

COMPARISON OF CANDIDATE MATERIALS FOR SEASONAL STORAGE OF SOLAR HEAT THROUGH DYNAMIC SIMULATION OF BUILDING AND RENEWABLE ENERGY SYSTEM

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ABSTRACT

In a survey recently conducted by ECN and the University of Utrecht in The Netherlands [Visscher, Oonk et al, 2004]), several potential thermo chemical materials (TCM's) for seasonal storage of solar heat were determined. This first selection was performed on literature data and a set of selection criteria alone.

A further selection was performed by a simulation-and-comparison procedure between storage materials in a building simulation environment, with a hot water store as a reference case.

In this way a few TCM's were identified that may offer chances for development of a new autonomous energy storage system with an effective energy storage density that is at least one order of magnitude larger than that of a hot water store.

INTRODUCTION

For a 100% solar heat supply for space heating and domestic water heating in the Northern climates it is a necessity to store energy (heat) for a period of at least half a year. In order to minimize the space requirements and associated cost of a heat storage facility in or near a residential building, the effective energy storage density of such a system has to be maximized.

As yet, no materials with a high energy storage density are known that operate between the minimum required supply temperature of about 60°C in a residential building, and the maximum operating temperature of about 250°C for a solar (vacuum tube) collector in the Northern climates. In order to assess potential candidates for such materials, a dynamic simulation of a building and its solar heat supply and storage system has been performed in the software environment Matlab/Simulink [The Mathworks, 2004].

The system concept simulated consists of four basic simulation blocks comprising the climate data, a solar collector, a simplified two-zone model of a residential building and the heat storage system. The simulation block for the heat storage system is defined as a configurable subsystem. This means that, depending on a selection parameter, the storage system is defined as a conventional hot water store, a PCM (Phase Change Material) store or as a TCM

(Thermo Chemical Material) storage system. Of these subsystem models, the TCM storage system is the most complicated one. It consists of two chemical reactors with heat exchangers for the reaction $C + \text{heat} \leftrightarrow A + B$ and a separate material buffer for each of the three reactants.

By using the configurable heat storage subsystem mentioned above, a direct comparison of different storage materials and associated storage technologies is performed in the very same building simulation environment. By using a hot water store as the reference technology, (thermo chemical) materials with an effective energy storage density that is higher than that of water can be identified. In order to maintain a fair comparison between all of the materials, the storage of reactant materials in the TCM system is under atmospheric conditions in all cases.

No definite statements can be made about the reaction rate and material conversion of the reversible chemical reactions in the TCM storage system. The materials identified therefore have to be considered as a first selection of materials that deserve further research.

BASIC REACTION PROCESS

The basic reaction process utilized here is:



Equation 1 Basic reaction process

This reaction is considered in thermodynamic equilibrium, where there is no net heat exchange between the reacting substances. The equilibrium temperature ("turnover temperature") of this reaction at standard pressure is calculated from thermodynamic data.

During summer, the solid C decomposes into the fluid or gas A and the solid B by adding solar heat at a reaction temperature that is higher than the turnover temperature. The materials A and B are stored separately until winter. In winter, A and B are mixed to start the reverse reaction at a temperature that is lower than the turnover temperature. This produces heat for residential use.

The aim of the present study is not to predict reaction rates and yields, but to assess whether a certain material would be suitable for energy storage if the

material conversion were sufficient. Material conversion is defined here as the mass fraction of the starting materials that perform the reaction desired.

Therefore, the reaction processes are supposed to take place near the turnover temperature at standard pressure, e.g. 20 K above and 20 K below this temperature. Reaction yields are supposed to be known and fixed, e.g. 80%.

ENERGY STORAGE DENSITY

Unavoidable losses in energy and space

As pointed out in the introduction, in order to minimize the space requirements and associated cost of a heat storage facility in or near a residential building, the effective energy storage density of such a system has to be maximized.

As a starting point, the thermodynamic storage density of a certain material is taken. This storage density is decreased by two factors:

- Energy losses
- Space losses

Energy losses are mainly caused by:

- Loss of reactive material due to hystereses in reaction temperature and reaction pressure
- Cooling down of hot materials leaving the reactors. This can be divided into sensible heat loss, associated with a decrease in temperature, and latent heat loss, associated with a phase change at constant temperature.
- Heat loss to the surroundings during reaction

Space losses are mainly due to:

- Geometrical free volume during storage of solid materials as granulates
- Expansion volume during chemical reaction
- Heat exchanger surface and volume

Separated versus integrated material stores and reactors

The influence of the losses mentioned above on the effective energy storage density cannot be avoided, but it can be decreased in some ways.

One way is to decrease void volume in the energy storage system. Choosing separate material stores and reactors instead of integrated stores and reactors in the storage system can do this.

This is illustrated in Figure 1 and in Figure 2. The system with separate material stores and reactors has a much smaller system volume because it does not need the reaction volume of the total material mass present, but only a relatively small reaction volume associated with the amount of material that is actually being converted in the chemical reaction.

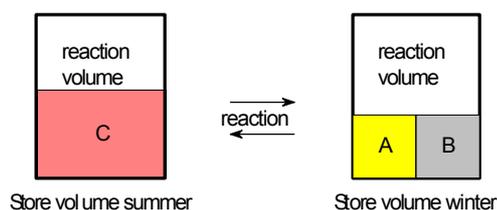


Figure 1 System volume for integrated material stores and reactors

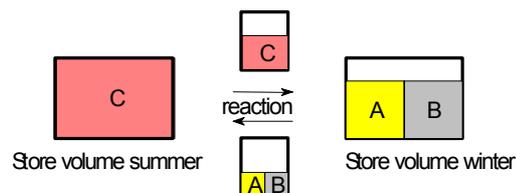


Figure 2 System volume for separate material stores and reactors

The main advantages and disadvantages of the integrated and separated system layout are summarized in Table 1.

Table 1
Integrated versus separated system concept

SYSTEM CONCEPT	ADVANTAGE	DISADVANTAGE
Integrated	No material transport	Large void reaction volume
Separated	Small void reaction volume	Transport of solids

In the system simulation in this article, the system layout with separated material buffers and reactors is chosen.

Example calculation of effective storage density

An example calculation for illustrative purposes now is made on the basis of unavoidable losses in energy and space. Here the separated system concept is taken. The expansion volume during chemical reaction then is negligible compared to the total volume of the material stores (due to relatively small reactors).

On the basis of a specific mass of 2800 kg/m³ of the starting material C, the next unavoidable losses are taken into account in this example:

- 50% volume increase due to material storage as a granulate
- 50 kJ/kg for grinding material to a fine powder after reaction and before storage of materials (2 times)
- 10 kJ/kg material transport by feeder between material stores and reactors (2 times)
- Material conversion in one-way reaction 80% (64% whole cycle)

The remaining (maximum) storage density after subtraction of unavoidable losses can now be calculated as a function of the thermodynamic storage density of a number of, yet unknown, solid thermo-chemical storage materials. In order to put this remaining storage density in the proper perspective, it is divided by that of a hot water store (temperature range 60°C-100°C; 60% storage efficiency).

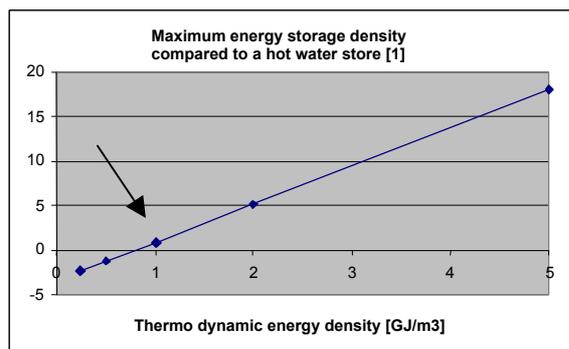


Figure 3

Illustrative example of effective energy storage density compared to that of a hot water store.

In Figure 3 the resulting data has been plotted. In this theoretical example, below a thermodynamic storage density of about 1 GJ/m³ the effective storage density is less than that of a hot water store.

As in this example calculation only unavoidable losses are taken into account, the effective storage density calculated is a maximum one. Therefore it seems fair to draw the general conclusion that a solid thermo chemical storage material will not perform better than hot water when its thermodynamic storage density is lower than about 1 GJ/m³.

PRELIMINARY MATERIAL SELECTION

Literature search

In a survey recently conducted by ECN and the University of Utrecht in The Netherlands [Visscher, Oonk et al, 2004], a list of potential thermo chemical materials (TCM's) for seasonal storage of solar heat was compiled.

The general demands for selecting materials were:

1. Decomposition reaction as in Equation 1.
2. Reaction temperature in between 60 °C and 250 °C
3. Energy storage density greater than 1 GJ/m³
4. Material is a mineral that is abundant and easy to mine.

The upper temperature limit in the second demand originates from the fact that state-of-the-art solar vacuum collectors can produce heat up to 250°C in the Northern climates. The lower temperature limit is dictated by the maximum temperature level needed in residential applications of heat (tap water heating).

The third demand originates from the reasoning in the first paragraph on unavoidable losses in energy storage systems. These losses have to be compensated for in order to maintain a higher effective storage density than that of a hot water store. Therefore a minimum thermodynamic energy storage density is needed to overcome these losses.

The fourth demand is of economic importance, as a material that possesses the right physical and chemical characteristics still would not be suitable if the cost per unit of energy stored would be higher than that of a hot water store.

In this way, approximately 88 minerals were selected for further investigation from literature data.

In many cases the values found in the literature appeared to be incomplete or inconsistent and therefore unreliable. If so, common thermo dynamical estimation methods were used to obtain the data.

Materials selection through discrimination

To narrow down the list of 88 minerals, a selection criterion was developed based upon the following characteristics:

1. Energy storage density (thermo dynamical)
2. Reactor temperature for storage process
3. Corrosiveness at storage and/or reaction
4. Environmental impact and toxicity of the material
5. Cost of the material (abundance / easy to mine)
6. Number of material components during synthesis reaction
7. Reactor pressure

These characteristics are chosen to be (as far as possible) independent of each other. For each characteristic, a so-called "potential" (ranging from 0 to 1) was defined as a function of the value of that specific characteristic. By doing so, the range of "best values", "bad values" and everything in between of this specific characteristic is designated by means of the potential curve.

By multiplying the separate potentials an overall "realisation potential" is calculated:

Realisation potential = product of separate potentials

The realisation potential thus is a measure for the extent to which a material may meet the "best values" of all of the characteristics 1 through 7 above.

This selection criterion is a very strict one that is highly discriminating. For instance, if some material has a potential equalling zero for only one of the characteristics 1 through 7 above, then the realisation potential is zero. In this way, most of the materials from the list of 88 received a realisation potential equal to zero.

By sorting the list of 88 minerals by their realisation potential, and setting a minimum for this, a shortlist was found. In Table 2, the minerals with a realisation potential higher than 1% are listed.

From Table 2 the top four materials are chosen as the storage material in a seasonal heat store as part of a dynamic building simulation.

Table 2
Minerals with a realisation potential higher than 1%.

MATERIAL	CHEMICAL FORMULA	REALISATION POTENTIAL
Magnesium sulphate	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	9.5%
Iron carbonate	FeCO_3	6.3%
Iron hydroxide	$\text{Fe}(\text{OH})_2$	4.8%
Calcium sulphate	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	4.3%
Magnesium sulphate	$\text{MgSO}_4 \cdot \text{H}_2\text{O}$	2.7%
Zinc carbonate	ZnCO_3	1.6%
Calcium chloride	$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	1.1%

SIMULATION

A dynamic building simulation model was set-up in the software environment Matlab/Simulink [The Mathworks, 2004]. The system concept simulated is illustrated in Figure 4. A solar vacuum tube collector receives solar radiation and delivers its heat to a seasonal heat store. A residential building uses heat from the seasonal store for space heating. The storage of heat is mainly in summer, and the use of heat from the store is mainly in winter.

The exchange of heat between model blocks is realised through capacity rates (capacity rate = mass flow times specific heat) and counter-flow heat exchangers. In this way it is ensured that everywhere in the simulation model the heat transport is due to some temperature difference and does not contradict the law of thermodynamics.

The seasonal heat store in Figure 4 is modelled as a so-called "configurable subsystem". This means that it contains several heat store models ("members"), from which one is picked during a simulation. In the current simulation, the members are an insulated hot water store and a TCM store. The advantage of this approach is that different heat store models can be compared directly in one and the same building simulation environment.

By using the hot water store as the reference technology, (thermo chemical) materials with an effective energy storage density that is higher than that of water can be identified.

In order to maintain a fair comparison between all of the materials, the storage of reactant materials in the TCM system is under atmospheric conditions in all cases.

Climate data

The climate data set used is a compiled set of data from the weather station at De Bilt in The Netherlands. This data set is usually referred to as the "standard De Bilt Climate data set" [KNMI, 1990's].

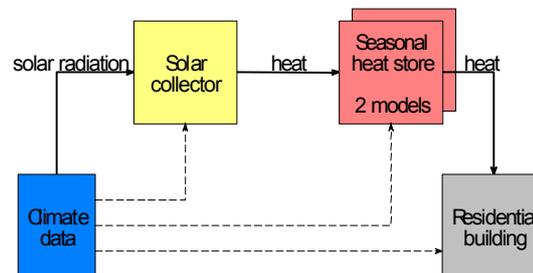


Figure 4 Basic simulation model

Solar collector

The solar collector is modelled by the well-known linear equation in the incident solar radiation and the difference between the averaged collector temperature and ambient temperature. [Duffie, Beckman, 1991]. Taking the mean of the inlet temperature and the outlet temperature approximates the averaged collector temperature. The result takes the form of the well-known collector equation with a flow rate dependent heat removal factor.

The collector coefficients for solar efficiency and thermal loss are taken from an existing concentrating vacuum collector of the so-called "Sydney-type" [Microtherm Energietechnik GmbH, 1999]. These coefficients have been determined independently by the SPF in Switzerland [Solartechnik Prüfung Forschung (SPF), 1999]. In the simulation, the collector is oriented to the south at an angle of 30 degrees with the horizontal plane.

Residential building

For the residential building a two-zone simple building model is used. The building is representative for newly built dwellings in The Netherlands. The yearly heat demand of the building is about 35 GJ, which would be equivalent to the energy content of about 1000 m³ of natural gas.

Hot water store

The hot water store is modelled as a water-filled container with heat loss to its surroundings. Its heat content is calculated from the enthalpy function of water with respect to the minimum demand temperature for heat, which is about 60°C in a residential dwelling.

TCM store

The TCM storage system consists of two chemical reactors with heat exchangers for the reaction $C + \text{heat} \rightleftharpoons A + B$ and a separate material buffer for each of the three reactants, as depicted in Figure 5.

The materials A, B and C are modelled by their enthalpy function at constant atmospheric pressure, so that sensible heat as well as latent heat is taken into account. Also heat losses are taken into account. The two reactors are thermally well insulated, and the three material stores are poorly insulated.

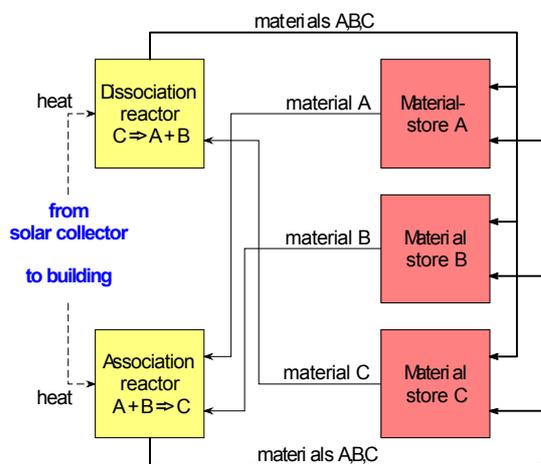


Figure 5 Basic TCM store model

When solar radiation is added to the dissociation reactor, Material C is transported from material store C to the dissociation reactor. In the reactor it is heated up to the reactor temperature and partly dissociated into materials A and B. Next the hot materials A and B and the remaining part of material C are transported back to their respective material stores, where they are allowed to cool down.

When heat is extracted from the association reactor, Materials A and B are transported from their material stores to the association reactor. In the reactor, the materials are heated up to the reactor temperature and partly associate into material C. Next the hot material C and the remaining part of the materials A and B are transported back to their respective material stores, where they are allowed to cool down.

Material stores

Each material store is modelled as a (large) material-filled container with a fixed heat loss coefficient of 100 W/K between the store and its surroundings. Its heat content is calculated from its enthalpy function with respect to some reference temperature. Its temperature is the result of inflowing and outgoing enthalpy flows.

The volume needed for a material store is calculated after each simulation run from the minimum amount of material needed in the store, and the storage density of that material. The volume of a fluid or gas (material A) is equal to its mass divided by its mass density. The volume of a solid (materials C and B) however is not, because it is stored as granulate or fine powder. From commercial abrasives (these are fine powders) it was found that on average the store volume is about 1.5 times the volume calculated from its pure material mass density.

Material transport losses

The transportation of materials between the material stores and the reactor vessels costs energy. For each material flow a characteristic value of 10 kJ/kg is

used that was derived from the energy consumption of a commercial feeder.

Reacted matter has to be stored as compact as possible. As in general it is not readily available as a fine powder, it has to be grinded before feeding it back to the material stores. For the energy consumption of grinding a characteristic value of 50 kJ/kg was derived from the breaking and grinding of natural gypsum on an industrial scale.

Simplified reactor model

The reactor vessels are modelled as containers with a fixed heat loss coefficient of 2 to 3 W/K. The volumes of the reactors are not taken into account, for these are thought to be negligible small compared to the large material stores for A, B and C. Their temperatures are fixed (see below).

As noted before, the chemical reaction $C + \text{heat} \rightleftharpoons A + B$ is supposed to take place near the turnover temperature at standard pressure. Reaction yields are supposed to be known and fixed.

In this case, the temperature of the dissociation reactor is taken 20°C higher and the temperature of the association reactor is taken 20°C lower than the turnover temperature. The material conversion for dissociation and for association is taken to be 80% and constant. The materials A and B are fed into the association reactor at stoichiometric proportions.

The reaction itself is modelled on basis of its enthalpy function. When heat is added to the dissociation reactor, material C is fed into it and partly converted into materials A and B, thus absorbing an amount of heat. This amount is taken to be the enthalpy change of the reaction at standard temperature and standard pressure (1 atm, 25°C).

The heat added to the dissociation reactor now equals the rise in enthalpy from the starting material C at store temperature to the final mixture of C, A and B at the known reactor temperature, plus the heat absorbed by the reaction, plus the heat loss from the reactor vessel.

When heat is withdrawn from the association reactor, materials A and B are fed into it and partly converted into material C, thus releasing an amount of heat. This amount is taken to be the enthalpy change of the reaction at standard temperature and standard pressure (1 atm, 25°C).

The heat delivered by the association reactor now equals the heat produced by the reaction, minus the rise in enthalpy from the starting materials A and B at store temperature to the final mixture of A, B and C at the known reactor temperature, and minus the heat loss from the reactor vessel.

Simulation runs

The top four of the minerals in Table 2 have been simulated with the TCM store model of Figure 5, and in the building simulation of Figure 4. Additionally an insulated hot water store has been simulated as a

reference case. The simulations have been assigned the run code numbers defined in Table 3. These numbers are only used to refer to a specific simulation run of the model in Figure 4 and serve no other purpose. The remark "Latent heat recovery" in Table 3 means that during the dissociation reaction the incoming mass flow is pre-heated by condensation of the water vapour resulting from the dissociation reaction.

Table 3
Simulation run codes

RUN CODE	MATERIAL	REMARK
100	Water	Reference case
200	Magnesium sulphate	No heat recovery
210		Latent heat recovery
400	Iron carbonate	
500	Iron hydroxide	No heat recovery
510		Latent heat recovery
600	Calcium	No heat recovery
610	sulphate	Latent heat recovery

The simulated chemical reactions, as well as the reference case (run code 100), are given in Table 4.

Table 4
Simulated chemical reactions of the materials

RUN CODE	MATERIAL REACTION		
	C ⇌	B +	A
100	H ₂ O	none	none
200	MgSO ₄ •7H ₂ O	MgSO ₄	H ₂ O
210			
400	FeCO ₃	FeO	CO ₂
500	Fe(OH) ₂	FeO	H ₂ O
510			
600	CaSO ₄ •2H ₂ O	CaSO ₄	H ₂ O
610			

Table 5
Thermo dynamic characteristics of the materials.

RUN CODE	MATERIAL C	THERMO DYNAMIC ENERGY STORAGE DENSITY	TURNOVER TEMPERATURE
		[GJ/m ³]	[°C]
100	H ₂ O	0.16	n.a.
200	MgSO ₄ •7H ₂ O	2.8	122
210			
400	FeCO ₃	2.6	180
500	Fe(OH) ₂	2.2	150
510			
600	CaSO ₄ •2H ₂ O	1.4	89
610			

As an illustration of the functioning of the building simulation with the TCM store, the temperature of material store A and the material mass in stores A, B

and C during the year are plotted in Figure 7 and in Figure 8. In Figure 6 the corresponding indoor temperature of the residential building and the ambient temperature are given.

The thermodynamic energy storage density, related to material C, and the turnover temperature of the chemical reaction at standard pressure are given in Table 5. The thermodynamic energy storage density of water is calculated for the temperature range 60°C-100°C with a storage efficiency of 60% (40% heat loss to the surroundings).

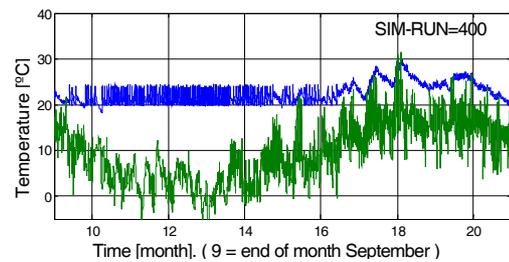


Figure 6 Building and ambient temperature.

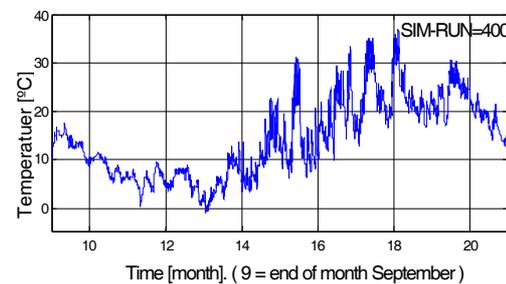


Figure 7 Temperature in material store A.

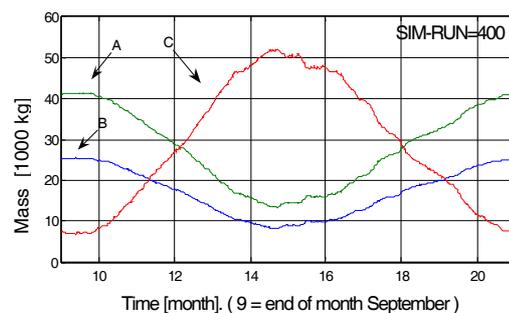


Figure 8 Mass in material stores A, B and C.

Initial conditions

The simulation year starts at October 1st with the heat store charged at 95% of its storage capacity. The initial storage capacity of the heat store is chosen to be 1.5 times the yearly heat demand of the residential building. The initial collector area is 25 m².

Determination of optimum collector area and optimum buffer capacity

The collector area for which the enthalpy in the heat store at the end of the simulation year equals that at the beginning is taken as the optimum. It is

approximated by recursively running a simulation for different collector areas. The recursive loop stops when the difference between the enthalpy at the beginning and the end of the year differs less than 2% from the buffer capacity that is actually used. The optimum collector area is approximated from the difference in enthalpy as a function of the collector area, as in Figure 9.

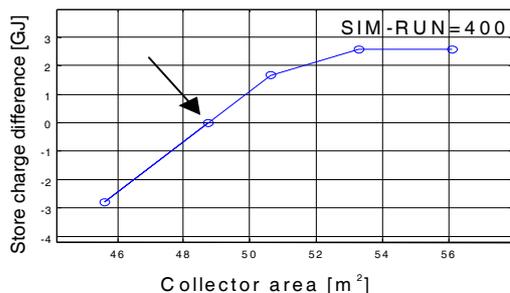


Figure 9 Determination of collector area

Next, the simulation is run for the optimum collector area determined, and the State Of Heat (SOH=actual enthalpy in store divided by its maximum enthalpy) during the year is plotted.

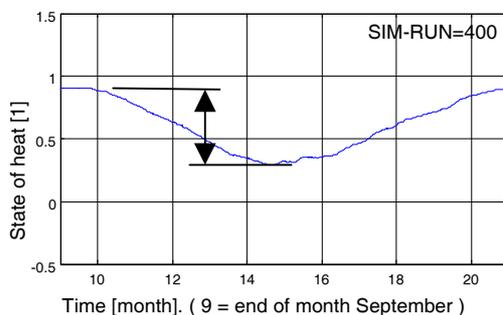


Figure 10 Determination of optimum capacity for a TCM store.

For a TCM store the optimum store capacity is simply the difference between the maximum and minimum enthalpy of the store, as in Figure 10. In the case of the hot water store, the store capacity is defined as the enthalpy of the store with respect to the minimum load temperature, which is 60°C. When its temperature is below 60°C, its enthalpy is negative. The optimum storage capacity now is found when the lowest value of the enthalpy during the year is zero

Performance characteristics

In order to be able to assess the performance of the TCM's simulated in the TCM store with respect to a hot water store some characteristic performance numbers have to be chosen for the building simulation model as a whole. Here we choose:

- Collector area
- Material store volume
- Cycle energy storage density

What the collector area and store volume are is clear, but the cycle energy storage density is not easy to

define. This is because we can measure the loss of energy over the whole cycle, but we cannot determine its partition over the storage and release of energy.

A way to overcome this difficulty is to make a practical definition that however cannot be derived from theory. Such a definition is in this case:

$$\text{cycle energy storage density} = \frac{\text{energy storage}}{\text{density}} \times \text{cycle efficiency}$$

- The energy storage density is defined as the maximum enthalpy change of the store divided by its total volume.
- The cycle efficiency is defined as the yearly heat released from the heat store divided by the heat added to it.

The definitions above are general in nature and apply to any kind of energy store.

SIMULATION RESULTS

In Table 6 the performance characteristics are given of the materials used in the heat store of the building simulation model. For the store volume and the cycle energy storage density two values are given for each material. In the case of water (run code 100) this is the gross volume, this is the water volume plus the thermal insulation foam volume, and the net water volume. In the case of the TCM's it is the volume for storing materials A,B and C, and the volume for storing only materials B and C. In the latter case the material A is a fluid or gas that can be release to and withdrawn from the atmosphere. For all but one run numbers this is water vapour. For run number 400 this is CO₂. However, its concentration in the atmosphere is too low to be of practical value.

Table 6
Performance characteristics of the materials.

RUN CODE	COLLECTOR AREA [m ²]	STORE VOLUME [m ³]		CYCLE ENERGY STORAGE DENSITY [GJ/m ³]	
		Gross	Material	Gross	Material
Water (reference)		Gross	Material	Gross	Material
100	67	375	321	0.03	0.04
TCM's		ABC	BC	ABC	BC
200	65	35	24	0.33	0.47
210	35	28	20	0.61	0.88
400	49	8724	25	0.00	0.73
500	90	54	41	0.21	0.27
510	49	43	33	0.37	0.49
600	50	57	47	0.18	0.21
610	31	57	47	0.28	0.34

From Table 6 a set of dimensionless performance numbers for the TCM's can be calculated by dividing each number by its corresponding number for the hot

water store (run code 100) in the same column. With the dimensionless performance numbers in Table 7 now it is easy to assess the performance of the TCM's simulated.

Table 7
Dimensionless performance numbers for the TCM's.

RUN CODE	COL-LEC-TOR AREA	STORE VOLUME		CYCLE ENERGY STORAGE DENSITY	
	[1]	[1]		[1]	
TCM's		ABC	BC	ABC	BC
200	0.97	0.09	0.08	10	12
210	0.52	0.07	0.06	18	22
400	0.73	23	0.08	0	18
500	1.34	0.14	0.13	6	7
510	0.74	0.11	0.10	11	12
600	0.75	0.15	0.15	5	5
610	0.47	0.15	0.15	8	9

DISCUSSION AND RESULT ANALYSIS

From Table 7 it follows that a reaction involving CO₂ as material A (run code 400) never performs better than a hot water store. This is mainly because CO₂ is a gas that cannot be condensed at ambient temperature and pressure. Further the release of CO₂ into the atmosphere for the dissociation reaction and the subsequent withdrawal for the association reaction is not of practical value because its concentration in the atmosphere is too low.

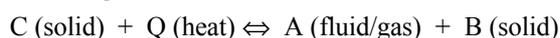
In all other run cases material A is water vapour and is released during the dissociation reaction. Water could be stored in liquid form, however a far higher cycle storage density is reached when it is released into the atmosphere. For the association reaction water vapour could be used from the atmosphere or from some water source. In all run cases where latent heat recovery is used, the cycle storage density is increased by more than 60% and the collector area needed is reduced by more than 40%.

The relative performance of the materials appears to be in line with the order of materials by thermodynamic energy storage density in Table 5. The best scoring materials are magnesium sulphate and iron hydroxide, with latent heat recovery.

However, the simulations performed make no prediction about the true material conversion, reaction rates and side reactions that result in loss of reactive materials. The simulations just show how the materials would perform at 80% material conversion.

CONCLUSION

In this research the application of several TCM's was simulated for a system layout with separate material stores and reactors. The TCM's perform the following reversible reaction:



Magnesium sulphate and iron hydroxide, both with latent heat recovery, appear to be the most promising materials for enhancing the cycle energy storage density by one order of magnitude compared to a hot water store.

No definite statements can be made about the reaction rate and material conversion of the reversible chemical reactions in the TCM storage system. The properties of the materials selected are in accordance with the required thermodynamic and technical conditions, but their practical application still has to be demonstrated. This can pose many practical problems.

ACKNOWLEDGMENT

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