Materials for compact thermal energy storage: a new IEA SHC/ECES Joint Task

Wim van Helden[1], Marco Bakker[1], Andreas Hauer[2]
[1] ECN, Energy Research Centre of the Netherlands, P.O. Box 1, 1755 ZG Petten, The Netherlands,
telephone: +31 224 56 4483, fax: +31 224 56 8966, email: vanhelden@ecn.nl
[2] Zentrum für Angewandte Energieforschung (ZAE), Walther-Meissner-Strasse 6, D-85748 Garching, Germany

Introduction

More than half of our primary energy resources are used to generate heat. Therefore, technologies for increasing the share of sustainable heat sources and for improving the efficiency of thermal systems are of key importance.
Thermal energy storage technologies are needed for both: to match the intermittent supply of sustainable heat and to optimise the thermal system performance. Examples of these are seasonal storage of solar thermal heat in buildings with little available space, the storage of heat in (micro) co-generation units, storage for cooling, for industrial waste heat and the storage of heat for uninterrupted, day-and-night, concentrated solar power generation.
Present thermal energy storage technologies, mostly based on water, perform well, but on a relatively low level of efficiency, particularly for long-term storage. These systems can only be improved marginally; new materials and systems are needed to enable a breakthrough.
In the recent past the International Energy Agency (IEA) conducted research into advanced thermal storage systems and materials. The systems were investigated in the IEA Solar Heating and Cooling program (SHC), in Task 32. Thermal storage principles and materials were studied in the Annex 17 of the IEA Energy Storage through Energy Conservation program (ECES). Both tasks came to the conclusions that with the available storage materials market niches of thermal storage can be filled and that advanced concepts of compact thermal energy storage technologies (TES) depend strongly on the development of novel compact thermal energy storage materials and components.
Therefore, a new IEA Task has recently been initiated to develop new storage materials. This Task is implemented as a Joint Task between the SHC ECES Implementing Agreements, and is entitled “IEA SHC/ECES 42/24: Compact thermal energy storage: material development for system integration”.
In this article, first a short overview of the state-of-the-art of the different technologies for storage of thermal energy is given. Then the objectives and the organisation of the new tasks are given, followed by a description of the subjects that are being investigated in the various Working Groups of the Task.

Thermal Energy Storage Technologies

There are several ways to classify the technologies with which thermal energy can be stored. One of these is to use the underlying physical principle for storage. This leads to four main groups of storage: sensible heat, latent heat, sorption and thermochemical. The state of these technologies is from market mature to in a research state, respectively. Next, a short description of the technologies will be given plus some examples of typical applications.

Sensible Heat

With sensible heat storage, the thermal energy is stored in the heat capacity of a substance, for instance water. When heat is supplied to the water its temperature will rise, hence the word sensible. The heat capacity of the material determines the amount of energy that can be stored per kilogram or volume. Because of its very high heat capacity water is an ideal heat storage medium. Therefore the vast majority of heat storage systems apply water as a storage medium. Above 100 degrees centigrade other materials, like thermal oil or concrete are used as storage medium, as the cost for a steam heat storage system are very high due to the high pressure equipment needed.

The range of storage capacities covered by sensible systems is also large. For district heating and large buildings heat and cold storage systems are used that use water-carrying underground layers called aquifers. Different layers on different depths are used to store the relative warm and cold water separately. The depths vary from 50 to several hundreds of meters. The water in the aquifer can only spread horizontally as it is enclosed between impermeable layers. Capacities of aquifer thermal energy storage systems range from several ten thousands of cubic meter water equivalent to more than a million.

On a somewhat smaller scale heat is stored in water pits or large buffer tanks. In these systems the temperature is higher than in aquifer storage systems and therefore thermal insulation is necessary to minimise the thermal losses of the system. In many cases these systems are used to store solar heat for district heating systems. Most of the systems can be found in Denmark, with central solar systems, or in Germany, where they are also composed of decentralised solar thermal collectors.

At building level, insulated water tanks are used to store heat. For solar domestic hot tap water typical storage volumes are from 100 litres up to several thousands in case of room heating, while for larger buildings the range can stretch to several thousand cubic meters.

For high temperature latent storage thermal oils like silicone oil or solid materials like concrete are used. An example of the application of the latter is for the heat storage in a concentrated solar power plant. At daytime, high temperature heat coming from the concentrating parabolic trough receivers is partly used directly to generate electricity in a steam driven power plant. Another part of the heat is stored at temperatures of 400 to 500 degrees centigrade in large, well insulated blocks of concrete. By storing the heat the power plant is able to generate electricity around the clock.

Latent Heat

It takes energy to let a substance change its phase, for instance from solid to liquid or from liquid to gas. The heat necessary for this transformation is called latent heat. It is latent because the transition takes place at a fixed temperature, the melting temperature or the boiling temperature, respectively. At these temperatures the addition of heat to the substance does not lead to a temperature increase.

Latent heat is also large compared to sensible heat. For instance, the amount of heat needed to melt 1 kg of ice is equal to the heat needed to heat up water from zero degrees to eighty degrees centigrade. The fixed temperature is a typical quality of latent heat storage. It greatly determines the type of applications for which this storage technology is suited.

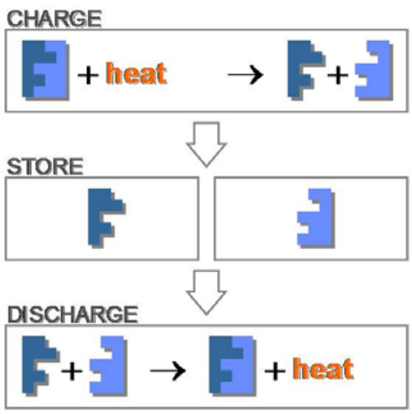
Latent heat storage materials are called phase change materials, PCM. Water is a low temperature PCM, while for room temperature applications paraffines or salt hydrates are used as PCM.

At low temperatures, latent heat storage is used in refrigeration or cooling systems, either to boost the maximum peak output of the systems or to enable the use of cheap, night time electricity for refrigeration or cooling at daytime.

At room temperatures PCM are used to increase the passive or active solar fraction of room heating. There are a lot of building products on the market now that have integrated latent heat storage material, like wood fibre board or gypsum board. With these, the heat capacity of construction elements in a building is increased which helps to increase the indoor thermal comfort.
Latent storage of solar thermal energy for hot tap water production is still in development. As the temperature difference is rather high, latent heat storage loses its relative advantage of high latent heat. The effectiveness of PCM is further decreased by its low thermal conductivity. Both the increase of latent heat storage capacity and of thermal conductivity are the main topics of R&D for this technology.
At higher temperatures, for concentrated solar power, molten salts are used as latent heat storage medium. Typically, mixtures of sodium nitrate and potassium nitrate are applied to store heat between 300 and 400 degrees centigrade. The search here is for new materials that enable storage at higher temperatures, as higher driving temperatures increase the CSP plant efficiency.

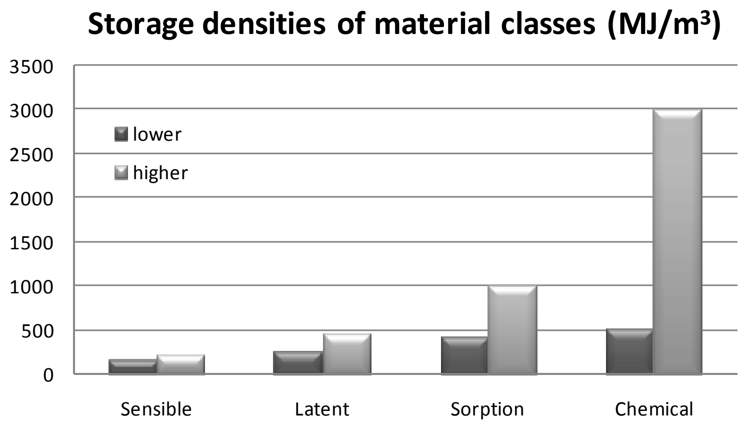
Sorption
The third class of thermal storage technologies is the sorption technology. This physical sorption principle can be subdivided into absorption and adsorption. With absorption, a vapour is absorbed by a liquid. When absorbed, a amount of heat is released that can be used externally. The temperature of absorption is dependent on the substances used and on the pressure of the system. When heat is stored again in the system, the vapour is driven out of the absorbing liquid.
Adsorption is the uptake of vapour by a porous solid. Well known adsorption materials are silica gel and zeolite. They can take up a mass of water vapour that is up to several times their own mass.
Both absorption and adsorption technologies are used in thermally driven cooling machines. The amount of active sorption material in these applications is not that large and therefore can have higher prices than for typical heat storage applications. The development activities for sorption thermal storage materials are therefore mainly aimed at finding materials that are sufficiently cost-effective.

Thermochemical
The highest potential for compact thermal storage is in thermochemical materials. The development of the technology is still in an early stage.



The principle of thermochemical storage is that heat is used to split a substance in two separate components, that can be stored separately without energy loss. When heat is needed, the two substances are brought together in a reactor to form the original compound again. The reaction produces the required heat. In principle, every reversible reaction between two components can be used. Most chemical reactions, however, generate high temperatures and thus also need high temperatures for heat storage.
Thermochemical materials that are being studied and developed most at the moment are chemical sorption materials. The storage principle is comparable to adsorption, but with chemical sorption the uptake of a vapour leads to a change in the crystalline structure and the chemical

properties of the material. Examples are salt hydrates, like copper sulphate, calcium chloride or magnesium sulphate. These have relative low hydration temperatures, making them suitable candidates for the storage of low temperature solar thermal energy.
Other chemical reactions that are studied for the storage of mostly higher temperatures are the reaction of magnesium oxide with water vapour to form magnesium hydroxide, at temperatures of around 350 degrees centigrade. Storage of heat at even higher temperatures between 450 and 500 degrees C is studied with the formation of ammonia from hydrogen and nitrogen.
The next figure gives a comparison of the ranges of the storage densities for the different thermal energy storage material classes.



The highest potential for more compact thermal storage systems is with the latent, sorption and thermochemical materials.

Task objective and organisation

The objective of the new IEA Task is to develop advanced materials for compact storage systems, suitable not only for solar thermal systems, but also for other renewable heating and cooling applications such as solar cooling, micro-cogeneration, biomass, heat pumps, concentrated solar power and district heating.
The Task covers phase change materials, thermochemical and sorption materials, and composite materials and nanostructures. It includes activities such as material development, analysis, and engineering, numerical modelling of materials and systems, development of storage components and systems, and development of standards and test methods.
The main added value of this Task is to combine the knowledge of experts from materials science as well as solar/renewable heating and energy conservation. Already at the start of the Task, 1 January 2009, more than 60 experts from over 25 organisations from 15 countries started their contribution to the Task work.
This work is subdivided into two main subtasks: Materials and Applications, reflecting the contribution from the two different IEA programs. Each subtask consists of several Working Groups that are shortly described below.

Materials Engineering and Processing
The heart of the work is in this working group, that has as objectives to study and understand compact storage materials and develop new materials with better properties, in combination with new processing technologies that enable low-cost and large scale production of these materials. This is really a long-term goal that will probably not be

achieved within the 4 year duration of the Task. The work will include the synthesis of new materials, the determination of materials characteristics, finding optimal methods for micro- and macro encapsulation of storage materials and developing novel production principles.
The first Materials activities, amongst others, are the characterisation of compound of salt hydrates as thermochemical materials, the improvement of synthesis methods of zeolites and the use of nano sized particles for the stimulation of crystallisation in phase change materials.

Materials Testing and Characterisation
The performance characteristics of novel thermal energy storage materials, like phase-change materials or thermochemical materials, often cannot be determined as straightforward as with sensible heat storage materials. In order to have proper comparison possibilities appropriate testing and characterisation procedures should be developed and assessed. The activities of this Working Group are aimed at developing these new procedures and include comparative testing of materials and their required methods, long-term stability determination and (pre-)standardisation of testing methods.

Numerical Modelling
With highly sophisticated numerical models it should be possible to find ways to optimise the storage materials in combination with the system components like heat exchanger or reactor. To this end, the existing models that describe the processes on very different length scales have to be combined. With multiscale modelling, it is possible to make the right coupling between models on the molecular scale with models on the scale a grain of storage material or on the scale of a reactor. Within this working group a series of steps is taken towards these multiscale models for phase change materials and thermochemical materials. The group has begun to describe the state-of-the-art modelling techniques for PCM and TCM on three different length scales: micro, meso and macro.

Apparatus and Component Integration
The storage apparatus is composed of the storage material and the equipment or components necessary to charge and discharge the storage material in a controlled and optimal way. These components include heat exchangers, pumps or fans and chemical reactors. In order to arrive at these optimised apparatus configurations, work will be done on: storage container and reactor design, storage apparatus design based on the selected storage material, heat transfer optimisation and apparatus and components performance assessment.

The Applications subtask has three Working Groups. The division is along the typical storage temperature of a group of applications:
Cooling, Heating and Domestic Hot Water and **High Temperature Applications.**
Although the applications themselves place very different requirements on storage technology, the steps that must be taken are very similar for all applications. Hence, the activities within the Working Groups in this Subtask are very similar as well.
The activities serve the underlying guidance principle of the materials development within the limitations of the application. The materials development will be directed by the desired system performance. A constant assessment of performance criteria for a given application will be used to determine the chances for a given material/system combination. These criteria can come from economic, environmental, production technology or market considerations. Activities in the Application Working Groups

include, amongst others, definition of application boundary conditions, definition of required thermophysical properties for each application, selection of relevant candidate materials and system technologies and performance assessment and validation.

Theoretical Limits, System Integration and Dissemination are three working groups that are common and not part of a subtask. In the first, the theoretical limits of compact thermal storage materials and systems from a physical, technical and economical viewpoint are determined. An estimate is made of the maximum possible performance to be expected from a thermal storage system in a given application, giving a set of reference points for the comparison of lab tests, field tests and commercial systems.
With System Integration, a mapping is made of all the problems to be solved when making the storage system a part of the complete energy system, while with the Dissemination work the necessary growth of involvement of new experts, especially from the materials field, is assisted.

Conclusion

If the task is successful, new compact thermal storage materials and components will become available in the future. These will enable a much higher fraction of solar thermal energy to be gained by solar thermal systems. And they will lead to better and more compact storage systems that will increase the efficiency of a number of other technologies, in buildings, industries, in districts and in power generation. The work in this Task has started in the beginning of this year and will last 4 years. Although the group already exceeds 60 experts from 15 countries, a lot of work has to be done and certainly the hands and brains of more experts are needed to increase the chances of success.
In the meantime, work on a political and decision-maker level has to be continued in order to increase the funding for better coordinated and more profound research in this field on an international level. Certainly, the creation of a new and strong Renewable Heating and Cooling – European Technology Platform, in which Storage Technology is identified as a key technology, will help this process. But most important is to attract young and enthusiastic researchers that can help to make compact thermal storage a real enabling technology.

References

(1) Website of the Joint Task 4224: www.iea-shc.org/task42

(2) *ESTTP* Solar Heating and Cooling for a Sustainable Energy Future in Europe. Vision, Potential, Deployment Roadmap, Strategic Research Agenda. 2008 www.esttp.org

(3) *PREHEAT* Heat Storage Technologies. Markets - Actors - Potentials. Work Package 4 report of the PREHEAT project. www.preheat.org

(4) J.C. Hadorn (ed.) *Thermal Energy Storage for Solar and Low Energy Buildings*. State of the art by the IEA Solar Heating and Cooling Task 32. June 2005. ISBN84-8409-877-X