Task 42

Compact Thermal Energy Storage–Collaboration Leads to Groundbreaking Work

For the first time international teams of materials experts and application experts collaborated to tackle together issues confronting thermal energy storage. This one of a kind research platform was created jointly by the IEA Solar Heating and Cooling Programme (IEA SHC) and the IEA Energy Conservation through Energy Storage Programme (IEA ECES).

Current thermal energy storage technologies, mainly based on water tanks, perform well for short-term storage. Due to heat losses, long-term thermal storage with water is not efficient for small and medium sized systems while for very large water storage systems, mostly connected to district heating networks, long-term storage efficiency is good. However, conventional storage systems based on hot water tanks are limited and thermal energy storage needs new materials and system technologies.

Innovative compact thermal energy storage technologies are based on the physical principles and properties of phase change materials (PCM) and on thermochemical materials (TCM). With these materials, heat can be stored in a more dense form and with fewer losses than with hot water storage tanks.

Storage is a huge issue for renewables so IEA SHC joined with IEA Energy Conservation through Energy Storage Programme (IEA ECES) to support IEA SHC Task 42/IEA ECES Annex 24 on Compact Thermal Energy Storage. The Task covered phase change materials (PCMs), thermochemical materials (TCMs), and composite materials and nanostructures. And, included activities on material development, analysis, and engineering, numerical modeling of materials and systems, development of storage components and systems, and development of standards and test methods. This Task was completed the end of 2015, but not to worry as a new Task on this topic is being developed under the leadership of Wim van Helden of AEE INTEC of Austria.

WHAT'S BEEN ACHIEVED?

Key results of IEA SHC Task 42/IEA ECES Annex 24 on Compact Thermal Energy Storage are described briefly below. To learn more and find reports on specific topics visit the IEA SHC Task webpage, http://task42.iea-shc.org/.

Materials Engineering and Processing

Lead country: Slovenia, Alenka Ristic, NIC National Institute of Chemistry

More than 20 institutions from more than 12 countries collaborated on the engineering and processing of TES materials and results include:

New and improved materials for compact TES

Different new and improved PCMs were investigated – eutectic binary mixtures of sugar alcohols, low cost paraffin, cement mortar + microencapsulated PCM, polystyrene (PS)/n-heptadecane micro/nano-capsules, inorganic PCM ternary mixtures, PEG 10,000, microencapsulated n-octadecane, binary mixtures of linear alkanes and saturated fatty acids, new sugar alcohol eutectic mixtures and others.

What's Needed to Drive Market Deployment

1. **Strong support of R&D work by governmental and international research programs as described above. Compact thermal energy storage systems based on phase-change and thermo-chemical material technologies are to a large extent still in their development stage. Single research groups cannot address the challenges and singularly achieved research results, but need a broad and internationally collaborative approach.**
2. **Companies involved in the development of compact thermal storage systems are often relatively small and highly innovative. They need strong support by governments to be able to apply their technology in the building and industrial processes sectors, in spite of the economic disadvantage they still may have.**
3. **Strong support of a growing number of demonstration projects is needed in order to gather operational experiences, to monitor and evaluate performance and to improve the performance of systems step-by-step. A much better basis for the further development and deployment of the huge potential of compact thermal energy storage systems will be established if these actions are taken.**

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And, new and improved TCM materials were synthesized and investigated – binder-free zeolite Y, activated carbon, composites of salt hydrates within porous matrices, etc.

Promising PCMs for different temperature ranges and applications
New PCMs with potential for solar thermal regulation of buildings and food storage containers are polymethylmethacrylate(PMMA)/capric-stearic eutectic mixture (C-SEM) micro/nano capsules can be integrated with conventional building materials polystyrene (PS)/n-heptadecane micro/nano-capsules.

With respect to solar heating and domestic hot water applications new binary mixtures of sugar alcohols comprising erythritol, sorbitol and xylitol were studied.

For cold storage new binary eutectic mixtures of salt hydrate-based PCMs were prepared.

Material properties investigated and the role of material containers
The properties of materials (nontoxicity, density, solubility, specific heat, thermal conductivity, enthalpy, viscosity, phase change, degree of subcooling, cycling stability, thermal stability, etc.), the structures (e.g., decanoic acid/chitosan-gelatine microcomposite) and the compositions (salt hydrates + porous carbon or silica, paraffin wax + multi-walled carbon nanotubes, sugar alcohols+ porous carbon etc.) as well as the role of material containers (e.g., stainless steel 316 can be used for storing the investigated inorganic PCM and TCM) were determined for latent, chemical and sorption heat storage.

Methods for TES-materials processing
Different optimal methods for materials processing were found, such as microencapsulation (caprylic acid/chitosan-gelatine, sugar alcohols), micro/nanoencapsulation (capric, lauric and myristic acids with polystyrene shell), phase change slurries (n-octadecane-water emulsion) for PCMs and new combinations of composite materials (PCMs and TCMs). TCM composite were prepared by wet impregnation ($MgCl_2$/porous carbon or vermiculite, APO/carbon) and incipient wetness impregnation ($CaCl_2$/porous silica). Improvements of TCM`s properties were achieved by the oxidation treatment of activated carbon and composites of $CaCl_2$/porous silica (hydrophilicity), dealumination of zeolite Y (lower regeneration temperature), preparation of APO/carbon or APO coating on metal plate (thermal conductivity), mixing $MgCl_2$ and $CaCl_2$ (preservation of cycling stability), etc.

This research ended up being mainly conducted in the field of PCMs, while only few research projects were performed in the field of thermochemical materials.

Test and Characterization of Phase Change Materials

Lead country: Germany, Stefan Gschwander, Fraunhofer ISE Institute for Solar Energy

Seven scientific institutions worked on the development of measurement standards for PCM characterization. Key results include:

New procedure for DSC measurement of PCMs
This procedure can be downloaded from http://task42.iea-shc.org/data/sites/1/publications/Task4224-Standard-to-determine-the-heat-storage-capacity-of-PCM-vers150326.pdf. It consists of five elements:

1. Heating and cooling rate test to determine suitable heating and cooling rates for the PCM to be measured. This is done by using the PCM to be characterized and applying heating and cooling rates starting from fast rates (e.g. 10 K/min) and slowing down the heating and cooling rates of consecutive cycles by halve the previous.
2. Calibration of the DSC by using 3 different calibration materials covering the desired temperature range (e.g. water, gallium and indium). The calibration has to be done with the determined heating rate.

Want to learn more?

The final Task results are available in one document and include:

- **Technology Position Paper: Compact Thermal Energy Storage (Matthias Rommel and Wim van Helden)**
- **Overview of the Task Compact Thermal Energy Storage (Matthias Rommel, Wim van Helden, Andreas Hauer)**
- **Engineering and Processing of PDMs, TCMs and Sorption Materials (Alenka Ristic et al.)**
- **Standardization of PCM Characterization via DSC (Stefan Gschwander et al.)**
- **Advanced Numerical Modelling Techniques to Tune the roperties of heHat Storage Materials for Optimal Reactor Performance (S.V. Gaaastra-Nedea, C.C.M. Rindt et al.)**
- **Applications of Compact Thermal Energy Storage (Wim van Helden, Motoi Yamaha et al.)**
- **A Simple Tool for the Economic Evaluation of Thermal Energy Storages (Christoph Rathgeber et al.)**

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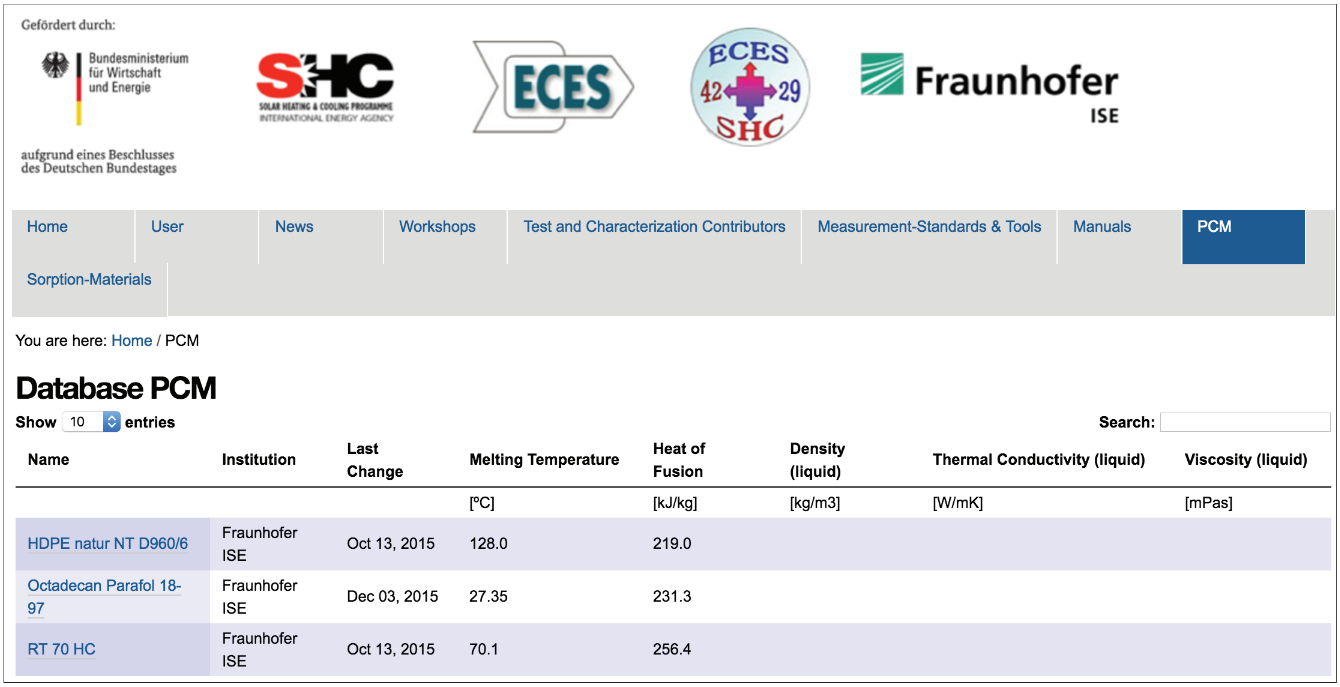

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Database PCM

Name	Institution	Last Change	Melting Temperature	Heat of Fusion	Density (liquid)	Thermal Conductivity (liquid)	Viscosity (liquid)
			[°C]	[kJ/kg]	[kg/m3]	[W/mK]	[mPas]
HDPE natur NT D960/6	Fraunhofer ISE	Oct 13, 2015	128.0	219.0			
Octadecan Parafol 18-97	Fraunhofer ISE	Dec 03, 2015	27.35	231.3			
RT 70 HC	Fraunhofer ISE	Oct 13, 2015	70.1	256.4			

▲ **Figure 1. Overview table of the PCM database.**

3. Measurement of the empty crucible using the determined heating and cooling rates.
4. Sample measurements by applying the sample to the crucible (apply the same sample mass as for the heating rate test) using the determined heating rate. Four measurement cycles have to be applied and three samples have to be measured.
5. Analysis of data, and if necessary, baseline correction (displacement to zero heat flow) has to be applied. Carry out subtraction of heat flow signal measured with empty crucible from the sample measurement. Final data evaluation and computation of enthalpy curves.

PCM database

PCM data measured according to the new standard was collected. The database provides an overview table of all stored PCMs (see Figure 1). By choosing a PCM all relevant measurement parameters are available (onset temperature, integration limits for the given heat of fusion, sample mass, heating rate, etc.) as well as the measured data, which is provided as an ASCII table for download. The database is still less detailed for TCMs, but will be extended in the future.

Numerical Modeling

Lead country: The Netherlands, Camilo Rindt, Eindhoven University of Technology

The activities in this area focused on the different level modeling and simulations. The experts investigated $MgCl_2$ hydrates as an example for developing and testing numerical models to understand and optimize material behavior.

Molecular models were used to check the effect of water vapor pressure on hydrolysis and dehydration reaction. The experts further used the results of the water diffusivity in the crystalline structure in higher-level models.

From the numerical results of material and thermophysical properties of PCM storage systems, it is clear that some deviation may occur if the enthalpy function does not perfectly fit the real behavior of the material. This may occur if the thermophysical characterization of the PCM is not correctly conducted. It is clear that further research work is necessary and material measurements have to be further improved so as to define reliable numerical and simulation methods.

Applications

Lead country: Japan, Motoi Yamaha, Chubu University

Experts from more than 20 research organizations worked on applications of compact thermal energy storage technologies. Application fields included cooling, room heating/domestic hot water and thermal storage for industry. The main challenges in the development of applications are in finding an optimal connection between the storage material and the other materials, the components and the system configuration. The problems to be solved are in the area of materials compatibility, like corrosion protection, prevention of side reactions and cycling stability; in the area of component design, with heat and mass transfer optimization; and in the area of system design with control strategies and cost reduction.

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Thermal storage for cooling applications is the most advanced. There are numerous examples of ice storage systems, running to get a higher system performance or to enable a shift of electricity consumption from daytime to nighttime. Challenges in these systems are the integration of novel PCMs with somewhat higher melting temperatures than water and the system optimization in connection with electricity grids and heating networks.

Most application developments in this IEA SHC Task 42/IEA ECES Annex 24 were in the area of thermal energy storage for room heating and domestic hot water preparation. Here, there is a broad collection of storage technologies and system concepts being developed and tested. Phase change materials and thermochemical materials are applied as active material in open and closed systems.

In the Task, special attention was paid to the interaction between materials researchers and system engineers. A compact thermal energy storage material only has value in a certain application, and the application will imply certain design conditions on the storage material. A first step towards a better interaction is for system engineers to understand how materials researcher evaluate the properties of a storage material, and for materials experts to understand the practical implications of integrating material into a storage system. In the Task, work was done to couple the material properties to system performance, although this is in most cases far from straightforward. For sorption storage technologies, an approach was set up using four typical operating temperatures with which the operation boundary conditions are determined and the performance of a storage material in an application can be determined (see paper by Hauer et al. for SHC-2015 conference).

Given a certain application, it is necessary to have a common basis for determining the performance of different storage technologies. To this end, a design has been made of a set of Key Performance Indicators KPI's of compact thermal energy storage for seasonal storage. In the future, these KPI's will be a valuable tool for comparison of different thermal storage concepts.

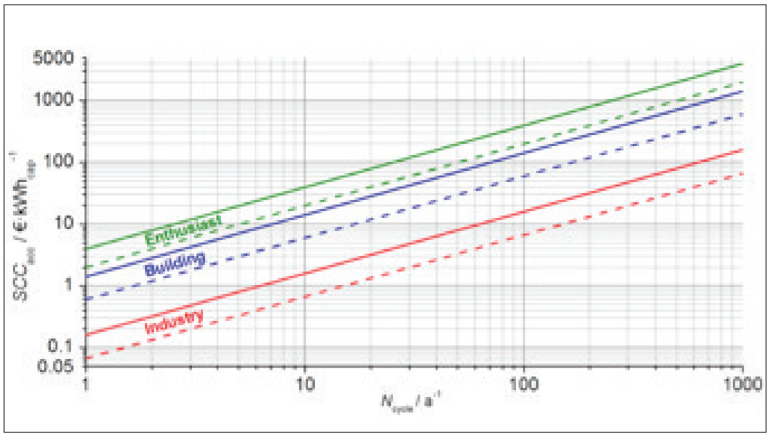
Theoretical Limits

Lead country: Germany, Subtask leader: Christoph Rathgeber, ZAE Bavarian Centre for Applied Energy Research

A tool for the economic evaluation of thermal energy storages was developed and tested on various existing storages. The storage capacity costs (i.e., the costs per installed storage capacity) of thermal energy storages were evaluated using a Top-down and a Bottom-up approach.

The Top-down approach

This approach is based on the assumption that the costs of energy supplied by the storage should not exceed the costs of energy from the market. The maximum acceptable storage capacity costs depend on the interest rate assigned to the capital costs, the intended payback period of the user class (e.g. industry or building), the reference energy costs, and the annual number of storage cycles.



▲ **Figure 2. Maximum acceptable storage capacity costs (SCCacc) as a function of storage cycles per year Ncycle, determined for the three user classes: industry, building sector and enthusiast.**

Figure 2 shows the maximum acceptable storage capacity costs (SCCacc) as a function of storage cycles per year Ncycle, determined for the three user classes (industry, building sector and "enthusiast", which denominates an investor group that accepts long payback periods and low interest rates, for example motivated by political or ecological reasons). A double-logarithmic scale was chosen to visualize both SCCacc of long-term storages with only few cycles per year and short-term storages with several hundred cycles per year. These results indicate that, for a fixed cycle period Ncycle, SCCacc depend on the user's economic environment. The low case of the industry sector and the high case of enthusiasts differ by a factor of about 60 in costs. Short-term storage with several hundred storage cycles per year, however, allows several hundred times higher storage costs because of the larger energy turnover.

The Bottom-up approach

This approach focuses on the realized storage capacity costs of existing storages. It has been applied to analyze the costs of 26 thermal energy storages, also including commercial water storages to check the evaluation methodology of the bottom-up approach. It has to be stressed here that the innovative storages of Task 42/Annex 29 are subject of ongoing research and by far not yet developed for application in the market. Hence, their corresponding costs are only very rough estimations. The comparison of SCCacc and SCCreal indicates that, at present, seasonal storage is only economical using large hot water storages; other technologies require at least an order of magnitude reduction in costs. This is a very strong indication and proof that the topic of compact thermal energy storage still needs much more R&D activities, especially with respect to long-

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term storage. It also means that the development of storage systems that allow a high annual number of storage cycles is economically favorable over seasonal storages.

In order to identify major cost drivers and, thereby, cost reduction potentials for the investigated storage systems, the composition of the investment costs has been analyzed. Figure 3 illustrates how the investment costs of thermal energy storages under investigation in SHC Task 42/ECES Annex 29 are divided into costs of the heat storage material itself and costs of the surrounding container or reactor including the charging/discharging device. So, the Bottom-up analysis showed that a major fraction of the investment costs of the investigated storages is not costs of the heat storage material itself, but costs of the storage container or reactor (including charging/discharging unit). Therefore, R&D activities on cost-effective Thermal Energy Storage systems have to consider both cost-effective heat storage materials and cost-effective storage container or reactor components.

This article was contributed by Matthias Rommel, SHC Task 42 Operating Agent. For more information visit the Task webpage.

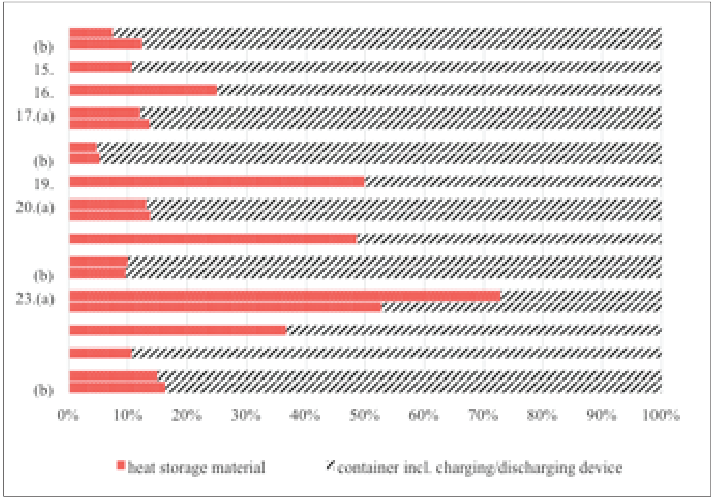

Figure 3. The breakdown of investment costs by material and container.