



TASK 58 ANNEX 33

MATERIAL AND COMPONENT DEVELOPMENT FOR THERMAL ENERGY STORAGE

Executive Summary of the Final Report

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ABOUT THIS REPORT

To **International Energy Agency**
Executive Committee of the Energy Storage technology col-
laboration programme (ES TCP).

Presented by **Bavarian Center for Applied Energy Research (ZAE Bayern)**

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LIST OF ABBREVIATIONS

DSC	Differential Scanning Calorimetry
IEA	International Energy Agency
PCM	Phase Change Material
T58A33	SHC Task 58 / ES Annex 33
TCM	Thermochemical Material
TCP	Technology Collaboration Programme (of the IEA)
TES	Thermal Energy Storage

KEY MESSAGES

GENERAL

- Collaboration in the IEA Task/Annex between materials experts and application experts leads to improved understanding and therefore accelerates development.
- Standards for measurement and for reporting are prerequisite for constructive discussions and rapidly addressing challenges and advancing TES technologies.

SUBTASK 1: ENERGY RELEVANT APPLICATIONS

- A large number of relevant application exists for compact thermal energy storage.
- Standardized reference conditions can be defined for the building sector. For industrial applications, however, the diversity of processes makes it very difficult!

SUBTASK 2: DEVELOPMENT AND CHARACTERIZATION OF IMPROVED PHASE CHANGE MATERIALS / THERMOCHEMICAL MATERIALS

- A number of innovative and improved materials were developed and continuously are being developed, tested in Subtask 3 and introduced in components in Subtask 4.
- Developed characterization methods are the basis for material evaluation and comparison and as well for the database input.
- The material properties cover not only the technical performance, but also questions like stability and compatibility.

SUBTASK 3: MEASURING PROCEDURES AND TESTING UNDER APPLICATION CONDITIONS FOR PHASE CHANGE MATERIALS / THERMOCHEMICAL MATERIALS

- Only testing under application conditions helps identifying the appropriate material for an actual application.
- The actual storage capacity and material stability have to be tested under realistic conditions and requirements.

SUBTASK 4: COMPONENT DESIGN FOR PHASE CHANGE MATERIALS / THERMOCHEMICAL MATERIALS

- Identification of component parameters is necessary to enable the comparison of compact storage concepts.
- The reachable charging/discharging power is strongly influenced by the component design, where the interaction of the storage material with the component is crucial.

MAIN RESULTS IN A NUTSHELL

The goal of Annex 33 is to support an application-oriented development of innovative and compact thermal energy storage materials: Phase Change Materials (PCM) and Thermochemical Materials (TCM). This includes, first, the characterization of a new material concerning its properties like heat of fusion or heat of reaction, specific heat, thermal conductivity, and others. In a second step, the material has to be tested under reference application conditions. These conditions shall be identified for energy relevant applications in a separate approach. The third step focuses on the interaction between the storage material and the storage component, and mainly with the heat and mass transfer performed in the component or reactor. Thereby, first results towards a reliable power and energy density can be deduced.

Subtask 1: “Energy Relevant Applications for an Application-oriented Development of Improved Storage Materials”:

The energy density of a storage material or its specific storage capacity – energy stored per mass or volume – is not a material property! It is strongly depending on the operation conditions during charging and discharging. Therefore, the testing of novel storage materials has to be performed under operation conditions given by relevant applications. These operation conditions have to be identified.

Energy relevant applications for thermal energy storage systems can be described by their impact on the energy system. The following fields of applications were listed by the participants:

- Industrial batch processes and peak shaving applications
- Heating and cooling for single family households (HVAC systems in the building sector)
- Combined heat and power systems
- District heating systems

The most important parameters for the evaluation of a latent or thermochemical storage processes are the temperatures involved. By defining just these temperatures the achievable storage capacity can be experimentally quantified. An approach using 2/4 temperatures for PCM/TCM was elaborated. The operation temperatures for a number of actual applications were collected and analysed. For building applications, reference conditions seem to be available. For applications like combined heat & power, district heating, and especially industrial applications, the definition of a set of standard operation temperatures is very difficult or even impossible. The diversity of the actual process parameters is to vast.

Subtask 2: “Development and Characterization of Improved Materials”

In total, 20 different Phase Change Materials (PCM) were developed or investigated by the experts. The focus of the survey was on the comparison of the melting enthalpies, melting temperatures, and the degree of supercooling of the PCM. PCM with melting temperatures between $-20\text{ }^{\circ}\text{C}$ and $+180\text{ }^{\circ}\text{C}$ and melting enthalpies up to 300 kJ/kg on material level were investigated.

Round robin tests on the PCM RT70HC (a paraffin) were performed to develop a procedure for measuring thermal diffusivity via laser flash method. Especially the way of preparing the specimen and the appropriate adjustment of the laser pulse energy turned out to have a significant influence on the measuring accuracy.

In order to establish a common wording of relevant phenomena in the context of PCM, a Wiki has been started. Experts have worked on definitions and explanations of terms such as nucleation temperature, supercooling, specific heat determination via DSC etc. The PCM Wiki is open for everyone to add further entries.

The databases for PCM and Thermochemical Materials (TCM) have been maintained and extended to add further material data, for example viscosity measurements. Material properties for PCM and TCM, partly “novel” materials, have been measured and uploaded to the databases.

The development of improved TCM included sorption materials (micro/mesoporous solids and liquids), chemical reactions (salt hydrates and metal oxides/hydroxides), and combinations of both (zeolites/graphite + salt hydrates/metal oxides). Sorption materials with desorption temperatures between 80 °C and 140 °C and desorption enthalpies up to 2,200 kJ/kg on material level were investigated. Chemical reactions with reaction temperatures up to 800 °C showed reaction enthalpies up to 1,500 kJ/kg on material level.

Subtask 3: “Measuring Procedures and Testing under Application Conditions”

In the context of PCM testing under application conditions, a comparison of material properties of PCM in the lab environment and under application conditions was elaborated. Thereby, most input was collected for the properties degree of supercooling, phase separation, storage capacity, and long-term stability of PCM. A step further was taken in the case of long-term stability of PCM: Information on experimental devices to investigate the long-term stability of PCM were gathered. The experiments include tests on the stability of PCM over thermal cycling, on the stability of PCM with stable supercooling, and on the stability of Phase Change Slurries (PCS).

In the context of TCM testing under application conditions, measurement procedures for mass and enthalpy change with defined conditions for sorption materials and salt hydrates were developed. In addition, a measurement procedure for specific heat capacity measurements of salt hydrates was tested. Round robin tests showed a good agreement with respect to mass change among the participants. Both enthalpy change and specific heat capacity showed larger deviations and, thus, pointed to the necessity to proceed with standardizing measurement methods including sample preparation and handling. Based on the measured material properties of zeolite 13X, a scale-up procedure from material properties to lab scale was proposed.

Subtask 4: “Component Design for Innovative TES Materials”

To provide an overview on PCM component design, an inventory of heat exchanger concepts was done. Following this, a definition of performance for

PCM components in term of capacity and storage density was agreed upon. In order to be able to compare different PCM concepts in terms of power, a review on assessment approaches was carried out. Therefore, power-time curves upon charging and discharging were compared, preliminary performance parameters were defined, and a procedure based on a validated numerical model was proposed.

In the case of TCM, the starting point was a basic description of investigated TCM storage processes and their impact on the component design. In addition, an inventory of actual TCM component designs currently under investigation was elaborated. Thereby, a common graphical representation was used to classify component concepts as open or closed and fixed or transported systems. Further efforts were undertaken to identify a possible TCM performance degradation from lab-scale measurements to pilot installations. A “Do’s and Don’ts” paper in the context of TCM component design is currently in preparation.

1 EXECUTIVE SUMMARY

1.1 SHORT DESCRIPTION OF ANNEX 33

Past IEA SHC and ECES Tasks/Annexes, especially Task42/Annex24 and its successor Task42/Annex29, achieved substantial progress in the understanding of compact thermal storage materials and systems and created a strong basis of collaborating experts from both the field of materials and systems applications from a large number of countries, mainly in Europe and Japan. From these seven years of collaboration, it was concluded that a continuation is needed, especially in the further material development, materials characterisation techniques and component development.

Annex 33 tries to support an application-oriented development of innovative storage materials in three steps. The **first step** is the characterization of the new material concerning its properties like heat of fusion or heat of reaction, specific heat, thermal conductivity, and others.

In a **second step** the material has to be tested under identified reference application conditions. Following the findings of Annex 24 and 29, these conditions include 2 temperatures for PCM (charging and discharging temperature) and 4 temperatures or concentrations for TCM (temperature and reactant concentration at charging and discharging). After this testing, for the first time, a theoretical energy density can be derived because the energy density is not a material property, but a process depending value!

The **third step** focuses on the interaction between the storage material and the storage component, and mainly with the heat and mass transfer performed in the component or reactor. Thereby, first results towards a reliable power and energy density, which is now related to the mass and volume of the component, can be deduced.

1.1.1 OBJECTIVES AND SCOPE

OBJECTIVES

The key objectives of the joint Annex/Task are:

- Mapping and evaluating the TES application opportunities concerning the requirements for the storage material
- Development and characterisation of storage materials to enhance TES performance
- Development of materials characterisation procedures and a methodology for material testing under application conditions
- Development of components for compact thermal energy storage systems

SCOPE

This joint Annex/Task deals with advanced materials for latent and thermochemical energy storage: Phase Change Materials (PCM) and Thermochemical Materials (TCM).

It covers the material development, the characterization, and the testing under application conditions. Finally, it describes the interaction between material and the storage component and the expected storage performance of the innovative materials.

Because seasonal storage of solar heat for solar assisted heating of buildings is the main focus of the IEA-SHC TCP, this will also be a focus area of this task. However, because there are many more relevant applications for TES, and because material research is not and cannot be limited to one application only, this task will include multiple application areas.

1.1.2 ORGANISATIONAL STRUCTURE

The work of the Annex has been divided into 4 Subtasks. Two of the planned subtasks will concentrate on the material itself, its characterization, and the definition of testing procedures. Subtask 1 and 4 deal with the relation between the new material and the storage component and the actual application, respectively.

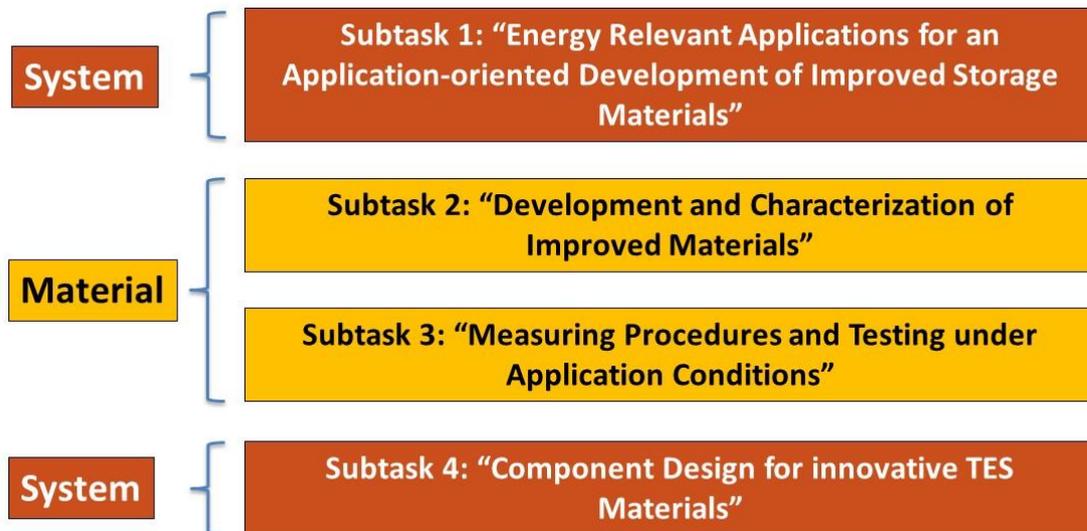


FIGURE 1.1-1: SUBTASK STRUCTURE OF ANNEX 33

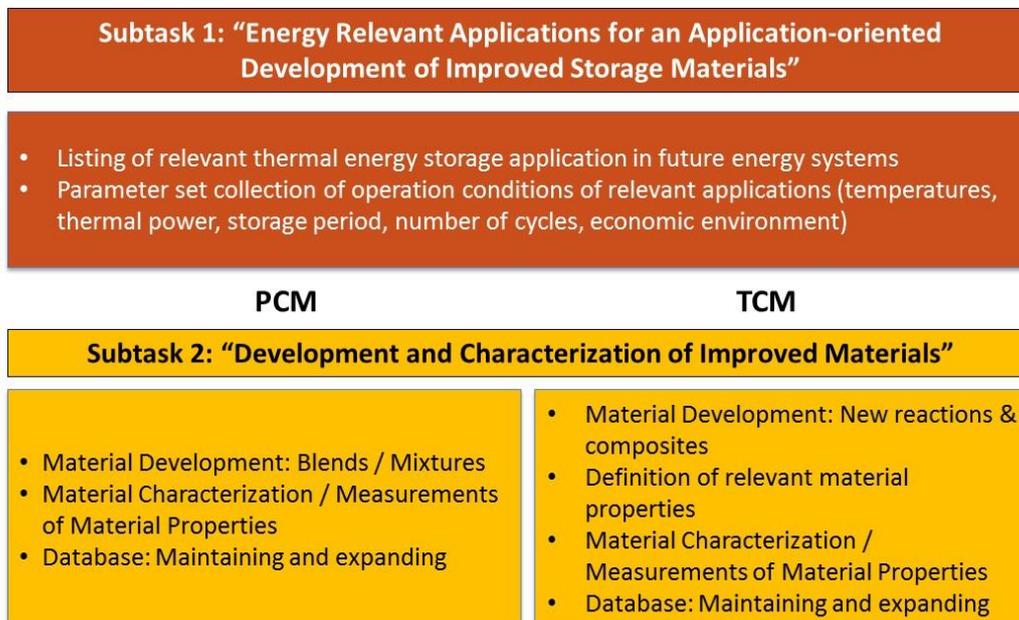
There are two reasons for a further breakdown of the materials and components subtasks into a PCM (-P) and a TCM (-T) track. The first is that, although there are a lot of common approaches for the two classes of materials, the basic materials principles differ and need a different approach. The second reason is that, with the relatively high number of experts, it is more effective to break down the work in a larger number of subgroups. However, this holds not for subtask 1, which is valid for both storage technologies. The following subtask division has been applied. Under each subtask (for the PCM and the TCM track), a subtask leader was appointed.



FIGURE 1.1-2: SUBTASK LEADERS OF THE PCM AND THE TCM TRACKS OF ANNEX 33

1.1.3 WORKPLAN

An overview of the activities within the Subtasks is shown below.



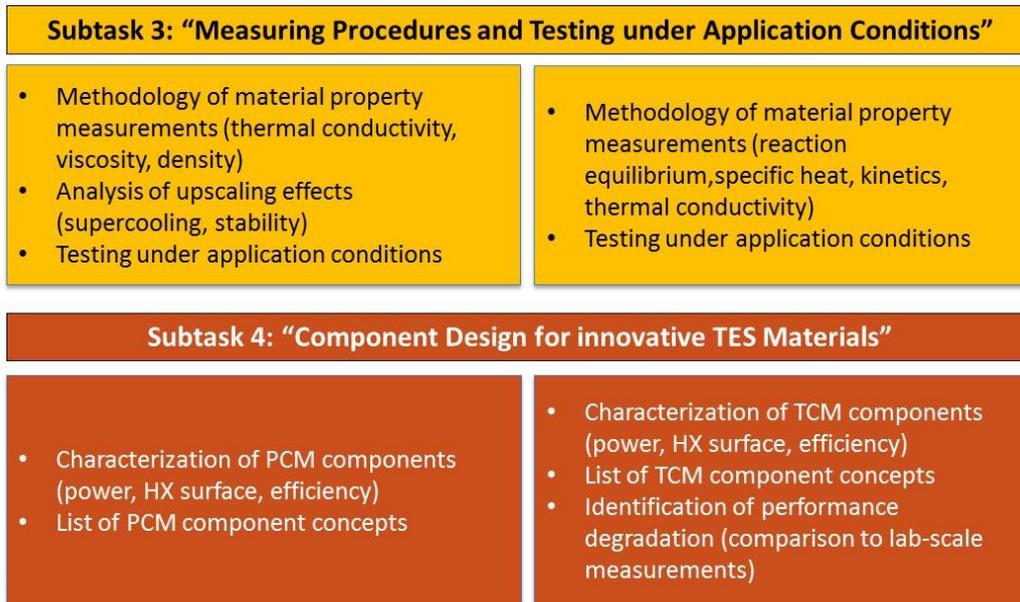


FIGURE 1.1-3: ACTIVITIES WITHIN THE SUBTASKS OF ANNEX 33

1.1.4 START AND END OF THE ANNEX

The activities of the joint Task/Annex started at 1 January 2017 and ended at 31 December 2019.

1.1.5 EXPERTS MEETINGS

The predecessor Task4224 and Task4229 covered a period of 7 years in which 14 Experts Meetings were held. The table below shows an overview of the expert meetings in Annex 33. Six experts meetings were held. The right column indicated the number of participants at a meeting.

Table 1.1-1: Expert meetings

#	Location	Country	Date	Participants
1	Lyon	France	April 5-7, 2017	64
2	Zurich	Switzerland	October 4-6, 2017	46
3	Ljubljana	Slovenia	April 9-11, 2018	45
4	Graz	Austria	October 1-2, 2018	42
5	Ottawa	Canada	May 1-3, 2019	43
6	Messina	Italy	October 9-10, 2019	42

1.1.6 STATUS OF PARTICIPATION

10 institutions from 8 countries participate officially in this Annex.

Table 1.1-2: Participating Countries

Country	Participant
Germany	ZAE Bayern
Germany	Fraunhofer ISE
Belgium	Univ. Mons
France	Univ. Bordeaux
Slovenia	NIC
Spain	Univ. Lleida
Spain	Univ. Zaragoza
Sweden	KTH
Switzerland	EMPA
Turkey	Çukurova Univ.

The list contains only the countries officially participating through the Energy Storage TCP. For example countries like Austria and Italy participated through the Solar Heating and cooling TCP in the beginning.

Overall more than 13 countries participated in the experts meetings and workshops.

1.2 SUMMARY OF SUBTASKS

1.2.1 SUBTASK 1 – ENERGY RELEVANT APPLICATIONS FOR AN APPLICATION-ORIENTED DEVELOPMENT OF IMPROVED STORAGE MATERIALS

THE APPROACH OF APPLICATION-ORIENTED DEVELOPMENT OF IMPROVED STORAGE MATERIALS

The energy density of a storage material or its specific storage capacity – energy stored per mass or volume – is not a material property! It is strongly depending on the operation conditions during charging and discharging. Therefore, it can be described as a process variable. The storage process is depending on the actual storage application. Parameters like the available charging temperature and the usable temperature at the consumer side are determined by the application.

The goal of this subtask is to provide a list of thermal energy storage applications relevant for our future energy system. The storage application sets the technical and economic environment of the storage system and defines the operation conditions. These conditions include available charging and required discharging temperatures, available and required thermal power in- and output, as well as the available reactant concentrations for the process in the case of thermochemical energy storage.

The list could also include parameters like the expected number of storage cycles, the predicted lifetime and the required system size. All these parameters can be utilized for integrated system simulations, which finally can give first estimations of performance improvement of the new storage materials.

This cross-cutting subtask was planned as an ongoing discussion forum, where the material designers meet the application engineers and, thus, the gap between these two groups could be bridged.

The actual approach is starting from defining relevant applications. In a next step these applications provide operation conditions. It has to be investigated whether the class of applications provides standard conditions or more individual energy storage solutions. The identified operation conditions are the basis of any application-oriented testing of novel thermal energy storage materials.

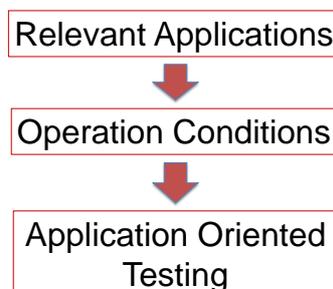


FIGURE 1.2-1: APPROACH OF SUBTASK 1 TOWARDS AN APPLICATION-ORIENTED TESTING

WHAT ARE ENERGY RELEVANT APPLICATIONS?

Energy relevant applications for thermal energy storage systems can be described by their impact on the energy system. This impact can be quantified with respect to the overall CO₂ emissions or to the final energy demand connected to this class of applications.

RELEVANCE BY STATISTICS

Looking at the statistical sectors – industry, private households, trade & commerce, and transport – the CO₂ emissions and final energy demand can be visualized. Figure 1.2-2 shows the different energy forms responsible for these emission in Germany. With focus on thermal energy, like process heat, space heating, domestic hot water (DHW), process cold and AC cold, the sectors industry, private households, trade & commerce seem to be relevant.

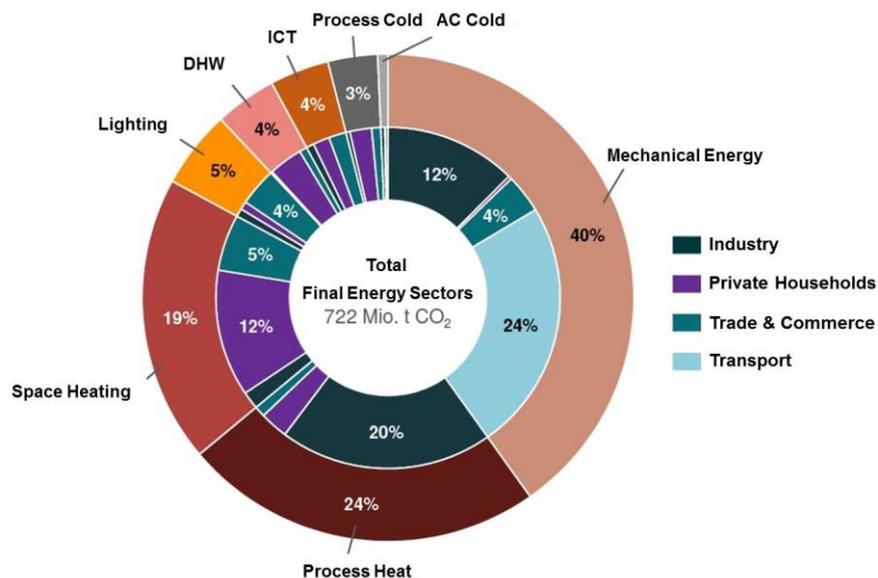


FIGURE 1.2-2: CO₂ EMISSIONS IN GERMANY LINKED TO STATISTICAL SECTORS AND ENERGY DEMAND [M. RASCH, A. REGETT, S. PICHLMAIR, J. CONRAD, S. GREIF, A. GUMINSKI, E. ROUYRRE, C. ORTHOFER AND T. ZIPPERLE, EINE ANWENDUNGSORIENTIERTE EMISSIONSBILANZ – KOSTENEFFIZIENTE UND SEKTORENÜBERGREIFENDE DEKARBONISIERUNG DES ENERGIESYSTEMS, FORSCHUNGSSTELLE FÜR ENERGIEWIRTSCHAFT FFE, BWK, AUSGABE 03/2017]

From the figure it is obvious that thermal energy demand and the connected emissions are with more than 50% the dominant factor for any measures to stop the global warming. This is a strong point for the relevance of thermal energy storage to support the integration of renewables and to increase energy efficiency in general.

RELEVANT APPLICATIONS

The most relevant fields of application for thermal energy storage systems can be defined as:

- Industrial Processes
- Buildings

These two fields of application would stand for 27% (process heat and cold) and 24% (space heating, DHW and AC cold) of the CO₂ emissions in Germany.

In the last phase of the Annex, this list was updated and only the most relevant applications were extracted:

- Industrial batch processes and peak shaving applications
- Heating and cooling for single family households (HVAC systems in the building sector)
- Combined heat and power systems
- District heating systems

In a first attempt, it was tried to collect operation conditions from these applications. And, if possible, to extract reference conditions for material testing.

HOW TO DEFINE OPERATION CONDITIONS

In order to develop a novel material for thermochemical heat storage (TCM) a strong link to the targeted application is crucial. The proposed approach offers an easy method for first experimental testing of new materials under real conditions.

WHY FOCUS ON TEMPERATURES?

The most important parameters for the evaluation of materials within latent or thermochemical storage systems are the temperatures involved. By adjusting just these temperatures, the achievable storage capacity can be experimentally quantified. Any other operation conditions (like the thermal power requirement or the number of cycles) should be neglected at this first step of testing. The presented approach will focus exclusively on the temperatures as the operation conditions.

2-TEMPERATURE-APPROACH FOR PCM

For PCM thermal energy storage systems, 2 temperatures are sufficiently describing the charging and discharging process in any application.

- **Charging Temperature T_{char}** : The necessary charging temperature is given by the melting temperature of the PCM. It has to be above the melting temperature in order to melt the PCM in the charging process. The minimum necessary temperature difference between charging and melting temperature, as fixed value for each material, is given by heat exchanger design.
- **Consumer Temperature T_{cons}** : The necessary discharge temperature is given by the application. Each application has its own fixed usable temperature level. Below this level, heat cannot be used. The consumer temperature should be below the melting temperature in order to utilize the melting enthalpy. The minimum necessary temperature difference between melting temperature and usable temperature level is given by heat exchanger design.

4-TEMPERATURE-APPROACH FOR TCM

For thermochemical energy storage, not only the heat transport in and out of the material, described by the temperatures, but also the mass transfer, given by the concentrations of the reactants, defines the achievable storage capacity. The concentrations however can be translated into available temperatures. These temperatures could be equivalent to partial pressures or dewpoints (in the case of water as the reactant) in open systems. In closed systems, the concentrations are given by the temperature of the condenser and the evaporator. In the following, these temperatures are called “ambient” temperatures, because they determine the actual heat flux in or out of the thermochemical energy storage system. Thus 4 temperatures are necessary to describe the charging and discharging process in any application.

- **Charging Temperature T_{Char}** : The available charging temperature, which is depending on the temperature of the heat source and the quality of the heat exchanger.
- **T_{AmbChar} (only for TCM)**: The ambient condition during charging is given by the dew point or partial pressure or concentration of the reactant for an open system and by the condenser temperature for a closed system.
- **Consumer Temperature T_{Cons}** : The minimum required temperature for the consumer (including the necessary temperature difference for the heat exchanger).
- **$T_{\text{AmbDischar}}$ (only for TCM)**: The ambient condition during discharging is given by the dew point or partial pressure or concentration of the reactant for an open system and by the evaporator temperature for a closed system.

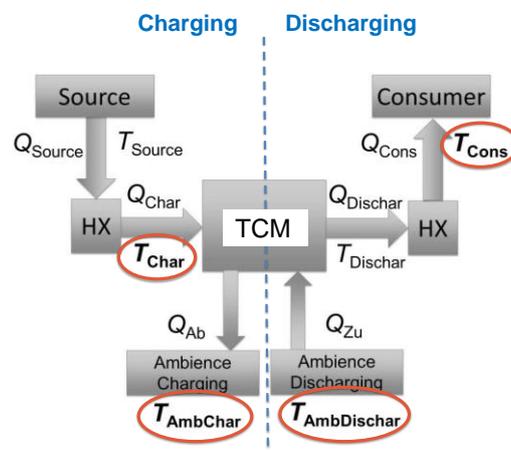


FIGURE 1.2-3: SCHEME OF A TCM SYSTEM AND THE 4 RELEVANT TEMPERATURES DURING CHARGING AND DISCHARGING

COLLECTION OF OPERATION CONDITIONS

The participants were asked to fill in templates for the most relevant applications in order to identify the operation temperatures according to the above-mentioned methodology.

BUILDING APPLICATIONS

Figure 1.2-4 shows the provided charging and consumer temperature for heating and domestic hot water applications. All applications are based on a solar-thermal input. This limits the

charging temperatures below or around 100 °C. Exceptions are coming from systems assuming high temperature thermal collectors (e.g. vacuum tubes) or electrical heating systems.

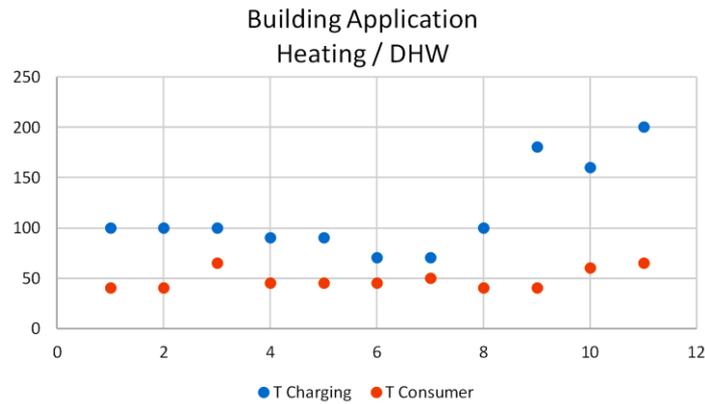


FIGURE 1.2-4: CHARGING AND CONSUMER TEMPERATURE FOR BUILDING APPLICATIONS

For the class of building applications, it seems possible to define reference conditions or at least temperature ranges in which a first material testing could be performed.

OTHER APPLICATIONS

The other relevant applications - combined heat and power, district heat, and process heat – are listed in Table 1.2-1.

TABLE 1.2-1: OPERATION TEMPERATURES OF MOST RELEVANT APPLICATIONS IN OTHER SECTORS ACCORDING TO PARTICIPANTS INPUT

Institution	Application	T Charging	T Amb Char	T Consumer	T Amb Dischar
Combined Heat & Power					
ZAE Bayern	CHP Waste Heat (low-T)/ Short Term TES / Process Heat (Food Industry)	80 °C	20 °C	100-110 °C	20 °C
ZAE Bayern	CHP Waste Heat (combustion gases)/ Short Term TES / Process Heat (Food Industry)	350 °C	20 °C	100-110 °C	21 °C
District Heating					
AEE Intec	Renewable Electricity / Short Term TES / District Heating	> 100 °C	10-20 °C	80 °C	10-20 °C
Process Heat					
Univ. Artois	Solar Wall / / Daily TES / Process Heat (Greenhouse effect)	<80°C		25°C - 35°C	
TUM	Renewable Electricity / Power-to-Process Heat & Power	> 650°C	160°C	475°C	120°C
TUM	Renewable Electricity / Power-to-Process Heat	> 650°C	160°C	192°C	90-100°C

The content of Table 1.2-1 is coming from actual R&D projects of the international participating institutes. It is no representative view on the real situation of relevant application. However, it remains obvious that a certain set of reference temperatures cannot be identified for the listed applications. Especially in the field of process heat and industrial applications, the diversity of operation conditions is huge. Thus, no reference conditions can be defined at the moment.

1.2.2 SUBTASK 2 - DEVELOPMENT AND CHARACTERIZATION OF IMPROVED MATERIALS

SUBTASK 2P

The work of Subtask 2P “Development and Characterization of Improved PCM” covered 4 topics:

- PCM Material development
- Developing measurement procedures
- Filling the PCM Database
- Developing a Wiki for terms used in the context of PCM

DEVELOPMENT OF NEW PCM

As the material development is done at different institutions, the first objective was to collect information on the PCM which are under development. Questionnaires from the experts were gathered to get an overview on the most relevant properties of these materials and the application which are addressed. Figure 1.2-5 depicts an overview of the investigated and/or developed PCM in terms of melting temperature vs. melting enthalpy. In total, 20 PCM with melting temperatures between -20 °C and +180 °C and melting enthalpies up to 300 kJ/kg on material level were investigated by the participants.

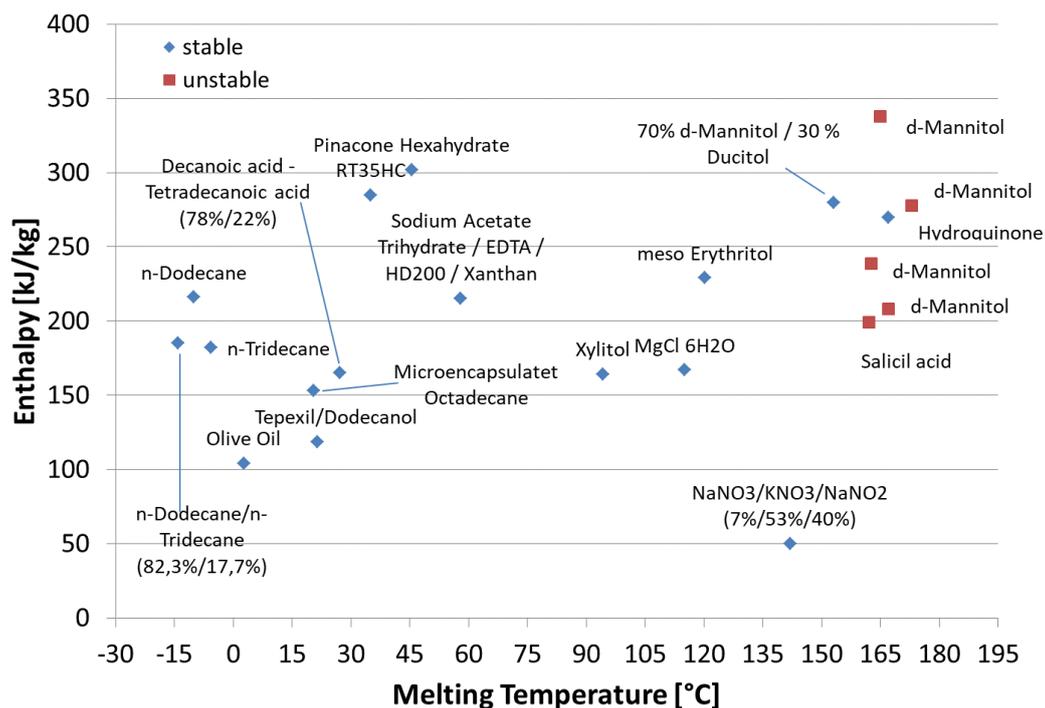


FIGURE 1.2-5: OVERVIEW ON MATERIALS COLLECTED WITH THEIR PHASE CHANGE ENTHALPY AND MELTING TEMPERATURE, RED INDICATES THE UNSTABLE MATERIALS

MEASUREMENT PROCEDURE FOR THERMAL DIFFUSIVITY

An intercomparative test of thermal diffusivity was carried out. The scope of the test was to develop a guideline for determination of thermal diffusivity and conductivity of PCM by means of flash technique in order to ensure reliable measurement data. The investigated sample material was RT70HC with a melting temperature around 70 °C. Two different cooling rates were

used for the sample preparation: slow cooling (2 K/h) or fast cooling (quenching with liquid nitrogen). In the first measurement round, the thermal diffusivity of the solid PCM RT70HC was measured at 40 °C and 50 °C. In the second measurement round, the pulse energy was varied systematically. With rising pulse energy, a trend towards lower thermal diffusivity can be observed for all measurements. In a third measurement round the specimens were prepared by the participating laboratories themselves in order to test the influence of sample preparation. As a consequence, compared to the previous measurement rounds, the standard deviation of the results was increased.

In Figure 1.2-6, the statistical results of the different measurement rounds demonstrate the achievements compared to the results obtained in the previous phase (T42A29). In the case of round 2, with uniform specimen and adjusted pulse energy, a very low standard deviation of less than 3% was observed among the participants.

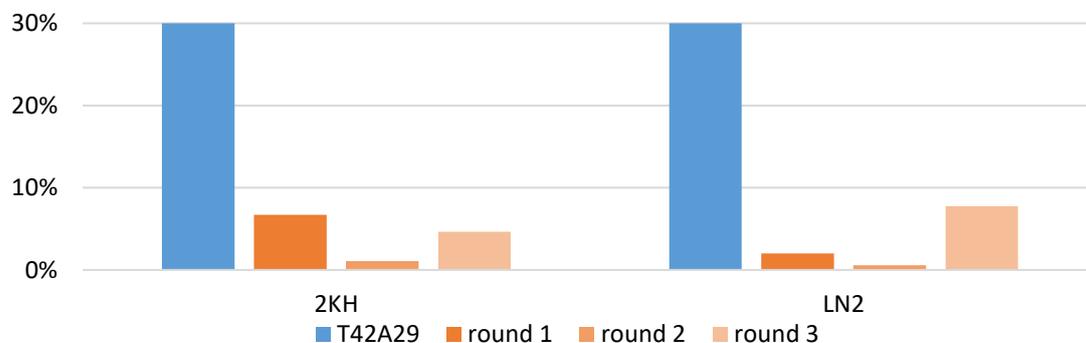


FIGURE 1.2-6: RELATIVE STANDARD DEVIATIONS OF THE MEASUREMENT RESULTS IN THE DIFFERENT MEASUREMENT ROUNDS FOR SPECIMENS WITH DIFFERENT COOLING RATES: 2 K/H (2KH) OR QUENCHING WITH LIQUID NITROGEN (LN2)

MEASUREMENT PROCEDURE FOR VISCOSITY

In addition, a measurement procedure for viscosity was developed. Therefore, a workshop on the measurement of viscosity via rotational rheometers was organized. Figure 1.2-7 depicts some impressions from the workshop.

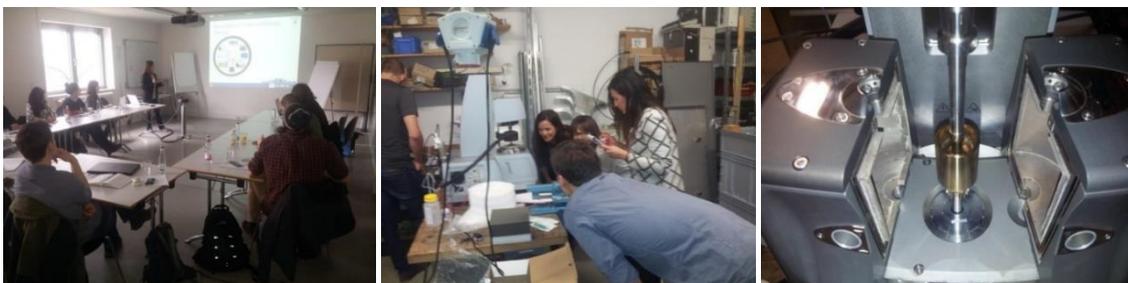
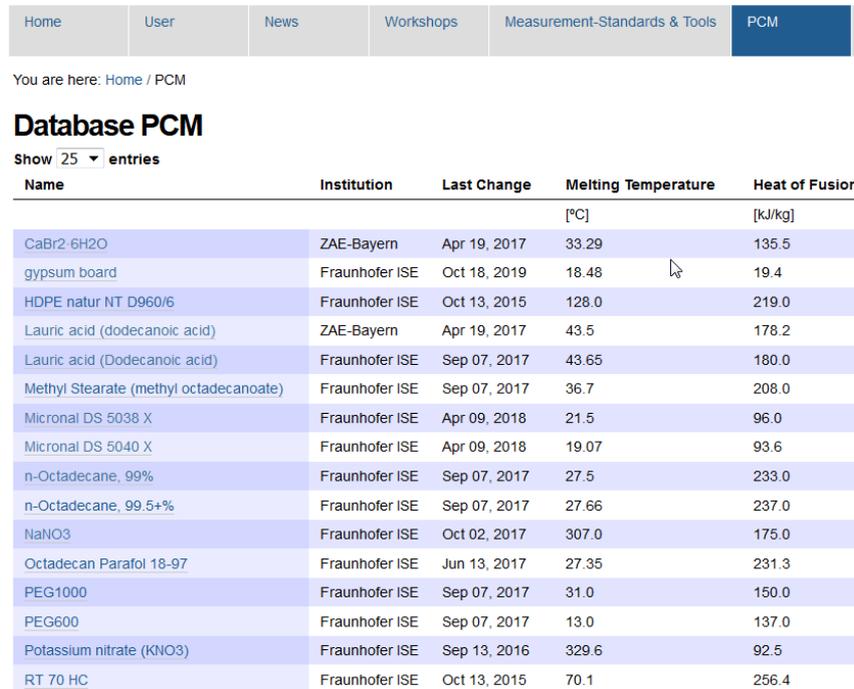


FIGURE 1.2-7: WORKSHOP ON MEASUREMENT OF VISCOSITY VIA ROTATIONAL RHEOMETERS, FROM LEFT TO RIGHT: PRESENTATIONS, THE HIGH TEMPERATURE MEASUREMENT GEOMETRY FILLED WITH MOLTEN NITRATE SALT, FILLING THE GAP FOR THE MEASUREMENT OF RT70HC

PCM DATABASE

New material properties have been feed into the database which was developed during previous tasks and annexes. So far, data of 56 measurements are available in the private section from

which 16 datasets are publicly available. Figure 1.2-8 shows on the overview table of public available materials.



Home User News Workshops Measurement-Standards & Tools **PCM**

You are here: Home / PCM

Database PCM

Show 25 entries

Name	Institution	Last Change	Melting Temperature [°C]	Heat of Fusion [kJ/kg]
CaBr ₂ ·6H ₂ O	ZAE-Bayern	Apr 19, 2017	33.29	135.5
gypsum board	Fraunhofer ISE	Oct 18, 2019	18.48	19.4
HDPE natur NT D960/6	Fraunhofer ISE	Oct 13, 2015	128.0	219.0
Lauric acid (dodecanoic acid)	ZAE-Bayern	Apr 19, 2017	43.5	178.2
Lauric acid (Dodecanoic acid)	Fraunhofer ISE	Sep 07, 2017	43.65	180.0
Methyl Stearate (methyl octadecanoate)	Fraunhofer ISE	Sep 07, 2017	36.7	208.0
Micronal DS 5038 X	Fraunhofer ISE	Apr 09, 2018	21.5	96.0
Micronal DS 5040 X	Fraunhofer ISE	Apr 09, 2018	19.07	93.6
n-Octadecane, 99%	Fraunhofer ISE	Sep 07, 2017	27.5	233.0
n-Octadecane, 99.5+%	Fraunhofer ISE	Sep 07, 2017	27.66	237.0
NaNO ₃	Fraunhofer ISE	Oct 02, 2017	307.0	175.0
Octadecan Parafol 18-97	Fraunhofer ISE	Jun 13, 2017	27.35	231.3
PEG1000	Fraunhofer ISE	Sep 07, 2017	31.0	150.0
PEG600	Fraunhofer ISE	Sep 07, 2017	13.0	137.0
Potassium nitrate (KNO ₃)	Fraunhofer ISE	Sep 13, 2016	329.6	92.5
RT 70 HC	Fraunhofer ISE	Oct 13, 2015	70.1	256.4

FIGURE 1.2-8: SCREEN SHOT OF THE PUBLIC AVAILABLE DATASETS (WWW.THERMALMATERIALS.ORG)

PCM Wiki

In order to establish a common wording of relevant phenomena in the context of PCM, a Wiki has been started. Experts have worked on definitions and explanations of terms such as nucleation temperature, supercooling, specific heat determination via DSC etc. The Wiki is open so that everybody can add new terms and definitions or to change/comment on existing ones. Figure 1.2-9 shows a screen shot of the PCM Wiki.

Offset Temperature	Wiki PCM	
Onset Temperature	How to use and edit	
Baseline	<p>To put a new entry to the Wiki go to the Wiki-PCM page and choose "Add new" -> "Page", give the title and go to "Body Text" to write the description. Therefore insert a table with 2 cols and 1 row. Please write text using format "Heading cell" into the left col and put images into the right col. You can also use subheadings to include sub headings in your text.</p> <p>Please insert images here (tree icon above) (graphs, pictures fotos) use png or jpg format. Best image width is 285 dots. Therefore upload images to the image-folder in Wiki-PCM (see description there).</p>	
Melting Temperature		
Nucleation or Crystallization Temperature		
Peak Temperature		
Enthalpy		
Zero-line	Offset Temperature	
Subcooling	<p>The extrapolated offset-temperature (according to DIN EN ISO 11357-1:2010-03) is the designed intersection point of the extrapolated baseline and the inflectional tangent at the end of the melting or crystallization peak (see image onset temperature). The baseline and the inflectional tangent are determined from the temperature-dependent heat flow signal.</p>	
Supercooling		
T-History		
Nucleation	Onset Temperature	
DSC	<p>The extrapolated onset-temperature (according to DIN EN ISO 11357-1:2010-03) is the designed intersection point of the extrapolated baseline and the inflectional tangent at the beginning of the melting or crystallization peak. The baseline and the inflectional tangent are determined from the temperature-dependent heat flow signal. In the case of pure and homogeneous materials, the onset-temperature can be indicated as melting temperature. In contrast to peak-temperature, the onset-temperature is less dependent on heating rate and sample mass. Furthermore onset-temperatures are usually used for temperature calibration of a DSC.</p>	
Specific heat determination (DSC)		

FIGURE 1.2-9: SCREEN SHOT OF THE WIKI FOR PCM (WWW.THERMALMATERIALS.ORG/WIKI-PCM)

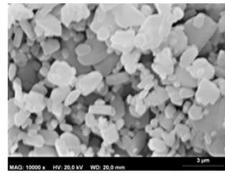
SUBTASK 2T

Subtask 2T "Development and Characterization of Improved TCM" included 4 activities:

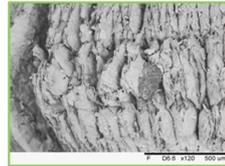
- Develop and identify novel chemical reactions and composite materials
- Define relevant material parameters
- Characterize novel reactions and materials by material properties
- Maintenance and expansion of the material database implemented in Task42/Annex 29

DEVELOPMENT OF NEW TCM MATERIALS AND COMPOSITES

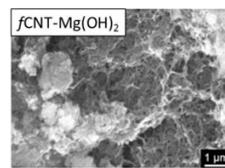
The development of improved TCM included sorption materials (micro/mesoporous solids and liquids), chemical reactions (salt hydrates and metal oxides/hydroxides), and combinations of both (zeolites/graphite + salt hydrates/metal oxides). Figure 1.2-10 shows microscope images different TCM materials developed and/or characterized by participants.



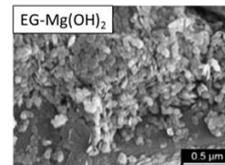
$\text{CaC}_2\text{O}_4 \cdot \text{H}_2\text{O}$
Institute of Applied
Synthetic Chemistry
(TU Wien)
Dr. Peter Weinberger



Vermiculite- CaCl_2
Swansea University
Dr. Jonathon Elvis



Carbon nanotube- $\text{Mg}(\text{OH})_2$



Expanded graphite- $\text{Mg}(\text{OH})_2$
University of Messina –
Engineering Department
Prof. dr. Candida Milone

FIGURE 1.2-10: IMAGES OF TCM MATERIALS DEVELOPED AND INVESTIGATED WITHIN THE GROUP OF EXPERTS

Sorption materials with desorption temperatures between 80 °C and 140 °C and desorption enthalpies up to 2.200 kJ/kg on material level were investigated (Figure 1.2-11).

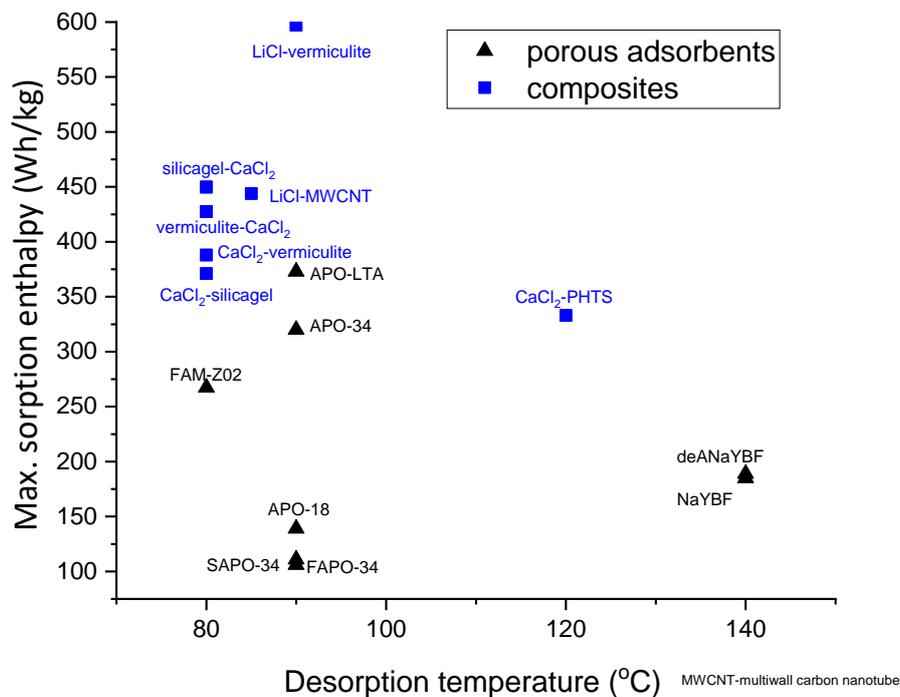


FIGURE 1.2-11: MAX. SORPTION ENTHALPY VERSUS DESORPTION TEMPERATURE OF POROUS SOLIDS AND COMPOSITES (ADSORBATE: WATER)

Chemical reactions with reaction temperatures up to 800 °C showed reaction enthalpies up to 1.500 kJ/kg on material level (Figure 1.2-12).

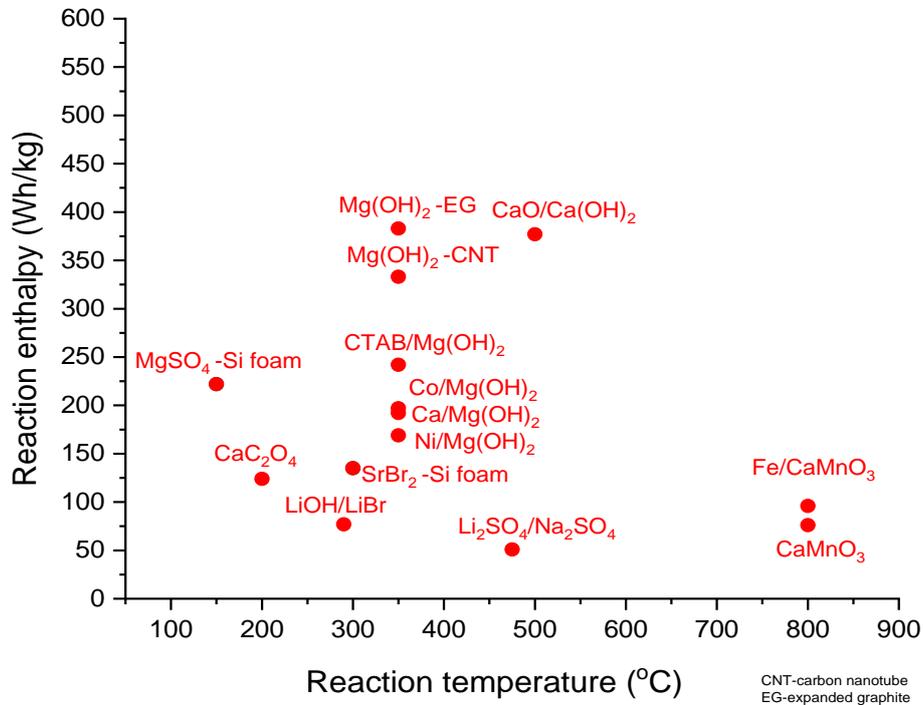


FIGURE 1.2-12: CHEMICAL REACTIONS AND COMPOSITES INVESTIGATED AS TCM: REACTION ENTHALPIES VS. TEMPERATURE

TCM DATABASE

Due to complexity and different relevant materials properties, it was decided to prepare three databases: one on chemical reactions (salt hydrates, oxides, composites), one on adsorption (porous solids and composites), and one on absorption (liquids). A screen shot of the chemical reaction database is shown in Figure 1.2-13.

Basic chemical composition	Name Dopant	Name Stabilizer/Matrix	E/V (kWh/m ³)	T _{eq} @ x mbar (K)	Price (€/kg)	Institute
K ₂ CO ₃ *1.5H ₂ O	-	-	-	-	1	Technical University of Eindhoven
MgCl ₂ *6 H ₂ O	-	-	-	-	-	Technical University of Eindhoven
Na ₂ S*5 H ₂ O	-	-	-	-	-	Technical University of Eindhoven
NaOH / H ₂ O	-	-	-	-	0,30	Empa
Mg(OH) ₂	-	-	194	531	-	University of Messina-Engineering Department
Mg(OH) ₂ + C	-	Expanded graphite	330	531	-	University of Messina-Engineering Department
Mg(OH) ₂ + C	-	Functionalized Carbon Nanotubes	326	531	-	University of Messina-Engineering Department
Na ₂ S.5H ₂ O	-	-	-	-	0,348	TNO

FIGURE 1.2-13: SCREEN SHOT OF THE CHEMICAL REACTION DATABASE (WWW.THERMALMATERIALS.ORG)

1.2.1 SUBTASK 3 - MEASURING PROCEDURES AND TESTING UNDER APPLICATION CONDITIONS

SUBTASK 3P

PCM testing under application conditions can be considered as a link between the measured material properties in the lab and the observed phase change behaviour of the PCM in an actual application (cf. Figure 1.2-14).

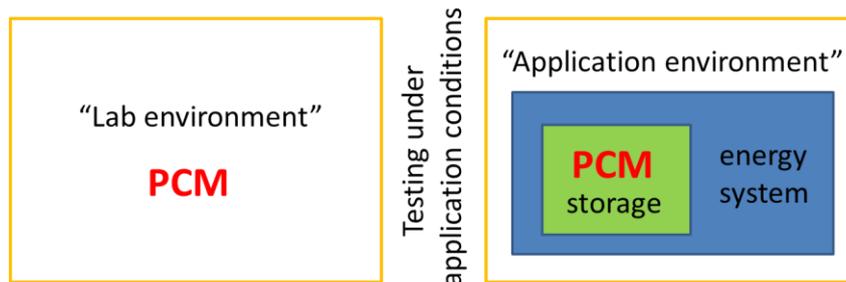


FIGURE 1.2-14: PCM TESTING UNDER APPLICATION CONDITIONS

In this subtask, a comparison of material properties of PCM in the lab environment and under application conditions was elaborated. Thereby, most input was collected for the properties degree of supercooling, phase separation, storage capacity, and long-term stability of PCM.

A step further was taken in the case of long-term stability of PCM: Information on experimental devices that are used by the experts of Task 58 / Annex 33 to investigate the long-term stability of PCM were gathered (some of them are shown in Figure 1.2-15). The experiments include tests on the stability of PCM over thermal cycling, on the stability of PCM with stable supercooling, and on the stability of Phase Change Slurries (PCS).

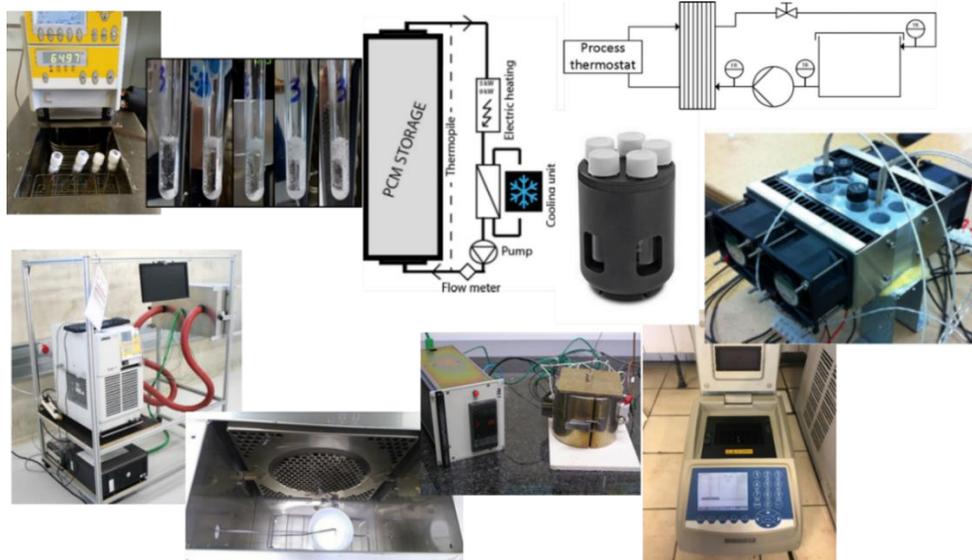


FIGURE 1.2-15: EXPERIMENTAL DEVICES USED BY THE PARTICIPANTS TO INVESTIGATE THE LONG-TERM STABILITY OF PCM

SUBTASK 3T

This Subtask aimed to have reliable thermal analysis methods/protocols and procedures for the characterization of material and reaction properties for sorption and chemical reactions of thermal energy storage (TES) applications.

Therefore, measurement procedures for mass and enthalpy change with defined conditions for sorption materials and salt hydrates were developed. The biggest part of the activities in this subtask was to develop a common sense for enthalpy and mass change measurements of sorption and thermochemical materials as well as a procedure to compare results on lab scale. Different round robin tests on a zeolite and salt hydrate were conducted and evaluated. These results were used to further develop the measurement procedures. In addition, a measurement procedure for specific heat capacity measurements of salt hydrates was tested.

The performed round robin tests showed a good agreement with respect to mass change among the participants. Both enthalpy changes and specific heat capacity showed larger deviations σ :

- Adsorption enthalpy of zeolite 13X: $\sigma(\Delta H_{\max}) \sim 12\%$
- Hydration enthalpy of SrBr \cdot 6H $_2$ O: $\sigma(\Delta H_{\max}) \sim 40\%$
- Specific heat capacity of SrBr \cdot 6H $_2$ O: $\sigma(c_{p,\max}) \sim 23\%$ (Figure 1.2-16)

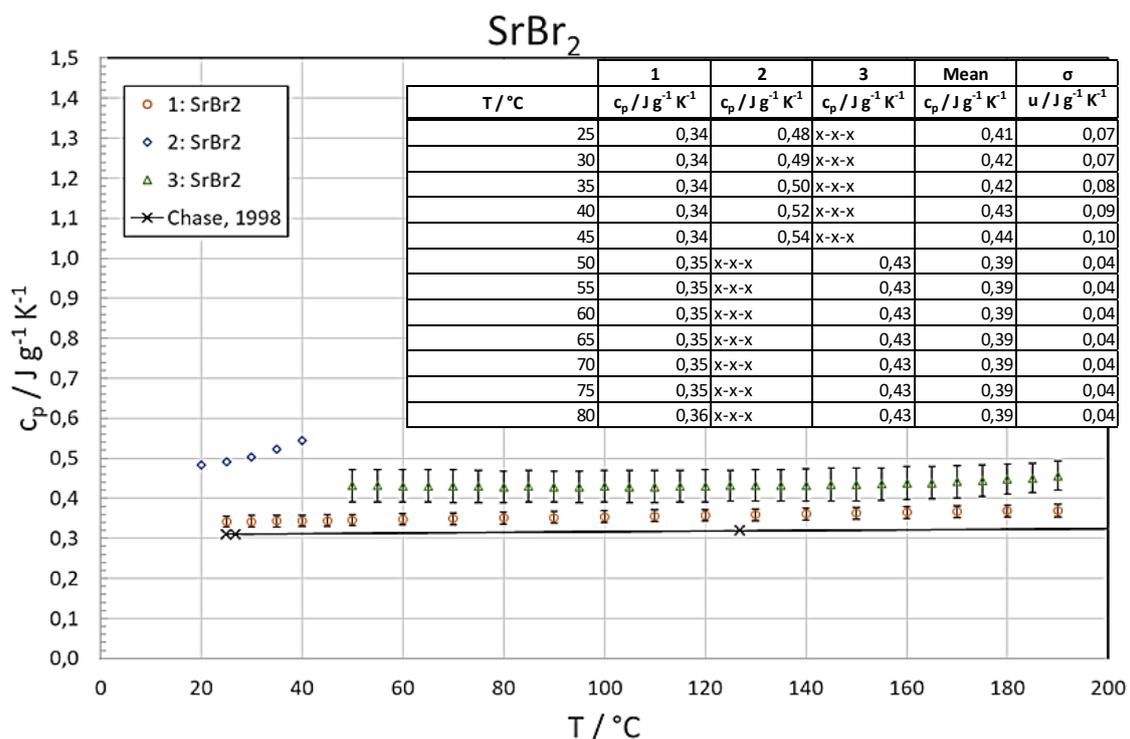


FIGURE 1.2-16: THE ROUND ROBIN TEST OF THE SPECIFIC HEAT CAPACITY OF A SALT HYDRATE SHOWED DEVIATIONS UP TO 23%

The deviations in terms of enthalpy point to the necessity to proceed with developing standardized measurement methods including sample preparation and handling.

1.2.2 SUBTASK 4 - COMPONENT DESIGN FOR INNOVATIVE TES MATERIALS

SUBTASK 4P

Latent heat storage systems using PCM should meet the application requirements in terms of technical and economical parameters. Among the technical parameters, high thermal power is one of the most challenging characteristics. Most of the materials used as PCM have an intrinsically low thermal conductivity, for which component design has to compensate for.

Several finished and ongoing projects have worked on improving the design of PCM components (storage containment, heat exchangers) with the aim to increase the thermal performance. As a first step for a performance comparison between the different solutions, this subtask listed the various concepts, previously or currently studies, for PCM thermal storage in terms of geometries, heat exchange systems and the nature of the PCM used. The following figures, Figure 1.2-17 to Figure 1.2-20, show examples of storage concepts developed by the participants.

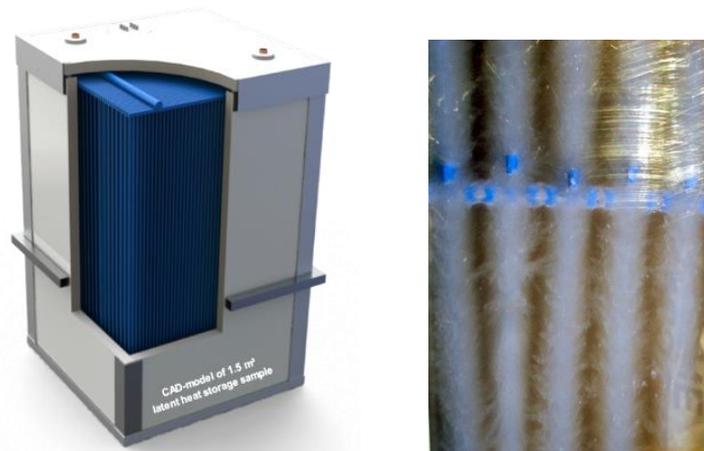


FIGURE 1.2-17: LEFT: CAD MODEL OF A PCM STORAGE WITH CAPILLARY TUBE HEAT EXCHANGER (SOURCE: ZAE BAYERN), RIGHT: PCM CRYSTALLIZING AT CAPILLARY TUBES (SOURCE: ZAE BAYERN)

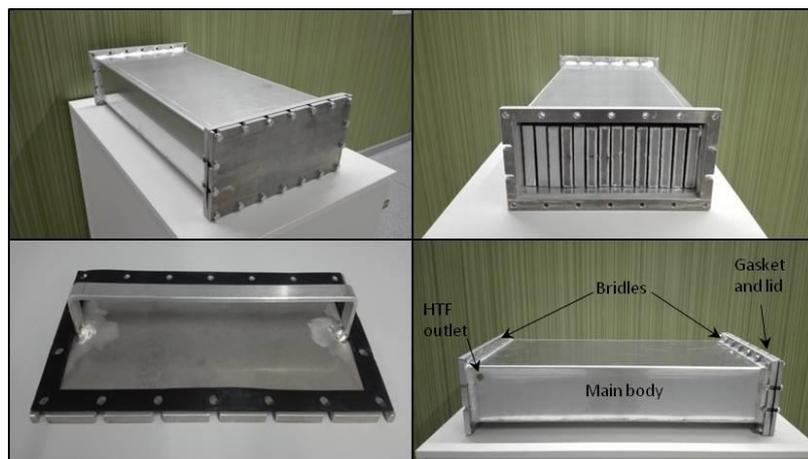


FIGURE 1.2-18: A LABORATORY-SCALE TES SYSTEM WITH MACROENCAPSULATED PCM IN FLAT PLATES PLACED IN PARALLEL (SOURCE: DIARCE ET AL. 2018).

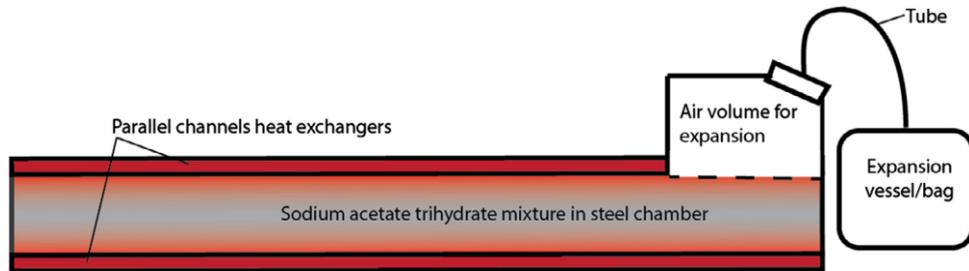


FIGURE 1.2-19: FLAT PLATE STORAGE WITH PCM CHAMBER AND EXTERNAL EXPANSION (SOURCE: DANNEMAND ET AL. 2016).

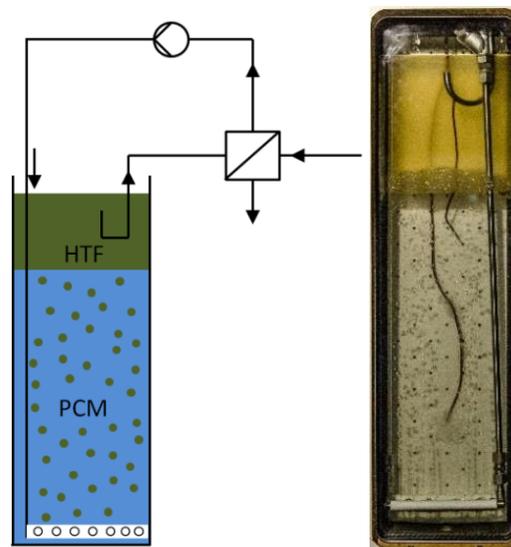


FIGURE 1.2-20: (LEFT) SCHEMATIC REPRESENTATION OF DIRECT CONTACT LATENT HEAT STORAGE PRINCIPLE WHERE THE HTF IS FLOWING DIRECTLY THROUGH THE PCM EXCHANGING HEAT AT THE BUBBLE/PCM INTERFACE AND CAUSING SOLIDIFICATION OR MELTING OF THE STORAGE MATERIAL; (RIGHT) DIRECT CONTACT LATENT HEAT STORAGE TEST-RIG DEVELOPED AT LUCERNE UNIVERSITY OF APPLIED SCIENCES AND ARTS (SOURCE: LUCERNE UNIVERSITY OF APPLIED SCIENCES AND ARTS)

Following this, a definition of performance for PCM components in term of capacity and storage density was agreed upon. In order to be able to compare different PCM concepts in terms of power, a review on assessment approaches was carried out. Therefore, power-time curves upon charging and discharging were compared (cf. Figure 1.2-21), preliminary performance parameters were defined, and a procedure based on a validated numerical model was proposed.

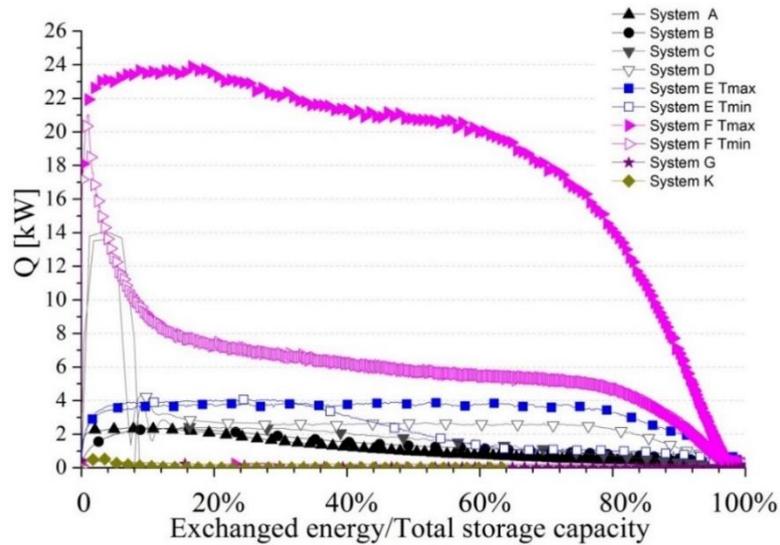


FIGURE 1.2-21: HEAT EXCHANGE RATE OVER STATE OF CHARGE OF THE PCM COMPONENTS STUDIED IN SUBTASK 4P

SUBTASK 4T

In the case of TCM component design, the starting point was a basic description of investigated TCM storage processes and their impact on the component design. In addition, an inventory of actual TCM component designs currently under investigation was elaborated. The following figures, Figure 1.2-22 to Figure 1.2-24, show examples of storage concepts developed by the participants.

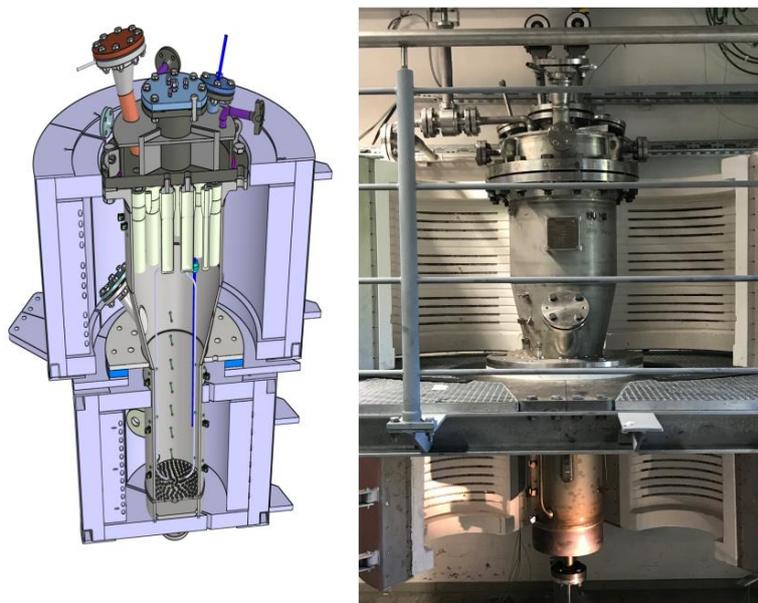


FIGURE 1.2-22: 3D-CAD IMAGE AND PHOTO OF THE FLUIDIZED BED REACTOR FOR HIGH TEMPERATURE HEAT STORAGE USING A REVERSIBLE CHEMICAL GAS-SOLID REACTION USING STEAM AND METAL OXIDES SUCH AS $\text{CaO}/\text{Ca}(\text{OH})_2$ OR $\text{MgO}/\text{Mg}(\text{OH})_2$ (SOURCE: TECHNICAL UNIVERSITY MUNICH)

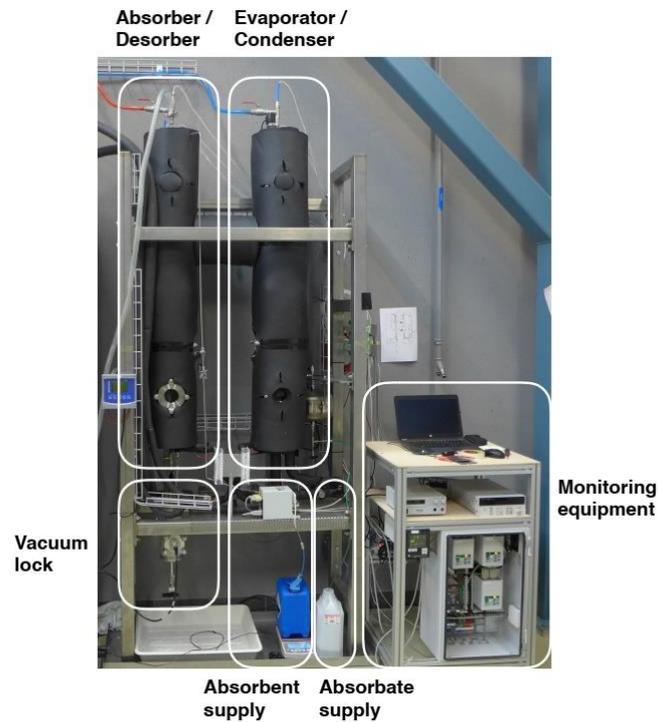


FIGURE 1.2-23: SCHEMATICS AND PICTURE OF EMPA'S NaOH / H₂O LABORATORY LIQUID ABSORPTION SYSTEM (SOURCE: EMPA)

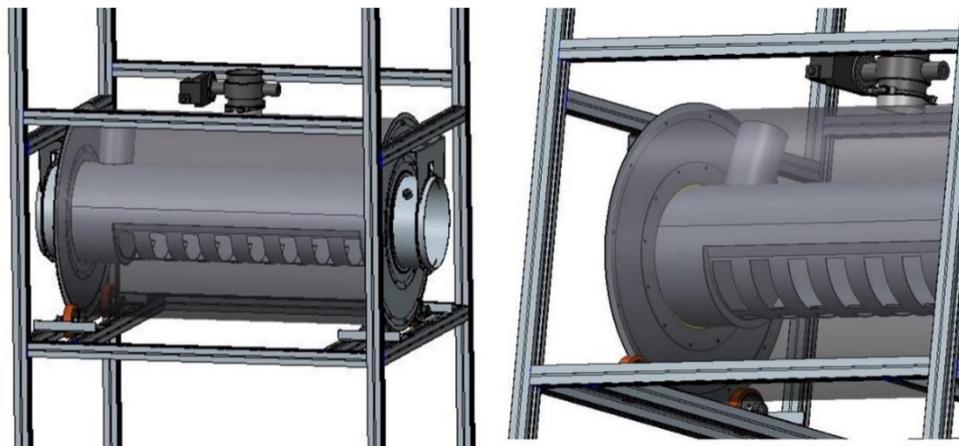


FIGURE 1.2-24: CONSTRUCTION DETAILS OF THE ROTATING CYLINDRICAL ADSORPTION REACTOR USING ZEOLITE-WATER AS SORPTION WORKING PAIR (SOURCE: UNIVERSITY FOR APPLIED SCIENCE UPPER AUSTRIA)

To compare and discuss different TCM component concepts, a common graphical representation was used to classify the concepts as open or closed and fixed or transported systems (Figure 1.2-25).

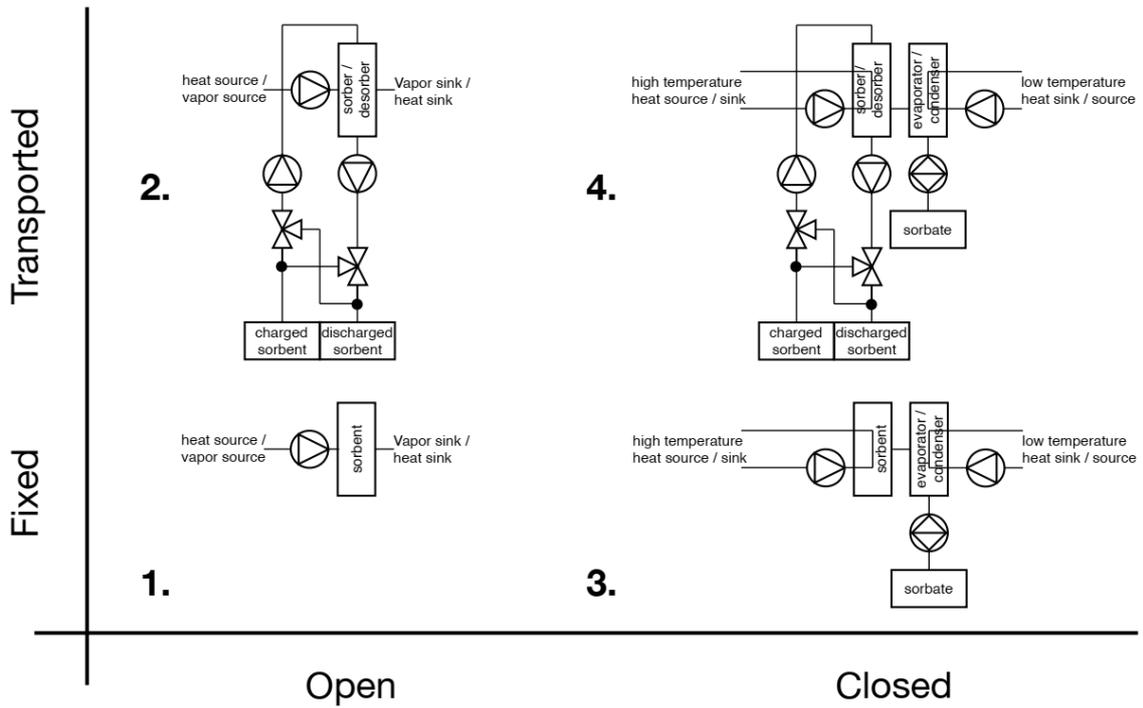


FIGURE 1.2-25: ILLUSTRATION OF THE BASIC SORPTION HEAT STORAGE SYSTEMS.

Further efforts were undertaken to identify a possible TCM performance degradation from lab-scale measurements to pilot installations. A “Do’s and Don’ts” paper in the context of TCM component design is currently in preparation.