature due to thermal losses in sensible heat storages:*
  - *A few degrees decrease per hour for lab-scale TES,*
  - *A few degrees decrease per day for industrial-scale TES.*

4.4.2. Evaluation

In order to calculate the thermal losses we can apply four methods:

a) Isothermal method (stationary heat losses)

b) Cool-down method (stationary heat losses)

c) Energy balance at constant temperature and flow rate (dynamic heat losses)

d) Comparison between two standardized charging-discharging tests (stationary heat losses)

All these methods can be repeated for different reference temperature levels, in order to build a curve of thermal losses as a function of the temperature.

4.4.2.1. Inputs needed

	Special storage parameters	**Initial conditions**	**Operating conditions**	**Instrumentation**
a)	None	Any condition	Idle period	• Temperature measurement in the storage (type, location, accuracy, quantity, resolution) • Logging the power consumption
b)	Storage media properties: density, specific heat			• Temperature measurement of thermal gradient (type, location, accuracy, quantity, resolution)
c)	None	Steady-state end of charge	Continue charging at tank temperature	• Inlet temperature measurement (type, location, accuracy) • Outlet temperature measurement (type, location, accuracy) • Mass flow rate measurement (type, location, accuracy)
d)		Any reproducible condition	Discharge with minimum outlet temperature setpoint (end of discharge criterion)	

4.4.2.2. Isothermal method - Procedure

The isothermal method involves the measurement of the power consumption of immersed electric heaters or external heat tracing over a long steady-state period (several hours/a day with no mass transfer) as the storage media is maintained at a constant target temperature. The target temperature and the accepted temperature tolerance used for the calculation must be clearly stated.

Temperatures sensors in the tank are necessary to define a reference temperature of the storage. This reference temperature is the controlled variable of the heating system

4.4.2.3. Cool-down method - Procedure

In the cool-down method, the thermal losses are estimated by the rate of change of the tank mean temperature. This is achieved by turning off the power supply systems (e.g. immersion heaters and electrical heat tracing or the indirect HTF flow into the storage device) and via monitoring and recording the tank temperature on storage media side over a defined period. For this calculation, the volume of the tank is devided by a number of temperature sensors in the tank. Thus, each sensor is assigned a partial volume of the tank surrounding it. By calculating the energy in each partial volume at the beginning and end of this test and the resulting difference, the thermal loss is determined. A steady-state temperature profile (with low temperature gradients) is required. Tank mean temperatures measured at the beginning and end of the test must be clearly stated.

For each elementary (or partial) storage volume, thermal energy content of the storage system can be evaluated as follows:

$$\mathrm{Q}(\mathrm{t}_1) = \mathrm{Q}(\mathrm{t}_0) + \rho(\mathrm{t}_1)\mathrm{V}\int_{t_0}^{t_1} c_p\,(\mathrm{T})\mathrm{dT}$$

With hypothesis of mean Cp : $\bar{c_p} = \frac{\boldsymbol{c_p(T_0)+c_p(T_1)}}{2}$

$$\mathrm{Q}(\mathrm{t}_1) = \mathrm{Q}(\mathrm{t}_0) + \rho(\mathrm{t}_1)\mathrm{V}\bar{c_p}(T_1 - T_0)$$

This method has the advantage of locating the areas with higher losses.

Remarks:

- *This method applies with a steady-state end-of charge or end-of-dischage temperature profile, so that "history effects" can be minimized.*
- *Out of steady-state temperature profiles, in stratified storages heat losses are specific to a temperature profile. Since the temperature profile imprinted on the storage depends on many influencing factors (flow velocity, temperatures, operation, previous idle times and additional electrical heating) it is difficult to predict the heat loss of a specific temperature profile. When the thermal losses at a specific point are of interest, that specific temperature profile needs to be produced previously by operating the storage in the corresponding way, which might be time consuming in some cases (e.g. for a cycled TES).*
- *This method does not include the possible change of mass or volume inside the storage when the storage system is cooling down. In some cases, when the HSM is*

shrinking, additional HTF or HSM may flow into the storage to compensate for the density variations.

4.4.2.4. Energy balance method - Procedure

In this method energy balance between inlet and outlet specific enthalpies on HTF side at constant inlet conditions after stabilization of steady-state temperature is calculated. Here no temperature sensors are needed inside the tank.

4.4.2.5. Test comparison method - Procedure

This method compares the discharge energy on HTF side from two standardized charging-discharging tests with different idle time (predefined amount of hours/days without mass transfer) between end of charge and beginning of discharge. Here no temperature sensors inside the tank are needed.

4.5. Storage efficiency

4.5.1. Definition

Ratio between the energy gained by the heat transfer fluid from the storage device during discharge and the energy delivered to it by the heat transfer fluid during charge, in consecutive charge and discharge. When rated conditions are applied, i.e. full charge and full discharge, rated storage efficiency is obtained.

In consecutive charge and discharge:

$$\eta_{\mathrm{TES}} = \frac{Q_{\mathrm{discharge}}}{Q_{\mathrm{charge}}} = \frac{Q_{\mathrm{HTF\_out}}}{Q_{\mathrm{HTF\_in}}}$$

Remarks:

- *Storage efficiency depends on TES initial state and may vary from cycle to cycle in case of repetitive cycles.*
- *This is a 1st law of thermodynamics approach. Energy quality (exergy) degradation is not taken into account.*

- These calculations can be repeated for different end of charge and end of discharge criteria, in order to build a curve of storage efficiency as a function of $T_{out,charge,max}$, and $T_{out,discharge,min}$. *A* ***Storage Efficiency Function*** *can be derived from this definition: The charge shall start from a steady-state discharge state and finished at a steady-state charge state or a defined maximum charge HTF outlet specitic enthalpy. The discharge energy is a function of the minimum discharge HTF outlet specific enthalpy (and of the maximum charge HTF outlet specific enthalpy. When rated inlet conditions are applied, i.e. rated flow rate and minimum and maximum operating specific enthalpies, the rated storage efficiency function is obtained. For a sensible heat TES system, the storage efficiency can be expressed as a function of* $T_{out,charge,max}$ *and* $T_{out,discharge,min}$*:*

$$\eta_{\mathrm{TES}}\left(T_{out,charge,max}, T_{out,discharge,min}\right) = \frac{\mathrm{Q}_{\mathrm{discharge}}\left(T_{out,discharge,min}\right)}{\mathrm{Q}_{\mathrm{charge}}\left(T_{out,charge,max}\right)}$$

With this definition, the Storage efficiency function does not depend on TES initial state.

- *Charge efficiency is the ratio between the energy stored in the TES device and the energy provided to the TES device in the same period, during a charge operation.*

$$\eta_{charge} = \frac{Q_{stored}}{Q_{HTF,in}} = \frac{\sum_{\substack{storage\\materials}} m_i \cdot \left(h_{max,i} - h_{min,i}\right)}{\int_{t_{start}}^{t_{end}} \dot{m}_{HTF,in} \cdot h_{in}\, dt}$$

- *Discharge efficiency is the ratio between the energy retrieved from the TES device and the energy stored in the TES device in the same period, during a discharge operation.*

$$\eta_{discharge} = \frac{Q_{HTF,out}}{Q_{stored}} = \frac{\int_{t_{start}}^{t_{end}} \dot{m}_{HTF,out} \cdot h_{out}\, dt}{\sum_{\substack{storage\\materials}} m_i \cdot \left(h_{max,i} - h_{min,i}\right)}$$

In consecutive charge and discharge operations the TES efficiency indicator can be calculated as the product of both charge and discharge efficicencies.

$$\eta_{TES} = \eta_{charge} \cdot \eta_{discharge} = \frac{Q_{stored}}{Q_{HTF,in}} \cdot \frac{Q_{HTF,out}}{Q_{stored}} = \frac{\int_{t_1}^{t_2} \dot{m}_{HTF,out} \cdot h_{out}\, dt}{\int_{t_0}^{t_1} \dot{m}_{HTF,in} \cdot h_{in}\, dt}$$

Again, when rated conditions are applied, i.e. full charge and full discharge, rated *efficiencies are obtained.*

- *For a thermocline tank the ideal operation in discharge would be to move the layer from the bottom to the top thus circulation one volume and "replacing" Tcharge for Tdischarge at all elements (fluid + filling material). The outlet temperature after one volume is circulated gives a measure on how far from ideal the process and the 1 volume extraction efficiency can also be calculated.*

$$\eta_{TES} = \frac{Q_{discharge}(1_{vol})}{Q_{charge}}$$

4.5.2. Evaluation

4.5.2.1. Inputs needed

Initial conditions (as defined in the Glossary section, choose one option)

- A) Steady-state full charge state,
- B) First cycle,
- C) Cycled TES.

Operating conditions

- Rated charge inlet conditions: temperature, HTF flow
- Maximum outlet temperature set-point (end of charge criterion)
- Rated discharge inlet conditions: temperature, HTF flow
- Minimum outlet temperature set-point (end of discharge criterion)

Instrumentation

- Inlet temperature measurement (type, location, accuracy)
- Outlet temperature measurement (type, location, accuracy)
- Mass flow rate measurement (type, location, accuracy)

4.5.2.2. Procedure

The storage efficiency evaluation procedure must include one charge and one discharge for any of the initial conditions defined in the Glossary section. This will allow to calculate the energy delivered to and by the storage. For options A and C, the result will be independent of the order in which the charge and discharge are done. For option B, the result can be influenced by the previous storage state and the calculated efficiency can be underestimated or overestimated (even above 1).

In the following procedure steps 1 and 2 may change their order.

1) Charge at rated flow rate and temperature until reaching the maximum outlet temperature (end of charge criterion)
2) Discharge at rated flow rate and temperature until reaching the minimum outlet temperature (end of discharge criterion)
3) Storage efficiency can be calculated from the following formula:

$$\eta_{\mathrm{TES}}\left(T_{out,charge,max}, T_{out,discharge,min}\right) = \frac{\mathrm{Q}_{\mathrm{discharge}}\left(T_{out,discharge,min}\right)}{\mathrm{Q}_{\mathrm{charge}}\left(T_{out,charge,max}\right)}$$

Remarks:

- *After enough cycles (initial conditions: Type C), the storage efficiency is only a way to characterize the thermal losses in the case of direct TES systems. Indeed, if a repetitive pattern is reached it means that the same amount of energy is going in and out and the Storage Efficiency reaches a constant value. However, these thermal losses may have a large impact, for example when the storage is left in stand-by during a long time between the end of discharge and the beginning of the next charge process. Moreover, for indirect storage systems, storage efficiency may integrate other phenomena (e.g. heat exchanger efficiency).*

4.6. Storage exergy efficiency

4.6.1. Definition

Ratio of exergy gained by the heat transfer fluid from the storage device during discharge to the exergy delivered to it by the heat transfer fluid during charge. Exergy (also known as available energy) represents that part of a quantity convertible to work in a reversible device within a reference environment. Exergy analysis takes into account the temperature level (and hence the quality) of the energy transferred. Storage exergy efficiency can be expressed as follows (Rosen, 1992):

$$\eta_{\text{ex}} = \frac{\epsilon_{\text{discharge}}}{\epsilon_{\text{charge}}} = \frac{\int_{discharge}\left(1-\frac{T_0}{T_{discharge,out}}\right)dQ}{\int_{charge}\left(1-\frac{T_0}{T_{charge,in}}\right)dQ}$$

Initial and final conditions of the charge and discharge processes must be clearly defined. Several simplifying assumptions are made here, including: constant temperature surroundings (T_0), constant storage volume, negligible work interactions (e.g., pump work); and negligible chemical, kinetic, and potential energy and exergy quantities.

Remarks:

- *$T_{charge,in}$ and $T_{discharge,out}$ are usually measured by the same sensor.*
- *This definition allows to take into account not only destratification issues due to axial thermal diffusion in thermocline tank and regenerators, but also other irreversible phenomena that may occur in TES systems, such as convection between storage fluid and internal solid material (fillers, heat exchangers…), and exergy losses towards the ambient.*
- *Exergy losses due to pressure drops are not taken into account in this definition. They are often negligible, excepted for regenerators where pressure drops may be an issue.*
- *This « black-box » approach does not allow to determine the source of exergy loss in the system (destratification, convection, thermal losses,…). To do so a complete model of the storage tank would be needed, validated with internal temperature measurements. Such an approach is described in McTigue, 2016.*
- *Various methods can be used to quantify specifically the degree of stratification of a thermocline storage tank, several of them are presented in Figure 2 below (Haller, 2009)*

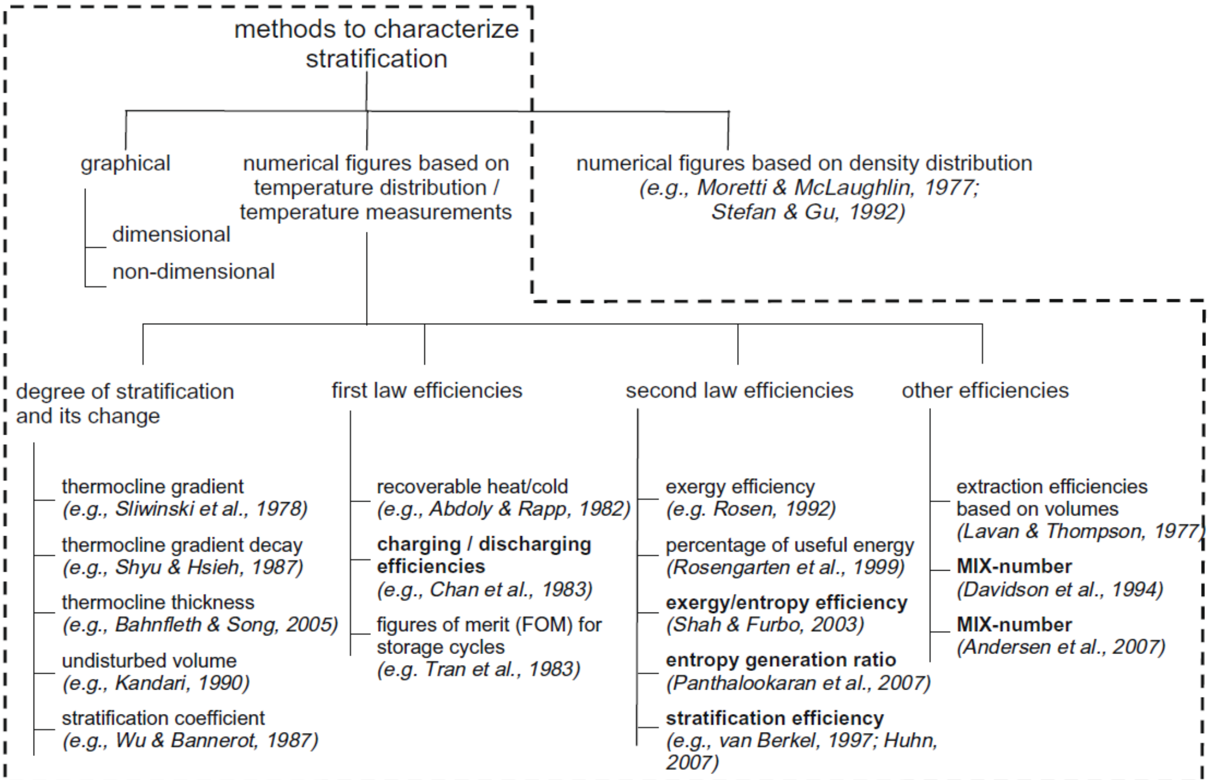


Figure 2. Methods to characterize stratification (Haller, 2009)

4.6.2. Evaluation

4.6.2.1. Inputs needed

Initial conditions (as defined in 2.2, choose one option)

- A) Steady-state full charge state,
- B) First cycle,
- C) Cycled TES.

Operating conditions

- Rated charge inlet conditions: temperature, HTF flow rate
- Maximum outlet temperature set-point (end of charge criterion)
- Rated discharge inlet conditions: temperature, HTF flow rate
- Minimum outlet temperature set-point (end of discharge criterion)

Instrumentation

- Inlet temperature measurement (type, location, accuracy)
- Outlet temperature measurement (type, location, accuracy)
- Ambient temperature measurement (type, accuracy)
- Mass flow rate measurement (type, location, accuracy)

4.6.2.2. Procedure

The storage exergy efficiency evaluation procedure must include at least one charge and one discharge for any of the initial conditions defined in the Glossary section. This will allow to calculate the exergy delivered to and by the storage.

To estimate exergy losses in stand-by (or idle) mode, the test-comparison method to calculate thermal losses can be adapted (see Section 4.2.5). In this method no temperature sensors are needed inside the tank.

4.7. Auxiliary power consumption

4.7.1. Definition

Electrical power consumption of the auxiliary devices needed to operate the TES system (pumps, fans, compressors, heat tracing of tanks and pipes, antifreezing heater, mixer…), if any. Some of these devices can be disregarded if they are not necessary for industrial scale facilities, however in this case it should be clearly stated by the authors.

Auxiliary power consumption (also called *parasitics power consumption*) can be expressed either in absolute value in W or in relative value. Relative value can be preferred to discuss scalability, but in this case the authors should clearly define how the reference value is calculated and what is taken into account.

4.7.2. Evaluation

4.7.2.1. Inputs needed

Power consumption of all auxiliary equipments (pumps, fans, compressors, heat tracing of tanks and pipes, antifreezing heater, mixer…) of the test loop must be monitored.

4.7.2.2. Procedure

Sum the power consumption of all auxiliary equipments under defined operating conditions (it can be charge, discharge, or idle period) of the test loop.

5. Evaluation check-list

The following table gathers, from an ideal point of view, all the necessary information to evaluate the KPIs of a TES prototype. As much as this metadata should be mentioned in some way in any publication or communication dealing with thermal performances assessment of a TES prototype.

Dataset used	File name		
System boundaries			*Describe the limits of the considered system*
Storage materials	Considered for theoretical storage capacity		*e.g. HTF, storage fluid, filler, walls, baskets, integrated heat exchangers, thermal insulation…*
Type of heat	Considered for theoretical storage capacity		*Sensible heat only, latent heat only, sensible and latent heat*

Storage geometry				
	Tank geometry			*Cylinder, parallelepiped,…*
	Tank boundaries			*Useable volume, with or without convex ends,…*
	Tank volume	m3		
Material properties				
HTF	Type			*e.g. air, water, oil, molten salt*
	Specific heat**	kJ/(kg.K)		
	Density**	kg/m3		
	Total volume	m3		
Storage media #1	Type			
	Specific heat**	kJ/(kg.K)		
	Density**	kg/m3		
	Total mass	kg		
Storage media #2	Type			*If any*
	Specific heat**	kJ/(kg.K)		
	Density**	kg/m3		
	Total mass	kg		
Storage media #3	Type			*If any*
	Specific heat**	kJ/(kg.K)		
	Density**	kg/m3		
	Total mass	kg		
Operating Conditions				
Initial conditions	Choose in the list			• *Uniform full charge state* • *First cycle* • *Cycled TES* • *Non reproductible conditions*
Ambient temperature	Value			

Start of charge criterion	Type		*Event corresponding to the start of charge*
	Value		*Value of the variable*
	Time		*Time of the event*
End of charge criterion	Type		*Event corresponding to the end of charge*
	Value		*Value of the variable*
	Time		*Time of the event*
Start of discharge criterion	Type		*Event corresponding to the start of discharge*
	Value		*Value of the variable*
	Time		*Time of the event*
End of discharge criterion	Type		*Event corresponding to the end of discharge*
	Value		*Value of the variable*
	Time		*Time of the event*
Test Conditions	HTF flow rate charge		*Variable used to measure HTF flow rate*
	HTF flow rate discharge		*Variable used to measure HTF flow rate*
	Inlet specific enthalpy during charge		*Variable used to calculate specific enthalpy*
	Inlet specific enthalpy during discharge		*Variable used to calculate specific enthalpy*
	Outlet specific enthalpy during charge		*Variable used to calculate specific enthalpy*
	Outlet specific enthalpy during discharge		*Variable used to calculate specific enthalpy*
Thermal losses	Can be estimated from this dataset? (Y/N)		
	If Yes, method used*		
Auxiliary power consumption	Do we monitor this? (Y/N)		
	if Yes, considered devices		*e.g. pumps, fans, compressors, heat tracing, mixers…*

* Thermal losses	A) Isothermal method	*stationary heat losses*
	B) Cool-down method	*stationary heat losses*
	C) Energy balance at constant temperature and flow rate	*dynamic heat losses*
	D) Comparison between two standardized charging-discharging tests	*stationary heat losses*

** If possible, defined as a function of the temperature

6. Unified testing procedure

The following procedure is a kind of “unified test” that can be used to estimate five performance indicators: heat losses, storage capacity, discharging time, storage efficiency, utilization rate, and storage exergy efficiency.

1. Discharge the TES at rated mass flow rate and minimum temperature until a steady-state end of discharge state in observed;
2. Dynamic heat losses (flow going up) can be measured at this moment;
3. Charge the TES at rated temperature until a steady-state end of charge state is observed (other end of charge criteria could be used, provided they are clearly described);
4. Dynamic heat losses (flow going down) can be measured at this moment;
5. Discharge the TES at rated mass flow rate and minimum temperature until a steady-state end of discharge state is observed;
6. From 1 to 3, the total energy transfered to the storage can be calculated Q_{charge}
7. From 1 to 3, the charging time can be calculated.
8. The accumulated energy extracted can be calculated as a function of outlet temperature from 3 to 5 $Q_{discharge}(T_{out,discharge})$
9. From 3 to 5, also discharging time canbe calculated.
10. The Storage Capacity equals the $Q_{discharge}(T_{out,discharge})$
11. The Utilization Rate can be calculated also as a function of $T_{out,discharge}$

$$UR(T_{out}) = \frac{\mathrm{Q_{discharge}}\left(T_{out,discharge}\right)}{\text{Theoretical storage capacity}}$$

12. The Storage Efficiency can be calculated as a function of outlet temperature

$$\eta_{\mathrm{TES}}(T_{out}) = \frac{\mathrm{Q_{discharge}}\left(T_{out,discharge}\right)}{\mathrm{Q_{charge}}}$$

7. Application to simulation results

With the exception of thermal losses the described KPIs can be also calculated in a 1D model. Moreover, other conditions besides full charge and discharge can also be tested. Thus, some of these KPIs and also some secondary KPIs can be calculated as a function of Tin or Tout temperature, namely storage capacity and storage level, utilization rate, charging and discharging time, mean thermal power, storage efficiency and storage exergy efficiency .

Depending on the chosen method, the thermal losses KPIs are not directly available in 1D model. Due to the nature of these KPIs, namely, to the fact that these KPIs foresee that temperature variations can exist in radial axis, they may need, at least, a 2D model to be calculated accurately. With regard to the auxiliary power consumption, usually TES devices models do not include auxiliary equipament, therefore this KPI cannot be calculated using this type of models. To calculate auxiliary power consumption a full system model must be set in place.

8. Specific issues about Particle storage systems

In particle TES systems, it is possible to heat particles at higher temperatures than the common TES heat transfer fluids can withstand. With the motivation of reaching higher temperatures either to supply high temperature industrial heat or to increase the thermodynamic cycle efficiency, solar particle receivers are under development. Similar to other CSP systems, if the receiver is for a power plant, peak hours of the electricity price after sunset is targeted for electricity generation, requiring storage of the hot particles. Hot particles coming from the receiver can be stored in an insulated tank for later use. This approach constitutes a very simple TES system.

For a particle TES system, the charging process is simply putting hot particles in the TES tank. During the time between charging and discharging the TES, some heat loss may occur through the insulation of the tank. Discharging of the particle TES can be done with two different approaches:

- Fluidizing the hot particles with air or any other gas as HTF is a viable option for discharging a particle TES. As an alternative to air, supercritical CO_2 is getting popular. In this case, an important parameter is the fluidization velocity. Since the particles need to be kept fluidized during the discharging process, the control of fluidization velocity and related pressure regulation are essential aspects of discharging a particle TES with a fluidized bed. After recovering heat, cold particles need to be sent to the receiver at the end of the discharging process.

- Draining hot particles through a heat exchanger to heat a heat transfer fluid in pipes is also considered a viable discharging process of a particle TES. In this case, good enough contact between the hot particles and the heat transfer surface is essential because the primary heat transfer mechanism is particle-wall conduction.

In the case of a particle TES system, when compared with common TES systems with a heat transfer fluid, there are many similarities together with some differences in key performance indicators:

- Theoretical storage capacity is calculated using only the thermal mass of hot particles that can be stored. Theoretically, the mass of particles that can fit into the tank is known and the maximum allowable temperature depends on the tank materials and the receiver.
- Storage capacity can be determined during discharging of the particle TES. For that, inlet and outlet states of the HTF can be used. Experimental determination requires weighing the stored particles and measuring inlet and outlet temperatures of the HTF outside of the tank.
- Utilization rate can be calculated by dividing the storage capacity to the theoretical storage capacity.
- Discharging time again can be calculated. The cut-off of the discharging process depends on the lowest beneficial HTF temperature.
- Thermal losses can be calculated by measuring the initial and final temperatures of the particles for a certain period of storage. When HTF passes through the tank for a short period of time, the measured outlet temperature reflects the average temperature of the particles.
- Storage efficiency can be calculated as in Section 4.5.
- When the particles are fluidized uniform temperatures are obtained thus there is no stratification in particle TES systems, and there is no need for stratification if the heat transfer fluid can reach to all particles. Storage exergy efficiency should not be a concern.

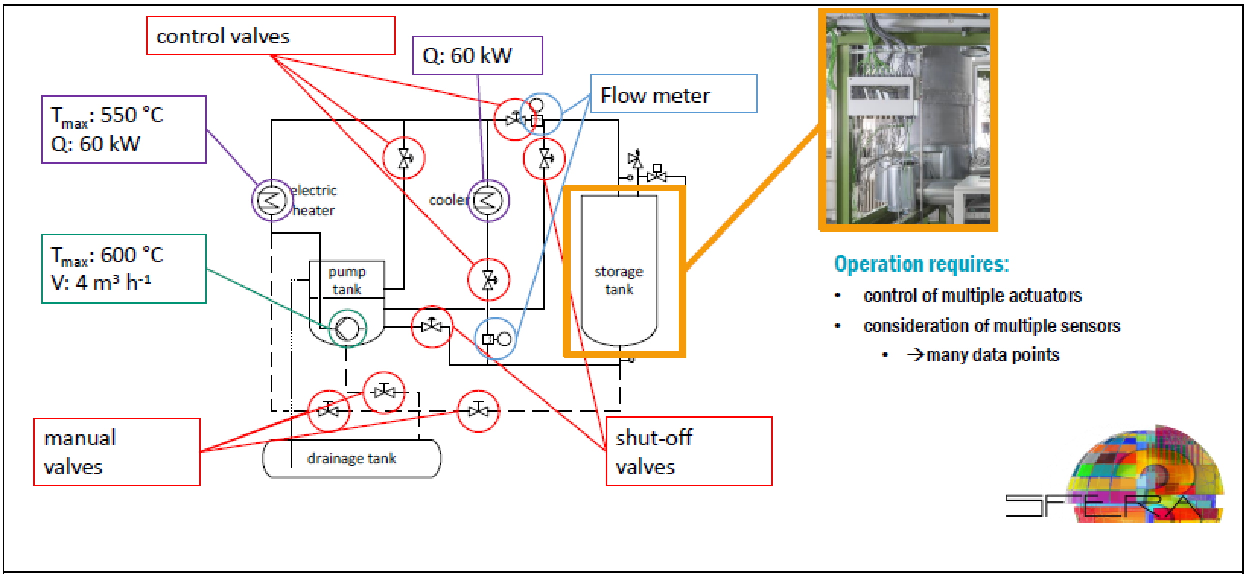
Auxiliary power consumption can be very high, and it can be calculated or measured.

9. Case studies

The following case studies have been presented at IRES 2022 conference. Complete presentations will be made available on the SFERA III webpage.

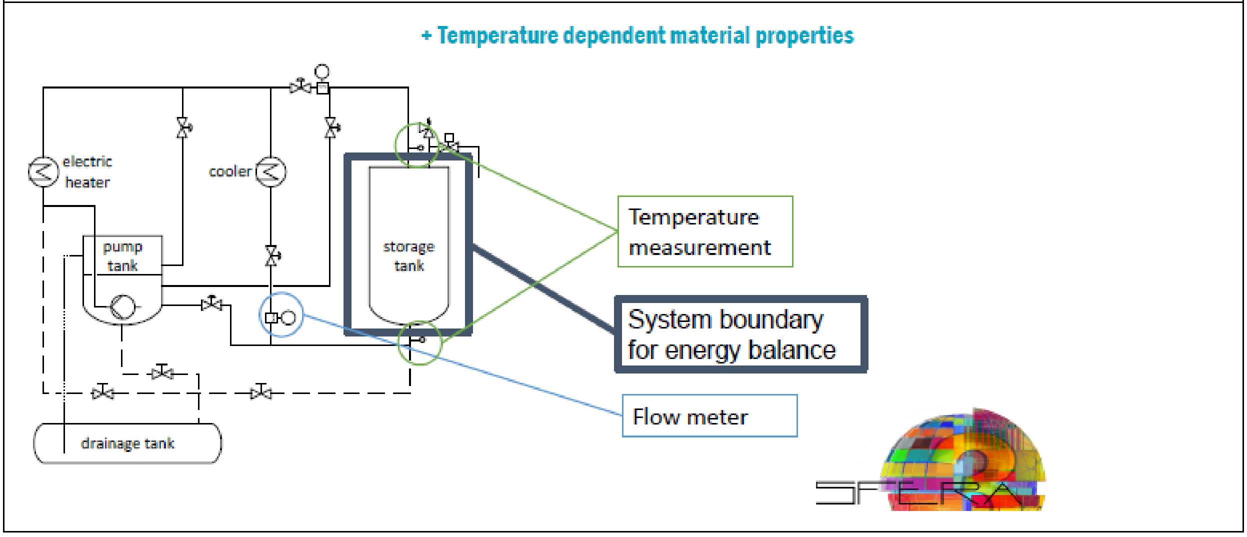
9.1. Case study on Sensible Heat Storage system

Considered prototype: Molten salt thermocline storage from Fraunhofer ISE

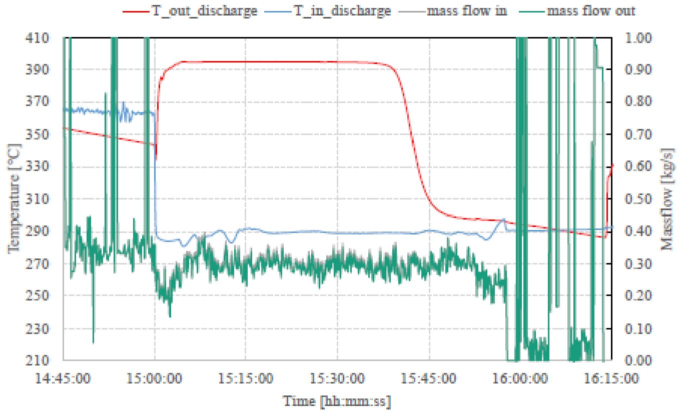


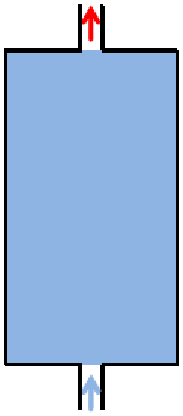
Operation requires:

- control of multiple actuators
- consideration of multiple sensors
  - →many data points

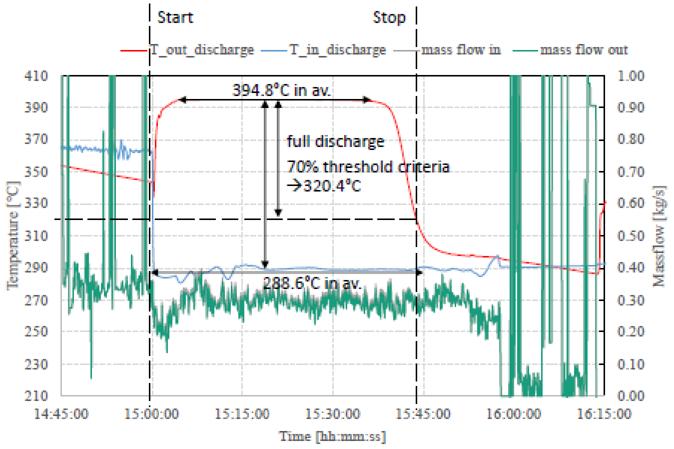


+ Temperature dependent material properties





Cold molten salt



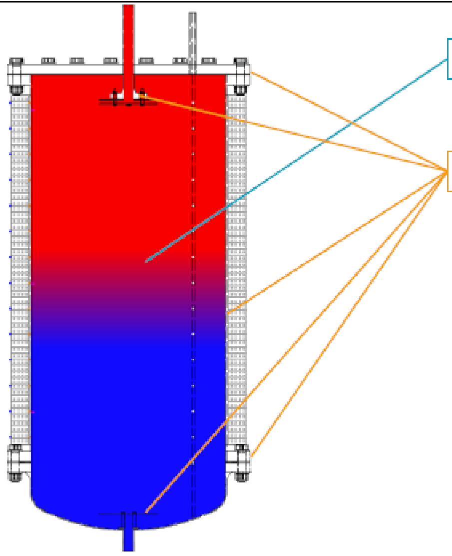
Evaluation of utilization rate:

$$\text{Utilization rate} = \frac{SC\ (\text{Storage capacity})}{SC_{th}(\text{Theoretical } SC)}$$

$$SC = \int_{t_{initial\ conditions}}^{t_{full\ discharge\ conditions}} (\dot{m}_{out}h_{out} - \dot{m}_{in}h_{in})\overset{?}{\boxed{dt}}$$

$$= 28.9 \text{ kWh}$$

$$SC_{th} = \boxed{V * \sum_{Materials}}(\rho_{ch} * h_{ch} - \rho_{dch} * h_{dch})$$



Volume of Salt 0,394 m^3

(including convex end)

Mass of steel 293,3 kg

- Not including thermal insulation

Evaluation of utilization rate:

$$\text{Utilization rate} = \frac{SC\ (\text{Storage capacity})}{SC_{th}(\text{Theoretical } SC)}$$

$$SC = \int_{t_{initial\ conditions}}^{t_{full\ discharge\ conditions}} (\dot{m}_{out} h_{out} - \dot{m}_{in} h_{in}) dt$$

$$= 28.9\ \text{kWh}$$

$$SC_{th} = V * \sum_{Materials} \overset{@\ rated\ conditions}{(\overbrace{\rho_{ch} * h_{ch}} - \overbrace{\rho_{dch} * h_{dch}})}$$

$$= 33.3\ \text{kWh (87\% salt and 13\% Steel)}$$

→ Utilization rate = 86.9 %

For fair and reproducible evaluation consent on calculation procedure and definitions is required.

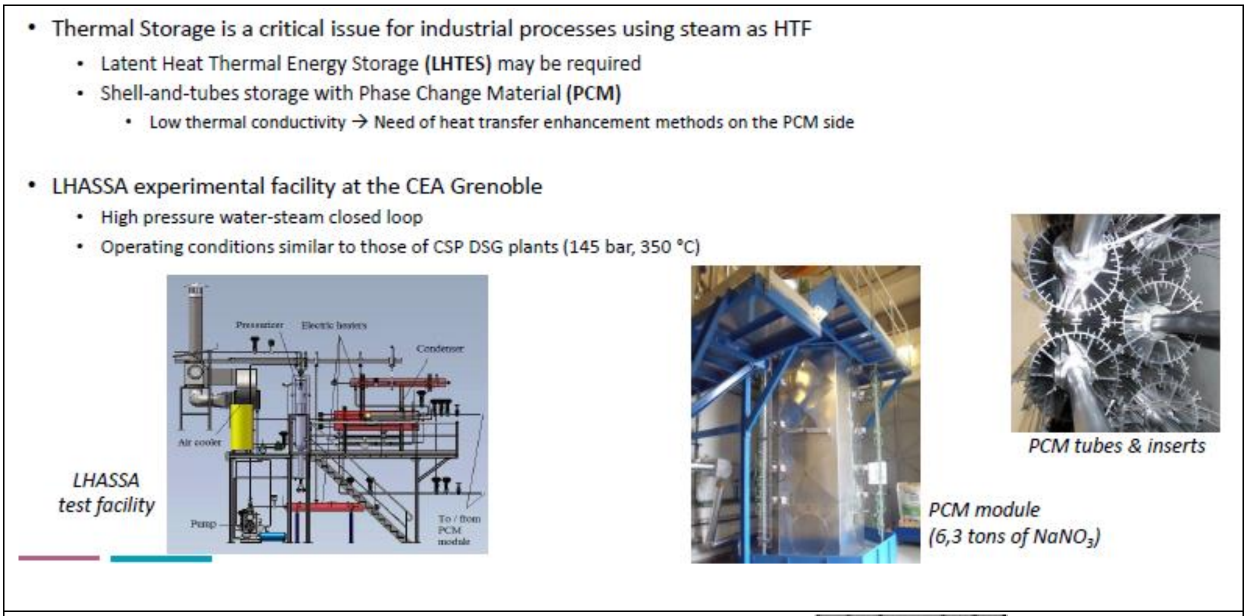
Besides this:

- Clear statement what has been considered as “rated conditions” (Not obvious as temperature in experimental conditions is not constant)
- Clear statement on definition of period of time that was evaluated and why (relevant valve control for operation modes, threshold temperatures, etc.)
- Provide the properties as used for the calculation (e.g. directly give temperature dependent enthalpy and not the thermal capacity, that needs to be integrated)

9.2. Case study on Latent Heat Storage system

Considered prototype: PCM steam storage from CEA Grenoble.

These results are further presented and discussed in a recent paper (Garcia, 2022).

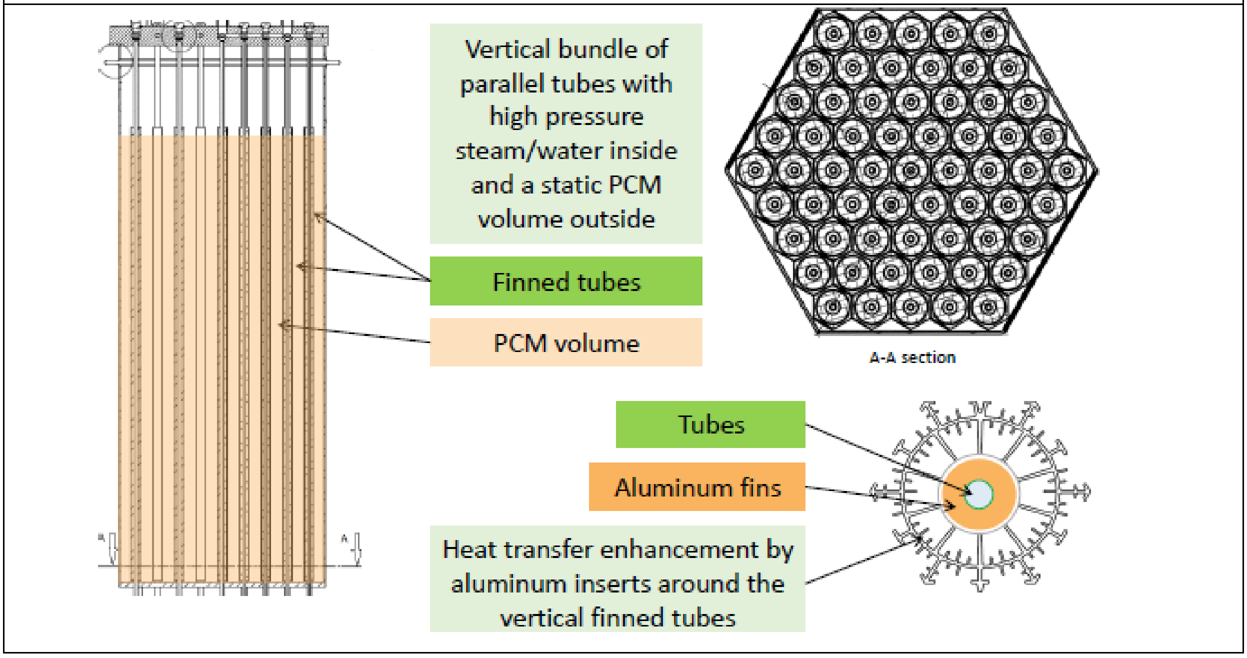


- Thermal Storage is a critical issue for industrial processes using steam as HTF
  - Latent Heat Thermal Energy Storage **(LHTES)** may be required
  - Shell-and-tubes storage with Phase Change Material **(PCM)**
    - Low thermal conductivity → Need of heat transfer enhancement methods on the PCM side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



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

Finned tubes

PCM volume

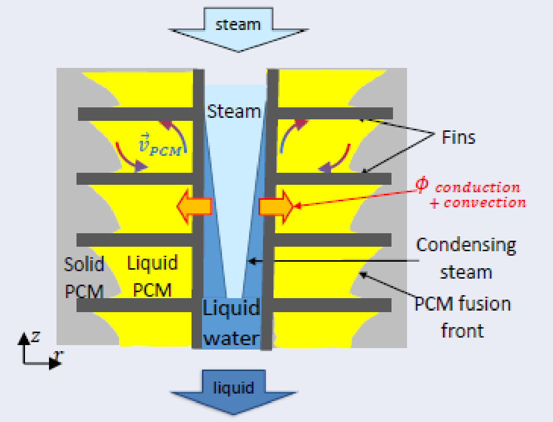
A-A section

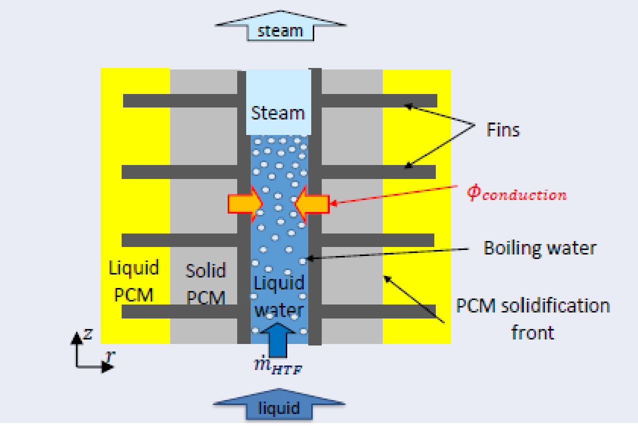
Tubes

Aluminum fins

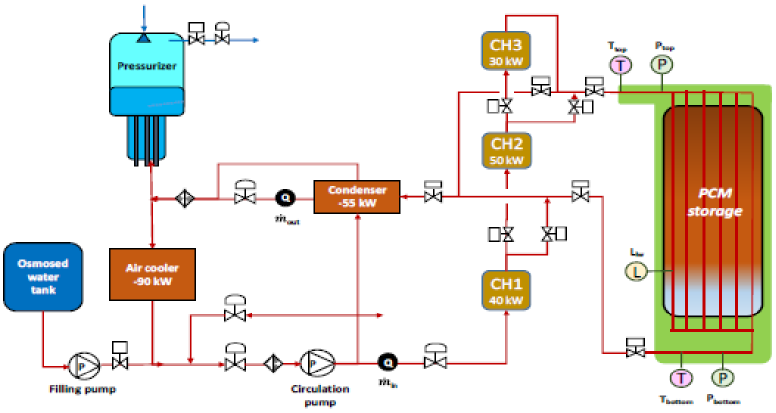
Heat transfer enhancement by aluminum inserts around the vertical finned tubes

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 $h_{in} = h_{bottom}$*

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%*

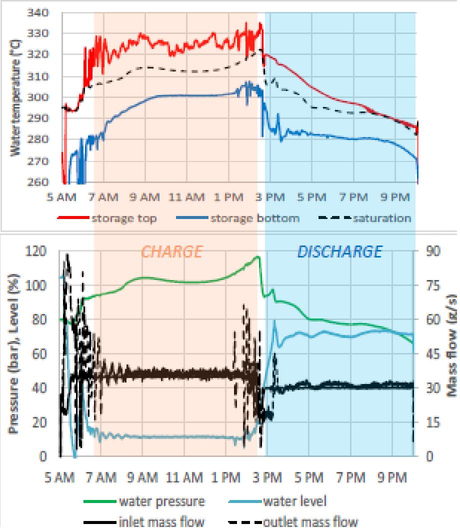
- **Complete charge and discharge close to rated conditions**
  - 17-hour duration
  - Sliding pressure
- Initial conditions: first cycle

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

- Operating conditions:

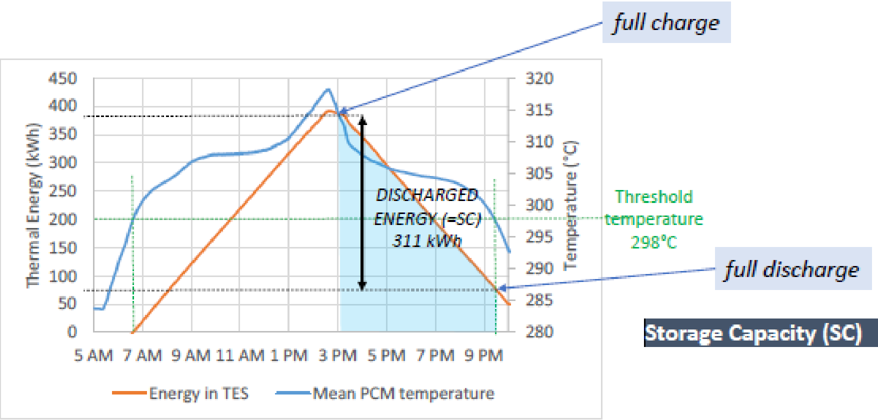
	Criterion	Threshold value	Time
Start of charge	Inlet steam temperature	$T_{sat} > T_{pc}$ (306 °C)	6:37 AM
End of charge	PCM temperature	All temperatures in PCM > 306 °C	2:37 PM
Start of discharge	Inlet water temperature	$T_{sat} < T_{pc}$ (306 °C)	2:50 PM
End of discharge	PCM temperature	$T_{mean} =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

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



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

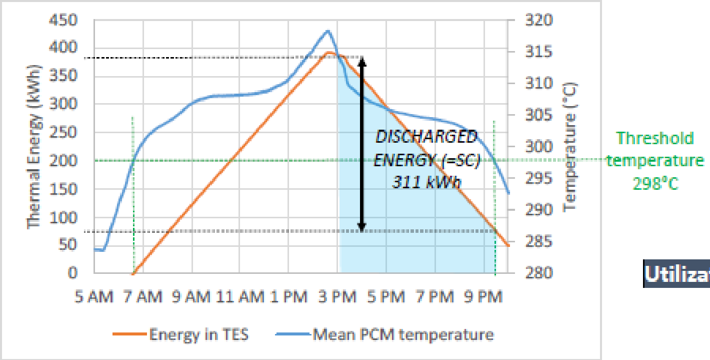
- Calculated on HTF side
  - $SC = \int_{full\ charge\ conditions}^{full\ discharge\ conditions} [\dot{m}_{out} h_{out} - \dot{m}_{in} h_{in}] dt$



Storage Capacity (SC)	**311 kWh$_t$**

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

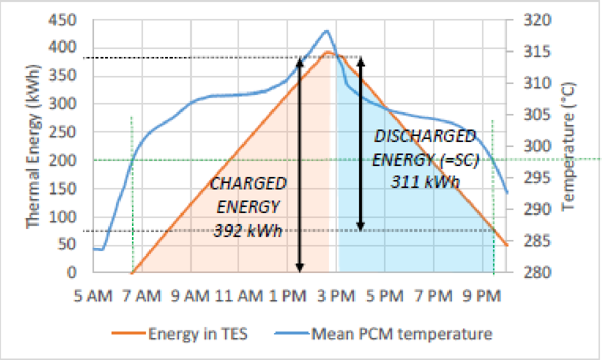
- $UR = \frac{SC}{SC_{th}}$
- With SC calculated on HTF side
- With SC_{th} calculated on storage materials side



Utilization rate (UR)	**82%**

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

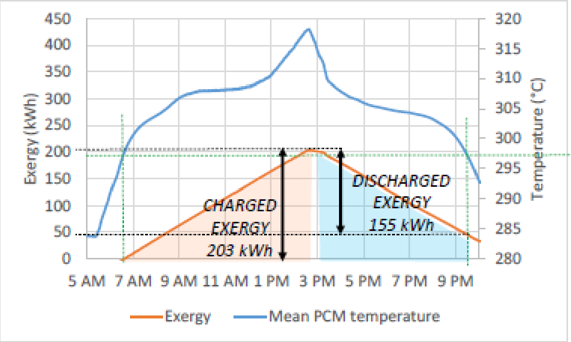
- $\eta_{TES} = \frac{Q_{discharge}}{Q_{charge}} = \frac{Q_{HTF\_out}}{Q_{HTF\_in}}$ (In consecutive charge and discharge)
- η_{TES} should be estimated in « cycling conditions »
  - With storage conditions at the end of discharge equal to those at the beginning of charge



Storage efficiency (η_{TES}) 79%

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%

- **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

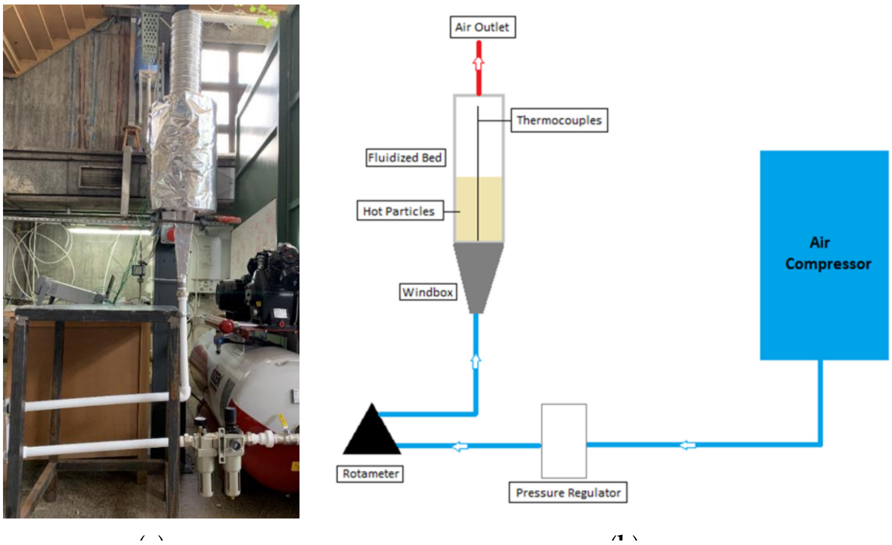
- **On the start / end criteria**
  - KPI are evaluated on the HTF side, but you sometimes need information from inside the tanks…
    - Concept of storage level
  - For an operator in an industrial plant, end of charge/discharge criteria will be system-related
    - e.g. temperature threshold, pressure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

9.3. Case study on Particle storage system

Considered prototype: particle storage tank from METU.

These results are further presented and discussed in a recent paper (Mehrtash, 2022).



Thermal experimental particle bed TES set-up for heating air with bubling hot particles during discharge

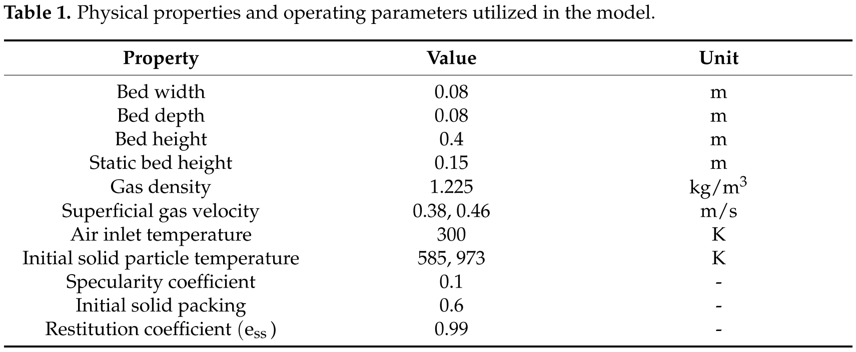


Table 1. Physical properties and operating parameters utilized in the model.

Property	Value	Unit
Bed width	0.08	m
Bed depth	0.08	m
Bed height	0.4	m
Static bed height	0.15	m
Gas density	1.225	kg/m^3
Superficial gas velocity	0.38, 0.46	m/s
Air inlet temperature	300	K
Initial solid particle temperature	585, 973	K
Specularity coefficient	0.1	-
Initial solid packing	0.6	-
Restitution coefficient (e_{ss})	0.99	-

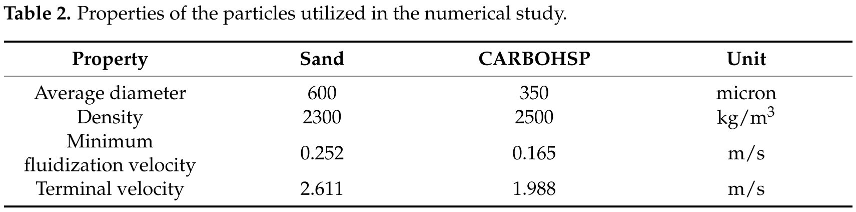


Table 2. Properties of the particles utilized in the numerical study.

Property	Sand	CARBOHSP	Unit
Average diameter	600	350	micron
Density	2300	2500	kg/m^3
Minimum fluidization velocity	0.252	0.165	m/s
Terminal velocity	2.611	1.988	m/s

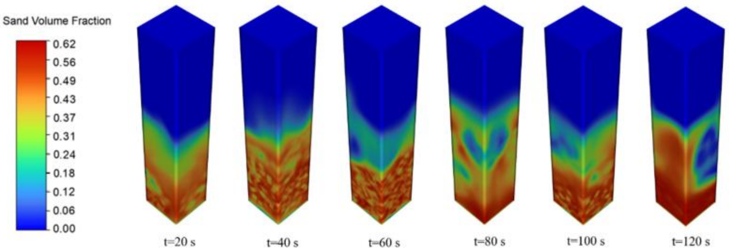
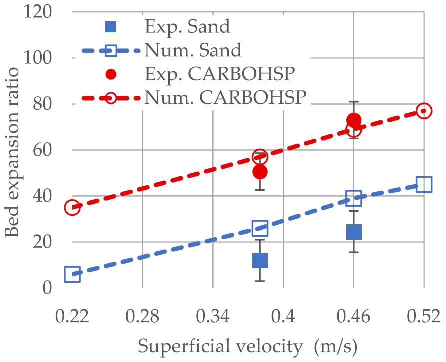


Figure 5. Contours of sand volume fraction at different times.



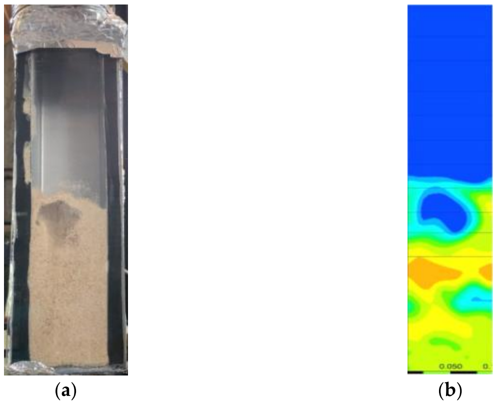
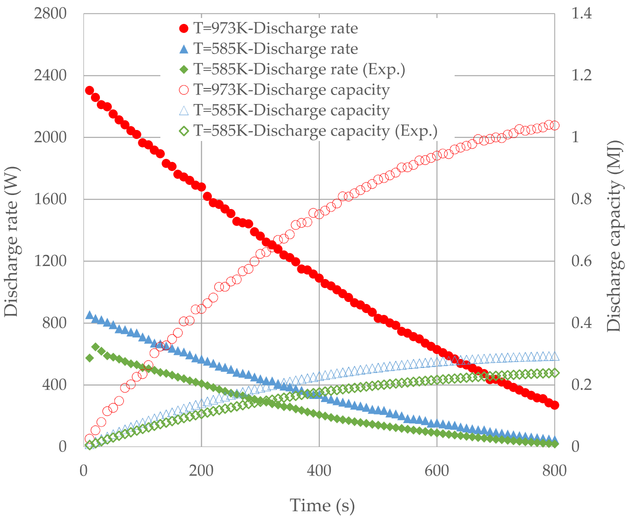


Figure 6. Typical bubble formation in **(a)** experimental and **(b)** numerical st



Discharge Capacity:

$$Q_{discharge} = \int_{\text{initial conditions}}^{\text{full discharge conditions}} \left(\dot{m}_{out} h_{out} - \dot{m}_{in} h_{in}\right) dt$$

Given that $h = \int_{T_0}^{T} c_p(T)dT$, and based on the mass balance equ $\dot{m}_{out} = \dot{m}_{in} = \dot{m}$, Equation (6) can be rewritten as:

$$Q_{discharge} = \dot{m} \times \Delta t \times \sum_{n=1}^{N} \left(T_{out} c_{p,out} - T_{in} c_{p,in}\right)$$

Discharge Rate:

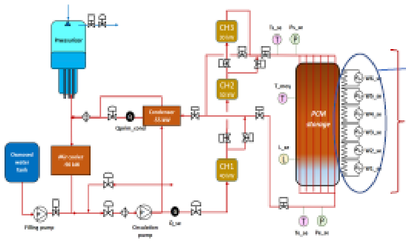
$$\text{Discharge rate} = \frac{Q_{discharge}}{\Delta t}$$

The variations in discharge rate and discharge capacity over time.

9.4. Case study on Thermal Losses

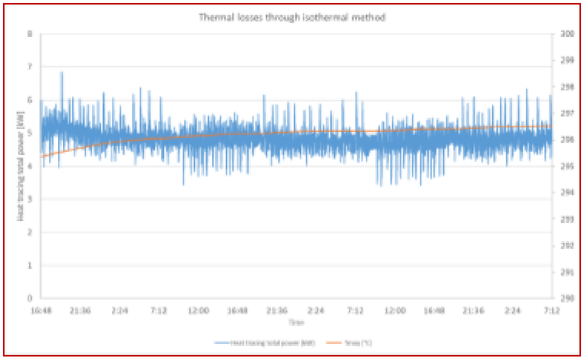
Considered prototypes: PCM steam storage from CEA and Concrete storage from ENEA

Experimental results from a pilot scale latent heat thermal energy storage for DSG power plants (CEA)



Isothermal method

Electrical power of the heat tracing at different section, calculated from voltage measurement

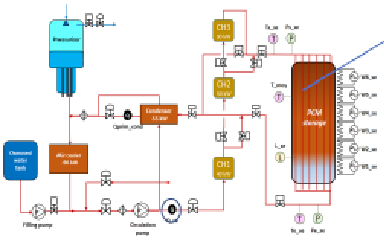


Data of the heat tracing powers were available at: 10 s

Average: 4.871 kW ⟶ Losses offset with heat tracing

Theoretical storage capacity: 379.6 kWh

Experimental results from a pilot scale latent heat thermal energy storage for DSG power plants (CEA)



Cool down method

Rate of change of the mean tank temperature. This is achieved by turning off the power supply systems (e.g. immersion heaters and electrical heat tracing) and via monitoring and recording the tank temperature on storage media side over a defined period.

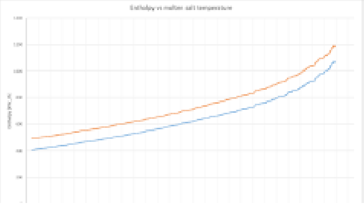
6 Volume fractions attributed to each measurement level

7 Volume fractions attributed to each measurement level assuming homogeneous T

Thermal losses assessment as enthalpy difference between two consecutive moment divided for the related time.

Enthalpy per each datum and level of the storage system including PCM (6330 kg), tubes (3795 kg) and aluminium inserts (1725 kg). In addition, it is possible to include also the shell (1137 kg), top (293 kg) and bottom (293 kg) of the tank.

Total enthalpy assessment for each datum

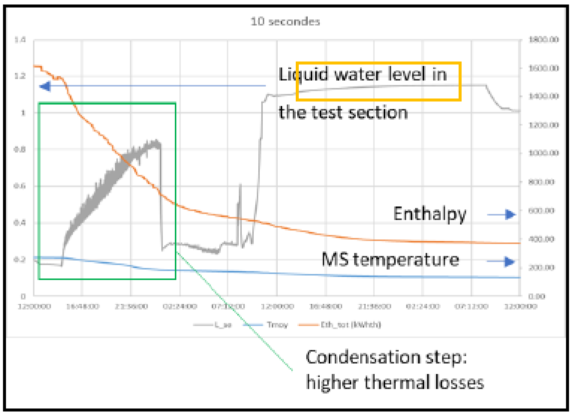


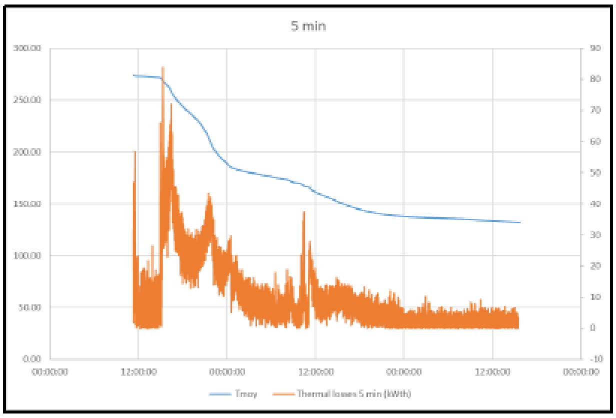
Data of the in/out temperatures and flows were available at: 10 s, 10 minutes and 1 hour.

Average: 2.11 kW or 2.41 kW including metallic shell, top and bottom (in the range 251-241 °C)

Theoretical storage capacity: 379.6 kWh

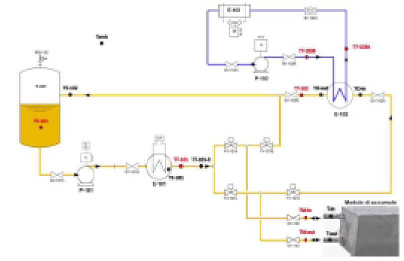
Experimental results from a pilot scale latent heat thermal energy storage for DSG power plants (CEA)

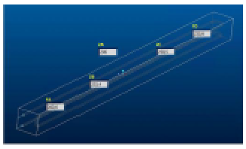


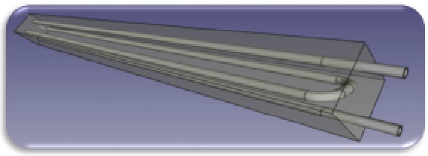


Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

Data collected by this facility allow to calculate thermal losses using the methods: cool down, energy balance at constant temperature, and comparison between two standardized charging-discharging tests.







A concrete storage module (220x220x300 mm) connected to the facility for handling, worming and cooling the HTF is composed of a concrete mixcture.
The HTF (Thermal oil) flows into an integrated stainless steel heat exchanger (L: 12 m; Φ_i: 13 mm).

Room pressure, HTF up to 320°C, 21 kW heating/cooling.

Flowmeter using Coriolis effect

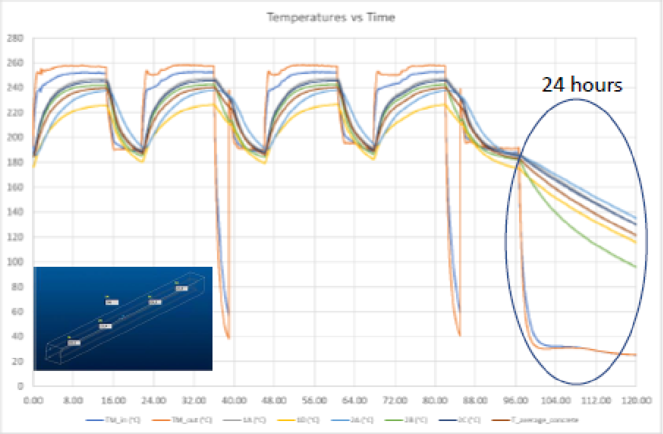
Magnetic drive pump

4.1 kWh_{th}, 347 kg of concrete, 6.5 kg of heat exchanger and 381 kg of insulation (rock wool 400 mm)

5 thermocouples at different positions in the module and 12 thermocouples installed on the system for reading the temperature HTF; those identified in red are internal and directly read the fluid temperature.

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

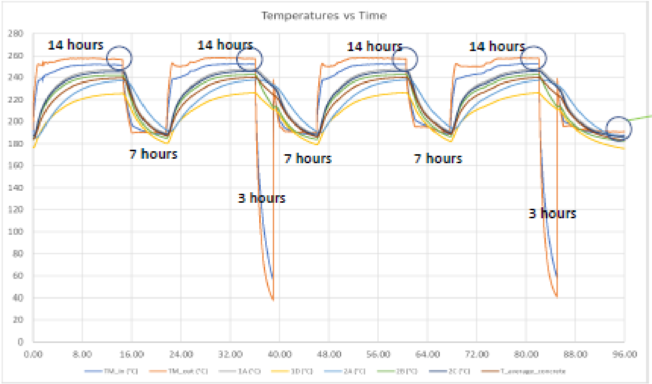
Cool down method



Average at 182-120 °C (cool-down) [kW] about 24 hours	
Initial time	14/6/22 7:18
Final time	15/6/22 7:06
Duration [s]	85704
Concrete initial T average [°C]	182.8
Concrete final T average [°C]	120.6
Metal initial T average [°C]	186.4
Metal final T average [°C]	73.0
Insulation initial T average [°C]	104.8
Insulation final T average [°C]	73.9
Thermal losses [kWh] (only concrete)	-3.79
Thermal losses [kW] (only concrete)	-0.16
Thermal losses [kWh] (concrete+exchanger)	-3.89
Thermal losses [kW] (concrete+exchanger)	-0.16
Thermal losses [kWh] (concrete+exch.+ins)	-7.26
Thermal losses [kW] (concrete+exch.+insulation)	-0.3

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

Energy balance at constant temperature



TM_in (°C)	TM_out (°C)
189.7	191.4
189.7	191.3
189.7	191.4
189.7	191.3
189.7	191.3
189.7	191.3
189.7	191.3
189.7	191.3
189.7	191.3
189.5	191.1

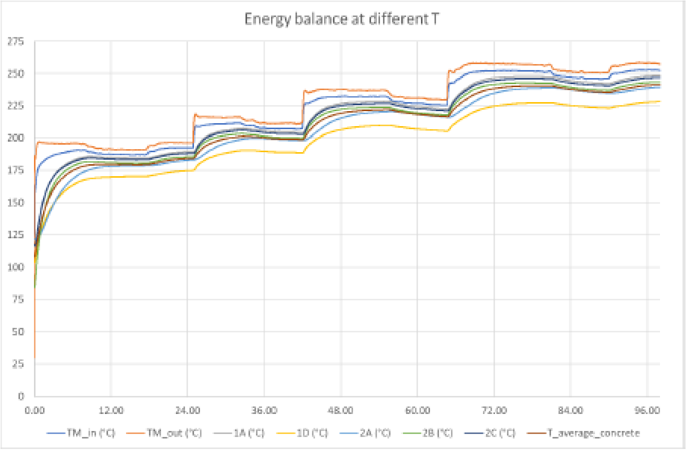
Energy balance between inlet and outlet specific enthalpies on HTF side at constant inlet conditions after stabilization of steady-state temperature is calculated.

Energy balance method 253 °C [kW] 1st charge	0.66
Energy balance method 253 °C [kW] 2nd charge	0.69
Energy balance method 253 °C [kW] 3rd charge	0.69
Energy balance method 253 °C [kW] 4th charge	0.69
Energy balance method 193 °C [kW] final discharge	0.37

It is very important the T sensor calibration and their proper contact with the HTF

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

Energy balance at constant temperature

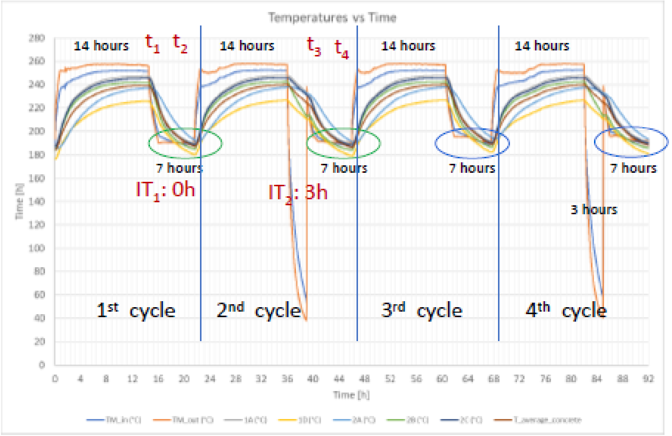


Energy balance between inlet and outlet specific enthalpies on HTF side at constant inlet conditions after stabilization of steady-state temperature is calculated.

Energy balance method 200 °C [kW] 1st charge	0.46
Energy balance method 220 °C [kW] 2nd charge	0.49
Energy balance method 240 °C [kW] 3rd charge	0.61
Energy balance method 258 °C [kW] 4th charge	0.65

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)

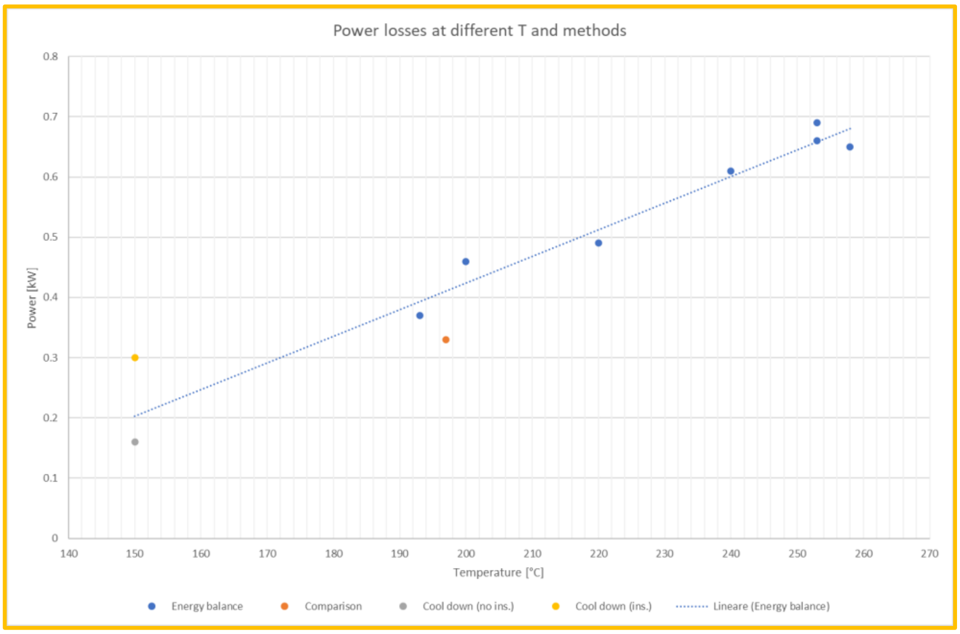
Comparison between two standardized charging-discharging tests



It compares the discharge energy on HTF side from two standardized charging-discharging tests with different idle time between end of charge and beginning of discharge.

Power losses [kW] (Comparison method)	T average concrete [°C]	Discharge energy [kWh]	Thermal losses [kW]
Discharge energy 1st cycle °C [kJ] after 0 min idle	195.83	-6667	
Discharge energy 2nd cycle [kJ] after 180 min idle	196.34	-3067	
Difference discharge energy [kJ]		-3600	-0.33
Discharge energy 3rd cycle °C [kJ] after 0 min idle	198.15	-5919	
Discharge energy 4th cycle [kJ] after 180 min idle	198.30	-2465	
Difference discharge energy [kJ]		-3454	-0.32

Experimental results from a pilot scale sensible heat thermal energy storage using concrete (ENEA)



Conclusions:

- Thermal energy losses are an important KPI evaluable by 4 different methods;
- These methods can be applied, if the prototype is equipped with the proper instrumentation & controls and the tests were carried out using the appropriate modalities;
- Two prototypes were here chosen because of more than 1 method could be applied:
  LHTTS (CEA): Latent heat Storage for isothermal (IM) and cool-down (CD) methods
  HS by concrete (ENEA) : Sensible heat Storage → cool-down, energy balance (EB) and comparison methods (CM);
- Cool–down method is the only one that needs T sensors installed inside the HSM;
- The results of CD, EB and CM are very similar, while IM is a little higher.

References

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