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Solar heating and cooling system with absorption chiller and latent heat storage - A research project summary -

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Abstract

A reliable solar thermal cooling and heating system with high solar fraction and seasonal energy efficiency ratio (SEER) is preferable. By now, bulky sensible buffer tanks are used to improve the solar fraction for heating purposes. During summertime when solar heat is converted into useful cold by means of sorption chillers the waste heat dissipation to the ambient is the critical factor. If a dry cooler is installed the performance of the sorption machine suffers from high cooling water temperatures, especially on hot days. In contrast, a wet cooling tower causes expensive water treatment, formation of fog and the risk of legionella and bacterial growth. To overcome these problems a latent heat storage based on a cheap salt hydrate has been developed to support a dry cooler on hot days, whereby a constant low cooling water temperature for the sorption machine is ensured. Therefore the need of a wet cooling tower is avoided and neither make-up water nor maintenance is needed. The same storage serves as additional low temperature heat storage for heating purposes allowing optimal solar yield due to constant low storage temperatures. Four pilot installations between 7 kW and 90 kW nominal cooling capacity were equipped with latent heat storages between 80 kWh and 240 kWh energy content. Annual in situ measurement data shows a positive effect on the seasonal energy efficiency ratio (SEER) for cooling up to 11.4. Furthermore simulation results under different climatic conditions indicate raising efficiency up to 64% compared to a system with solely dry re-cooling. Long-term test bench measuring data concerning performance and durability as well as a new approach for a state of charge detection for latent heat storages are presented as well.

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Keywords: sorption chiller; latent heat storage; phase change material; dry re-cooling;seasonal performance; annual simulation

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1. Motivation and solution approach

In reliable solar thermal installations for heating, cooling and domestic hot water preparation a high solar fraction with minimum effort on auxiliary electricity and primary energy consumption is preferable.

During the heating season the solar yield is directly used for space heating or stored in buffer and hot water tanks for later use. In order to achieve high solar fractions bulky sensible storages up to a specific volume of 100 liter per square meter collector area are installed. Due to the increase in temperature up to 95 °C of the sensible heat storage medium (mostly water) during loading the average solar thermal collector temperature rises resulting in diminished total collector system effectiveness. Furthermore the high buffer tank temperatures cause high radiation and convective losses if no enhanced insulation is applied. This deteriorates the specific electricity consumption of the useful heat supplied to the building and for domestic hot water preparation.

In summertime when chilled water for climatisation is needed the harvested solar thermal energy is converted into useful cold by means of Ab- and Adsorption machines starting at driving heat temperatures above 60 °C, whereby their performance is mainly influenced by the temperature level of the three main hydraulic circuits namely chilled water, cooling water and driving heat. While the chilled water supply temperature is defined by the HVAC installation of the building and material properties limit the driving heat temperature to 100 °C, the cooling water temperature depends on the climatic conditions and cooler type.

In most sorption cooling installations wet cooling towers are applied for waste heat dissipation to the ambient allowing a minimum cooling water return temperature of about 8 K above the wet bulb air temperature. This approach can be reduced by disproportional increase of the heat exchanger surface and/or air flow in the cooler, whereas less than 4 K will be extremely cost-intensive and/or auxiliary electricity consuming. On the one hand the low cooling water temperatures, even below the ambient air temperature, have a beneficial effect on the chilling capacity and thermal Coefficient of Performance (COP) of the sorption chiller. But on the other hand due to the open water system of wet cooling towers the risk of legionella and bacterial growth as well as calcification and fouling require a costly water treatment system and high maintenance/inspection effort. Furthermore legal restrictions concerning vapor plumes, noise prevention and bacterial monitoring as well as limited market availability of wet cooling towers for small scale sorption cooling systems are hindering facts for their use.

If an almost maintenance-free dry air cooler is installed cooling water return temperature increases significantly and is in economic terms limited to 4 K above the ambient air temperature. As a consequence of the increase in cooling water temperature the thermal Coefficient of Performance (COP) falls as well as the chilling capacity if the driving heat temperature is not increased accordingly. Due to the solely sensible heat transfer a huge specific heat exchanger surface resulting in an enormous footprint and a high air flow through the cooler is needed.

Hybrid cooler combine the advantages and disadvantages of aforementioned cooler types. But due to the high investment costs and the open water system a comprehensive implementation especially in small to medium sized solar heating and cooling systems is questionable.

A favorable situation is given when low temperature heating and cooling facilities, e.g. floor or wall heating systems, activated ceilings or fan coils, are applied in the building. Especially for this kind of low exergy space heating systems a latent heat storage allows low operating temperature of the solar thermal system, yielding efficient operation with solar gain due to constant low storage temperatures. High amounts of thermal energy can be stored at a certain phase change temperature while the storage material changes its phase (e.g. solid to liquid). Particularly at small temperature differences between loading and unloading the volumetric storage density of latent heat storages is significantly higher compared to common sensible water buffer tanks.

During summertime when chilled water is provided by the sorption chiller, the same storage can be used in combination with a low-maintenance dry cooling tower to avoid an unpreferable wet cooling tower. By partly absorbing the waste heat of the chiller during daytime the latent heat storage supports the dry cooler and ensures constant low cooling water temperatures even on hot days. The accumulated waste heat is then dissipated to the ambient during nighttime. By that means heat dissipation of the chiller is shifted partly to periods with lower ambient temperatures, i.e. night time, or to off-peak hours.

Nomenclature

COP	Coefficient of performance
dc	Solar cooling installation with solely dry re-cooling
dc+lhs	Solar cooling installation with dry re-cooling supported by a latent heat storage
HVAC	Heating, ventilation, air conditioning
LHS	Latent heat storage
NTU	Number of transfer units
PCM	Phase change material
SEER	Seasonal energy efficiency ratio
SOC	State of charge of the latent heat storage

2. System concept

The goal of the novel system concept is an overall enhanced system efficiency concerning high solar fraction and reduced auxiliary electricity consumption to improve the seasonal energy efficiency ratio (SEER) at acceptable investment and maintenance effort.

In the following the general energy flows between the main components of the solar heating and cooling system (SHC-System) and nominal temperatures within the hydraulic circuits are described. Figure 1(a) shows the system in cooling mode. Solar thermal energy from the solar collectors (orange circuit) is provided to the desorber of the chiller at about 90 °C to run the internal sorption process producing 15 °C chilled water for the cooling system of the building (blue circuit). Heat surpluses are stored in a small hot water tank, installed in parallel to the chiller, which serves as additional heat source in times of insufficient solar power. Thus, a constant operation of the sorption chiller at cloudy days and an extended run-duration in the evening is ensured. The heated cooling water (green circuit) enters the dry air cooler with a nominal temperature of 40 °C. The usage of a dry cooler instead of a wet cooling tower avoids legionella growth, the effort for water treatment, the need of fresh water and additional electricity for the spraying device. At a design point ambient air temperature of 32 °C the dry air cooler dissipates about 50 % of the total waste heat and reduces the heat carrier medium temperature to about 36 °C. Following this, an additional cooling takes place in the latent heat storage by melting a phase change material (PCM). By means of this combination the cooling water return temperature to the chiller remains constant at 32 °C even at ambient air temperatures above nominal values. On colder days firstly the waste heat storage ratio in the latent heat storage and secondly the fan speed of the dry air cooler is reduced according to the cooling water return temperature.

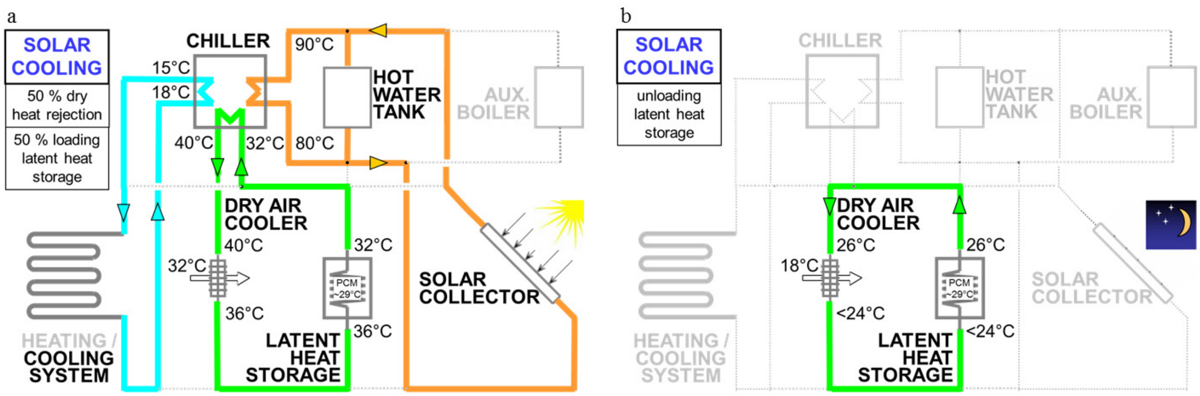


Fig. 1.(a)System concept in cooling mode during daytime to support a dry cooler on hot days; (b)System concept in cooling mode during nighttime when unloading of the latent heat storage takes place

Depending on the ambient air and cooling demand a certain amount of phase change material in the latent heat storage is molten at the end of a day and has to be solidified until the next morning. Figure 1 (b) shows the active cooling circuit (green) during nighttime while unloading the latent heat storage. In general ambient air temperature has to fall significantly below phase change temperature for an efficient unloading. The variability of unloading time and duration according to the ambient air conditions and state of charge (SOC) as well as the consideration of flexible off-peak energy prices allow for an efficient and economic waste heat dissipation. Thus far, the conceivably usage of the stored energy for tap water preheating is not taken into account.

The system is mainly designed for cooling mode; nevertheless the harvested solar energy can be directly used to assist the heating system in the cold season as well. If the return temperature of the heating system is below the phase change temperature of the storage preheating is possible. In this case the same latent heat storage serves as additional low temperature storage allowing for significantly increased solar fraction due to enhanced collector efficiency at lower average aperture temperatures and reduced thermal losses.

Figure 2(a) describes how solar energy is either directly used in the heating system of the buiding or stored for later use. In this connection the advantages of both thermal storage technics are taken. Depending on the insolation solar energy is either stored at high temperatures in the hot water tank mainly for hot water preparation and/or accumulated in the latent heat storage at constant level for preheating the return flow of the buidling as shown in Figure 2 (b). In times with insufficient insolation an auxiliary boiler ensures a reliable heating of the building.

Although the shown outlet temperature of the latent heat storage of 27 °C seems very low for heating purposes most of the solar yield is harvested in the transition time where the necessary supply temperature to the heating system is quite lower than the exemplary 32 °C.

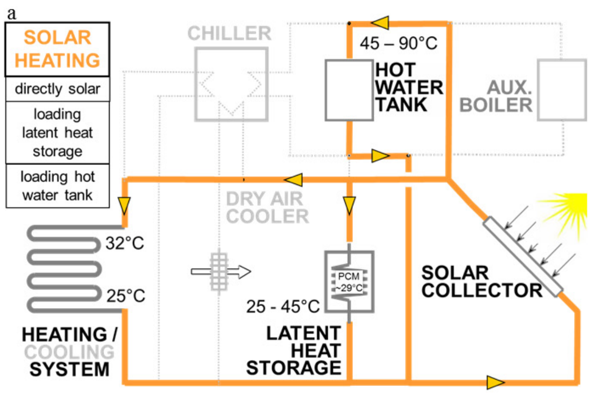


Fig. 2.(a) System concept in heating mode at sunny days when solar energy is directly used in the building heating system or accumulated in the two different thermal storage types; (b) System concept in heating mode during nighttime or overcast sky when heat is provided by the storages.

3. Methodology and tools

The triennial research project with industrial cooperation comprises latent heat storage sample development and extensive testing concerning thermodynamic performance and long-term durability. The ideal thermal design of the heat exchanger matrix is determined by a Mathcad Simulation and several small scale samples were tested. In parallel, the containment was design and evaluated by CAD and FEM methods. To characterize the performance of the latent heat storage a full scale sample is tested on a test bench with more than 200 cycles for two years. A Matlab-Simulink simulation is set up to analyses the efficiency of the novel system concept under different climatic conditions. Furthermore the latent heat storage sample is installed in 4 solar cooling pilot installations in Germany, France and Austria to investigate the functionality of the novel system concept and storage. The nominal cooling capacities are between 7.5 kW and 90 kW and all systems run with just a dry cooler. The installed energy amount of the latent heat storage varies from 80 kWh to 240 kWh.

4. Latent heat storage

For the given application in a solar heating and cooling system, thermal energy has to be stored in a very narrow temperature range in order to fulfill both tasks. Supporting the heat dissipation system of the chiller requires a phase change temperature below 32 °C and for acceptable preheating of the building a phase change temperature above 26 °C is necessary.

With a phase change temperature around 29 °C Calcium chloride hexahydrate fits perfectly these requirements. In this application the solid to liquid phase change of the phase change material with a melting enthalpy of about 150 J/g or 240 kJ/Liter between 22 °C and 36 °C. is used. The specific storage capacity comprises both sensible and latent heat. Of course the dominating portion is to be attributed to the latent part.

4.1. Latent heat storage development and testing

In close collaboration with our industrial partner Clina-Bionic Systems GmbH, Berlin two different latent heat storage module sizes with internal heat exchanger matrix have been developed; one storage containing 1 m³ of phase change material providing 14 kW nominal thermal power and a storage capacity of 83 kWh and another one with 1.5 m³ storage volume and 21 kW nominal thermal power at 124 kWh storage capacity. The heat exchanger exists of capillary tubes providing 36.7 m² heat exchanger surface per cubic meter phase change material and generates really low pressure loss in the external hydraulic circuit.

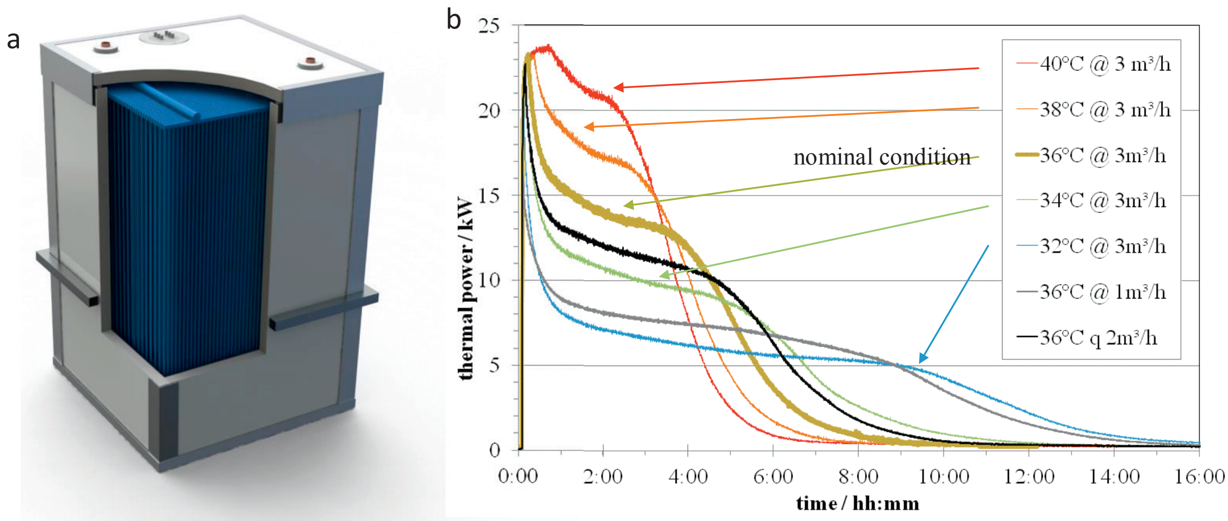


Fig. 3. (a) Latent Heat Storage sample 1.5 m³ (CAD break-out view); (b) performance of the storage at different conditions.

Figure 3 (a) shows the rendered CAD-model of a 1.5 m³ latent heat storage sample with a footprint of 1x1 meter and 1.7 m height. The cross-sectional view gives free insight to the blue capillary tube matrix. Figure 3 (b) displays the test bench measuring results of a 1 m³ latent heat storage sample containing only a reduce amount of 0.9 m³ of phase change material due to further analysis while loading with different flow rates and temperatures. The latent plateau between 0:00 and 4:00 hours is quite stable and a thermal power of 22 kW can be reached at a external heat carrier medium flow of 3 m³/h at 40 °C inlet temperature. The nominal operation condition at 36 °C inlet temperature at 3 m³/h is shown as well. The thermal power at the latent plateau is between 16 kW and 12 kW and the duration of the plateau can be evaluated to four hours. Further details have been shown earlier. [1]

4.2. Durability and long-term stability testing

Despite the favorable thermodynamic properties of the inflammable, cheap and nontoxic storage medium Calciumchloride hexahydrate tends to separate. Because of that a low cost anti-separation-unit has been developed which continuously circulates the storage material.

To evaluate a possible decrease in thermal power or energy content, the nominal condition cycle (volume flow of 3 m³/h, 36°C inlet temperature at loading, 22°C at unloading respectively) has been tested continuously in the past two years within more than 240 cycles. The results of the quarterly examination concerning heat content and thermal power are shown in Figure 4 (a) and (b). The maximum deviance between measured energy content at unloading (22°C, 3 m³/h) is ± 1%. The measurement data at loading (36°C, 3 m³/h) shows higher variation, because the insulation of the inlet and outlet pipe had been improved after March 2012. While unloading (22°C, 3 m³/h) the difference between the measured thermal power is negligible, at loading, the thermal power before insulation is little higher due to higher energy losses, but the shape of the plateau is equal.

To evaluate the separation and methods for regeneration of the storage in case of a malfunction of the anti-separation-unit, this device had been shut off between June 2012 and September 2012. As expected the PCM separated after the first nominal condition cycle and a decrease in thermal power and storage capacity was detected. After 14 complete cycles with deactivated mixing device over 1 month the thermal power decreased by 22% and a reduced storage capacity of almost 10% was measured. With reactivating the anti-separation-unit and heating the PCM above the melting temperature of its separation components, a full regeneration was accomplished.

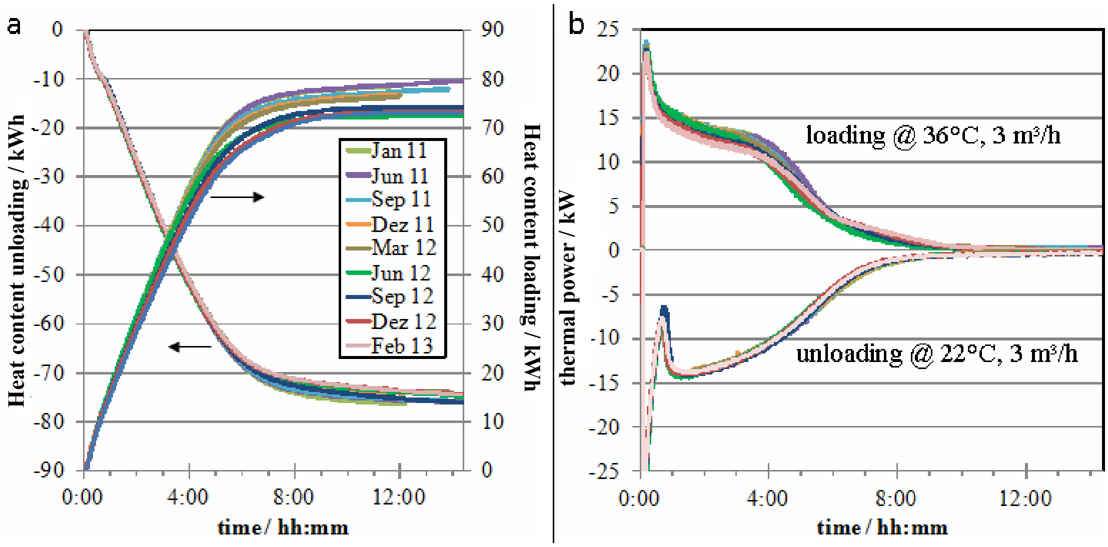


Fig. 4. Long term stability test of a 1m³ latent heat storage sample with 3 m³/h external heat carrier medium flow and temperatures of 36 °C during loading and 22 °C during unloading. Measured heat content (a) and power (b) at nominal cycle, repeated quarterly over 2 years.

The shown data of the complete loading and unloading cycles is measured by a calibrated heat meter. When such a latent heat storage is installed in a solar cooling and heating installation the exact state of charge has to be known for efficient operation. There an energy balancing by heat meters is inaccurate due to non-detectable heat losses during the recurrent half cycles and idle time. While the instantaneous amount of stored energy for a sensible storage can be easily detected by temperature measuring of the storage material, a new method has to be developed for latent heat storages due to the constant storage temperatures in the latent phase.

4.3. State-of-charge determination for latent heat storages

The state-of-charge (SOC) of sensible heat storages can easily be determined via temperature measurement. However, due to the isothermal phase change this method does not work with latent heat storages. At the moment, state-of-charge determination for latent heat storages is limited to ice storages. The commercial systems avail themselves of the anomalous density of water and are therefore limited to this very PCM.

For that reason a new system for measuring the SOC of latent heat storages has been developed at ZAE Bayern and extensively tested on a functional model of a PCM-storage for HVAC applications. The results have high repeat accuracy and show good correlation to a heat meter which measures the heat transferred to the storage. The next step of development is to transfer the technology to a full-size latent heat storage with a heat capacity of 120 kWh.

Figure 5 shows measurement data of five unloading (0 – 14 h) and loading cycles (14 – 28 h). The black broken line is the reference SOC measured with a calibrated heat meter. Note that a heat meter can be accurate and almost immune to environmental influences, the deviation between different cycles is small. However, thermal loss leads to significant errors if the meter is not reset every complete cycle (see hours 24 – 28).

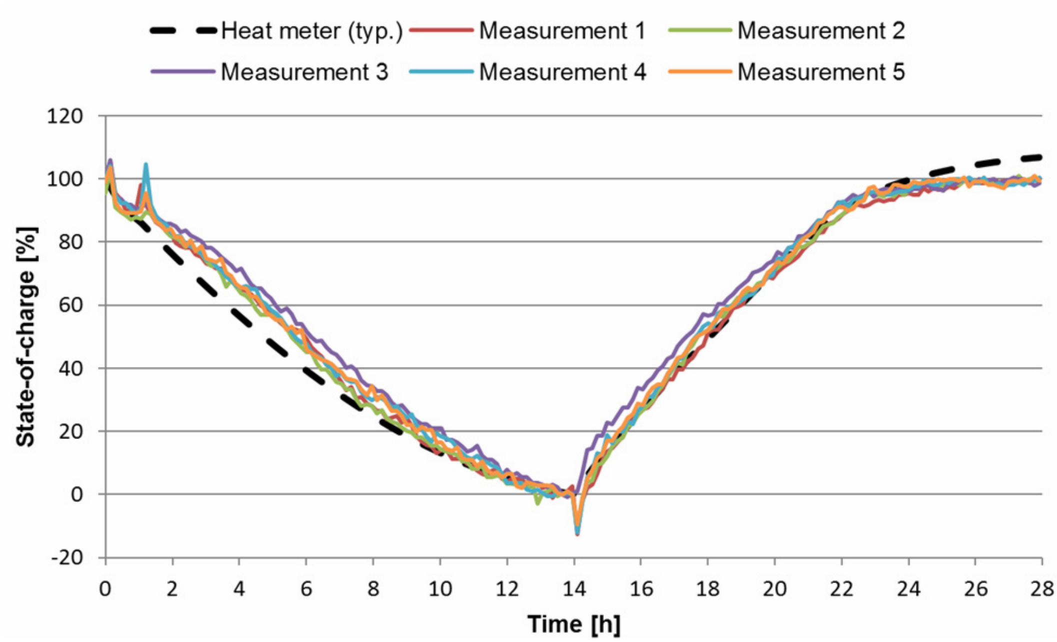


Fig. 5. Analysis of 5 nominal measuring cycles (Loading at 36 °C and Unloading at 22 °C). Heat meter vs. state-of-charge- detection 1 to 5.

The examined SOC determination shows acceptable deviation between measurements 1 – 5 due to environmental influence. But this tradeoff is compensated by its ability to calibrate automatically and impassiveness to heat losses of the storage itself in idle times.

5. System simulation under different climatic conditions

For annual simulations of the energy system under different climatic conditions the energy system is modeled as time continuous simulation in Matlab Simulink. The system is modeled according the real solar cooling system at ZAE Bayern in Garching, Germany with a nominal chilled water power of 10 kW at design point conditions.

All components except the buffer storage are modeled as 1-dimensional components with part-load behavior following physical correlations. The flat plate collector's efficiency curve is modeled according to DIN 1245 and the heat exchanger follows the NTU-method. The hot water buffer storage is modeled as finite-volume model with n-cylindrical slices, where for every slice free and forced convection, conduction and energy loss is calculated. For the absorption chiller the 'characteristic equation' [2, 3, 4] is used, which allows a calculation of the energy balance by only taking into account the external capacity flows. The part-load behavior is described by a plant-specific linear correlation between the instantaneous external temperatures and the thermal power of the evaporator and the desorber. In the waste heat cycle, the dry air cooler heat exchanger is modeled with NTU-method using the air and water flow rate dependent heat transfer coefficient given by the manufacturer. The latent heat storage is described with the temperature dependent enthalpy function of the phase change material and the heat flow through the shell-and-tube heat exchanger. Because the building load is calculated separately, a model for the building is used where the return flow temperature is increased according the load and capacity flow. The return flow temperature is limited pursuant to VDI's maximum room temperature and the energy balance is matched mathematical using a back up chiller.

For every component the change of the input temperature vector according the currently ambient conditions and mass flow is calculated for every time step. The main components are connected with pipe models, which represent thermal losses and thermal capacities. Pumps and control valves are used in addition to control and regulate the whole system by varying the flow rate through the main components, in order to match the required output temperature. The absorption chiller is regulated by the supplied driving heat temperature into the desorber, to continuously provide chilled water at 14°C. In the waste heat cycle a mixing valve after the dry cooler adjusts the flow through the latent heat storage to ensure a cooling water return temperature to the chiller of 32.5°C. The electrical energy consumptions of pumps and dry air cooler are calculated with the 3rd order correlation between flow rate and power and a component specific efficiency factor.

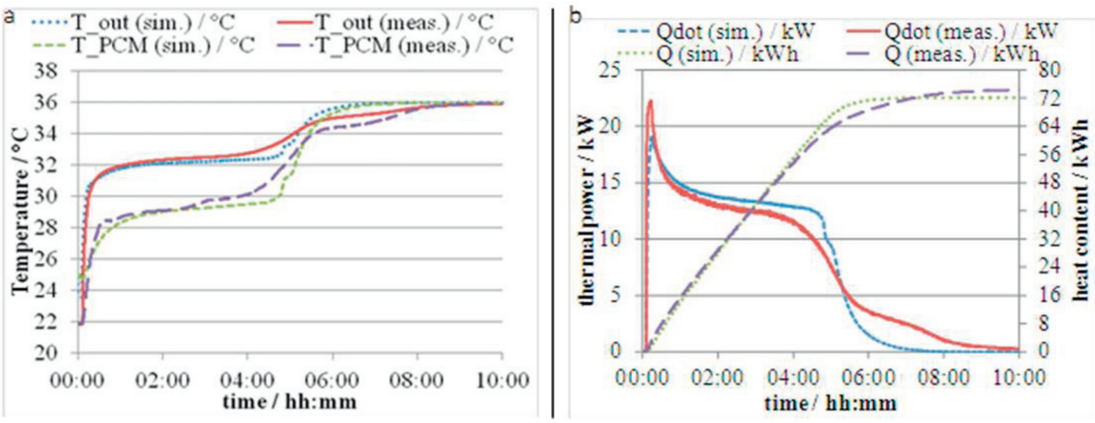


Fig. 6.Validation of latent heat storage model. (a) internal PCM and external heat carrier medium inlet and outlet temperatures; (b) heat content and thermal power during a loading cycle

Two models with consistent components and control strategies for cooling, but one with (dc) and one without (dc+lhs) latent heat storage, are used to survey the influence of the different waste heat systems on the annual system performance. A standard solar thermal collector system consisting of 40 m² flat plate collector (18 kW nominal, 40° slope, orientation S) and 2500 liter sensible hot water storage is set up.

The absorption chiller has a nominal chilled water capacity of 10 kW at supply/return temperature of 17°C/14°C, a desorption capacity of 14 kW at 90°C/80°C and a waste heat capacity of 24 kW at supply/return temperatures of 32°C/40°C.

To match the design point conditions under different climatic conditions, the size of the dry cooler and the building has to be varied. Therefore a correlation between the dry coolers surface, the maximum air flow rate and the thermal power has been determined which allows a fast designing. The building size is scaled to reach a design cooling load of 10 kW at each location. Then the load profile is calculated hourly with the software tool "Load Generator" [5] using weather data from the software tool METEONORM. The accuracy of single circuits and components were validated with measured data. The validation result of the latent heat storage is shown in figure 6 (a) and (b). The deviation between measured data and simulation at the end of the latent plateau is caused by the simplified 1-dimensional model. Because the simulation results will only be compared to each other, and the deviation mostly occurs at the end of the loading process this inaccuracy is accepted. As key figure and benchmark for the annual simulation results under different climatic conditions in Europe, the Seasonal Energy Efficiency Ratio (SEER) according to equation (1) for the cooling period is used.

$$SEER = \frac{\int_{t1}^{t2} \dot{Q}_{Evaporator}}{\int_{t1}^{t2} \dot{P}_{Electrical}} \qquad (1)$$

$P_{electrical}$ comprises the total auxiliary electricity consumption (pumps, fan) of the solar heating and cooling system except the distribution pump in the building. The improvement in the seasonal energy efficiency ratio (SEER) between the two systems is calculated with $SEER_{dc+lhs}$in relation to the $SEER_{dc}$. The solar fraction gives the percentage of cold provided by the sorption chiller in relation to the annual cooling demand of the building.

The results of the annual simulation of the system with dry cooler only (dc) and the system with dry cooler assisted by latent heat storage (dc+lhs) at selected climatic conditions in Europe are shown in figure 7. Solar fractions between 60.3% and 83.5% are reached with the solar cooling systems. While systems with dry cooler only showing SEER between 7.0 and 7.7, the integration of the latent heat storage to the waste heat cycle in order to support the dry cooler on hot days improves the SEER by 10.9 to 12.5. That means a minimum improvement of 56.6% and maximum improvement of 63.8%. The average accumulated waste heat in the latent heat storage differs between 12.2% and maximum 20.5% of the total dissipated heat to the ambient in cooling mode.

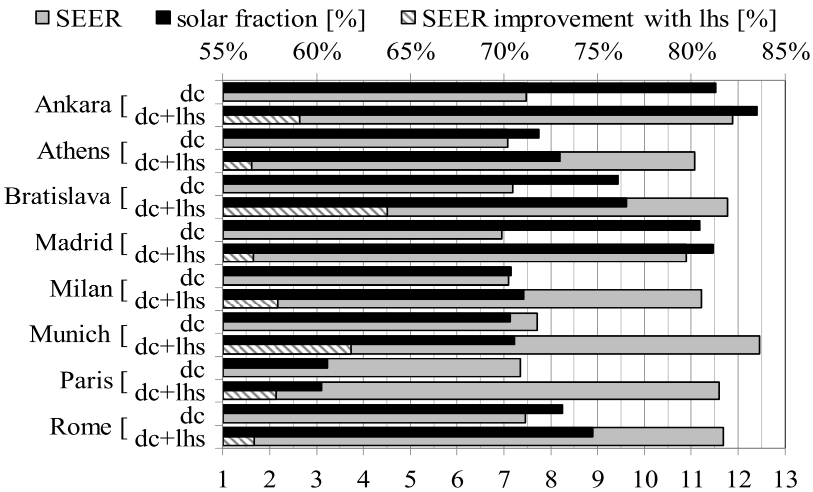


Fig. 7.Results ofannual system simulation in cooling mode under different European climatic conditions;
Improved seasonal energy efficiency ratio (SEER) and solar fraction by integrating a latent heat storage in addition to the dry cooler

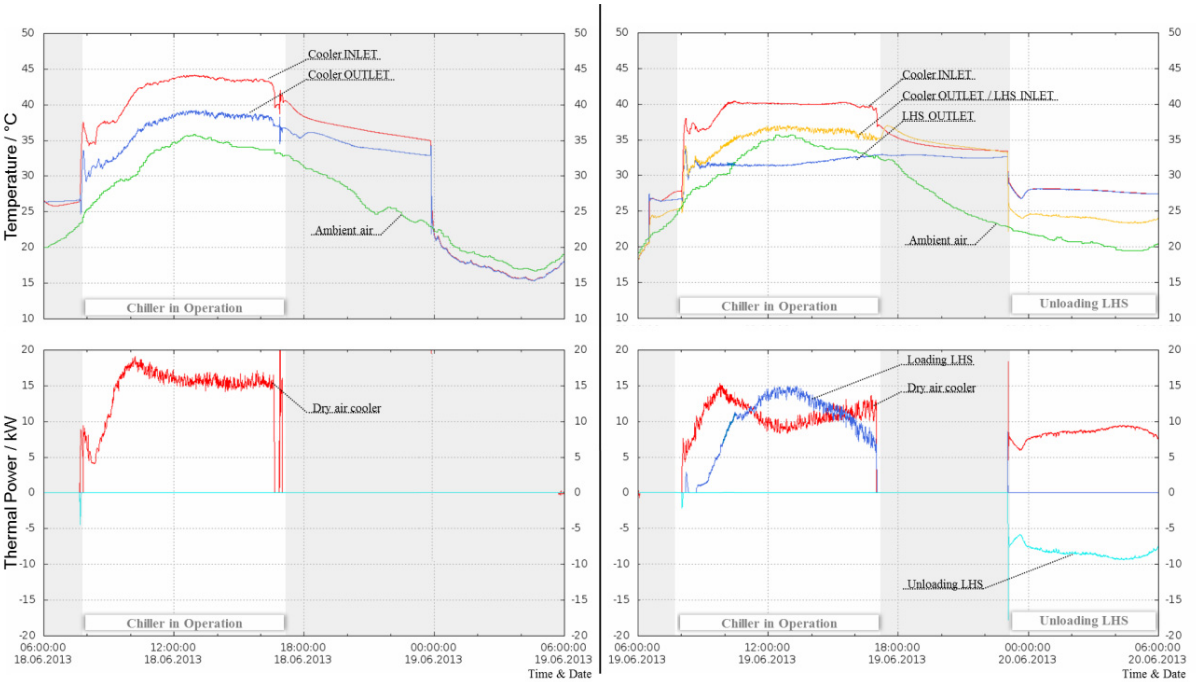
6. Pilot installation: in situ measurements of performance figures

In the following, measurement data of one selected pilot installation with an absorption chiller providing a nominal cooling capacity of 10 kW and a 57 m² flat plate collector field are presented. Thermal energy is stored depending on the temperature level in a 2000 liter hot water buffer tank and a 1500 liter phase change material containing latent heat storage with 120 kWh (22 to 36 °C). The wooden low energy building with 400 m² heated floor space is equipped with activated ceilings. Thus, moderate supply temperatures of 15 °C in summertime and maximum 31 °C in wintertime are sufficient. The dry cooler with a design capacity of 12 kW has a heat exchanger surface of 195 m² and a maximum air flow of 8800 m³/h [6,7,8].

The solar fraction in cooling mode reaches 60 % of the annual cooling demand, although the system is design to cover only 50 % of the maximum cooling demand of the building. The daily EER varies between 8 to 15, while the annual SEER for the cooling season in 2013 is 11.4.

6.1. Direct comparison of solar cooling systems with and without latent heat storage

The in situ measurements at the installation in Garching, Germany confirm the positive effect of the latent heat storage integrated into the cooling water circuit of the absorption machine. As already announced in the simulation section a field test at consistent ambient conditions (Insolation 447 vs. 445 kWh; max. temperature 36.9 vs. 36.8 °C) and control strategies with and without latent heat storage was carried out on 18/19 June 2013.



36.9 / 16.4 / 27.0 °C	Temperature (max/min/average)	36.8 / 19.8 / 27.8 °C
447 kWh	Insolation on collector surface	445 kWh
54.3 kWh	Chilled water production	75.6 kWh
0 %	Latent heat storage ratio	49 %
8.8	Daily Energy Efficiency Ratio, EER	11.4
0.69	Daily thermal Coefficient of Performance, COP	0.73

Fig. 8.Temperature and thermal power during the curse of a day:(a) with solely dry re-cooling; (b) novel system concept with latent heat storage

Figure 8 (a) shows the dry cooler inlet and outlet temperature in relation to the ambient air temperature as well as the corresponding power during 8:00 and 17:00 o'clock as long as the absorption chiller is in operation. Especially on such hot days with high ambient air temperatures (here above 35 °C) the coolant temperature increases enormously resulting in a reduced daily chilling capacity of only 54.3 kWh at deteriorated average thermal COP of 0.69. In addition to that the energy efficiency ratio EER reaches only moderate 8.8 during this day. The next day the latent heat storage was activated in the morning at chiller start at 8:00 O'clock again.

As visible in figure 8 (b) the dry cooler manages the heat dissipation solely in the first hour during warm up phase of the system. But when ambient air temperature and chilling power of the absorption chiller increase, the thermal capability of the cooler is insufficient to dissipate the total waste heat. Then the latent heat storage is switch on in addition. As a result the chilled water return temperature (LHS OUTLET) remains constant at 32 °C even when the ambient temperature rises to its maximum of 36.8 °C at noon. At this time nearly 60 % of the waste heat of the chiller is accumulated in the latent heat storage; during the course of the day about 49 % is stored. Due to the low cooling water return temperatures a total chilling capacity of 75.6 kWh with a good average thermal COP of 0.73 is achieve during this test until 17:00 o'clock.

Unloading of the latent heat storage starts during nighttime when ambient air temperature drops below 23 °C at about 23:00 o'clock. The average thermal power during the unloading process is 8 kW. Ambient air temperature, state of charge, fan speed of the dry cooler and mass flow in the hydraulic circuit connecting the latent heat storage to the dry cooler are influencing factors for an efficient unloading of the stored heat. Depending on the ambient air temperature fan speed, mass flow and start time is chosen from a parametric table to ensure a complete unloading of the stored heat until 6:00 o'clock the next morning. By minimizing the necessary electricity consumption per stored heat during unloading an auxiliary energy saving compared to the direct heat dissipation during the day is obtained which can be seen in a significantly increased daily Energy Efficiency Ratio of 11.4.

6.2. Daily and seasonal performance & key figures of the solar cooling installation

The following key figures show the daily (6:00 O'clock until 6:00 o'clock of the next day) ambient conditions and performance figures of the re-cooling circuit during the cooling period from June to August 2013.

In figure 9 the yellow bars represent the total available insolation on the collector aperture area as well as maximum, minimum und average ambient temperatures (black vertical lines). Because nighttime minimum temperatures always drops below the phase change temperature of the storage material (horizontal dotted line) a reliable unloading is guaranteed.

Figure 10 gives the daily energy efficiency ratio (EER). The values vary between 8 and 15 and an average EER of 11.4 for the whole cooling season is achieved. Values significantly below 6 are caused by a very short operation time (less than one hour) of the chiller at which a lot of energy is lost to warm up the system to nominal operation temperatures.

The directly dissipated daily waste heat via the dry cooler (light grey bar) and the stored heat (dark grey bar) are shown in figure 11. Especially on hot days at the end of July nearly 50 % of the waste heat is accumulated in the latent heat storage, whereupon the maximum storage capacity of 120 kWh is sufficient and never reached.

The daily energy balance during loading and unloading of the latent heat storage is given in figure 12. Mostly, the accumulated heat during daytime is directly dissipated in the following night. Deviations are caused by inaccurate heat meters or thermal losses and could be completely eliminated by the suggested novel state of charge detection device. In total about 22 % of the waste heat, produced by the sorption chiller, is accumulated in the latent heat storage and dissipate to the ambient at nighttime.

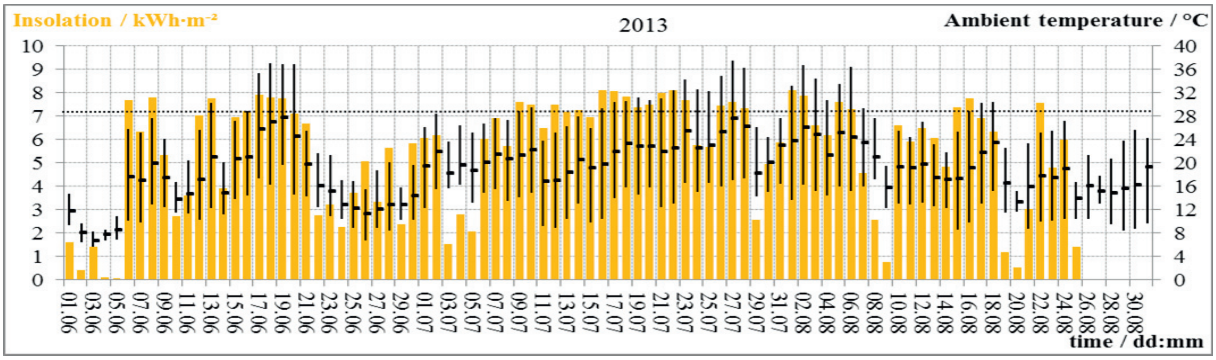


Fig. 9. Daily insolation on aperture area and maximum, minimum and average ambient air temperature from June to August 2013.

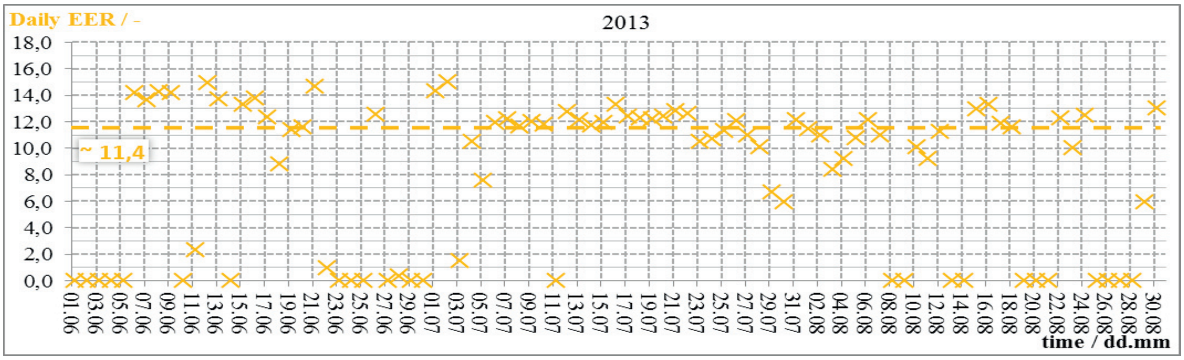


Fig. 10. Daily Energy Efficiency Ratio (EER) of the complete solar cooling installation.

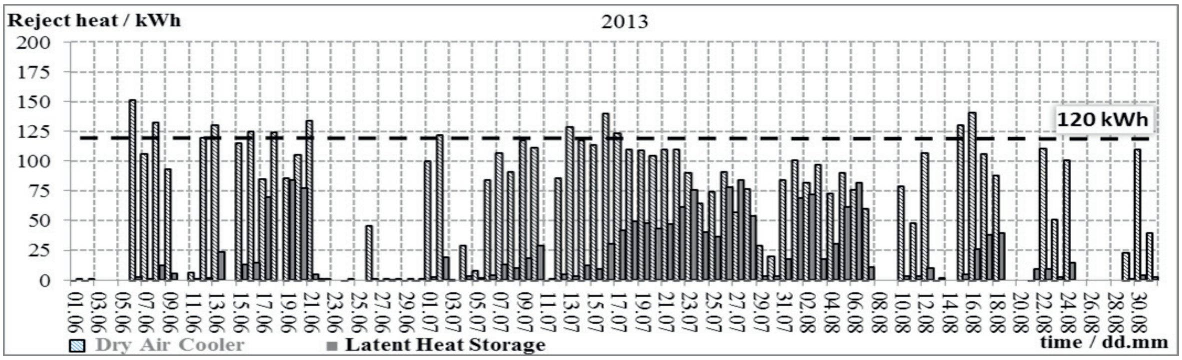


Fig. 11. Portion of the waste heat dissipated by the dry air cooler and accumulated in the latent heat storage for time shifted heat dissipation

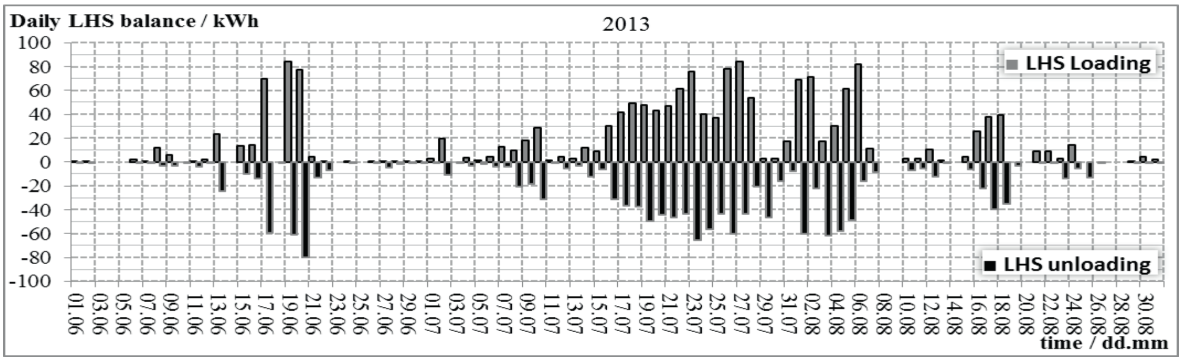


Fig. 12. Daily latent heat storage (LHS) energy balances for loading and unloading

7. Conclusion

In a triennial research project a novel system concept for a solar heating and cooling installation comprising dry re-cooled sorption chiller and a new low temperature latent heat storage had been developed und tested. During cooling mode the latent heat storage supports the dry air cooler especially on hot days to ensure a constant low cooling water return temperature to the sorption chiller. In comparison to a wet cooling tower maintenance and operational costs are considerably less. Furthermore the unloading process during nighttime at favorable ambient conditions allows efficient heat dissipation. In heating mode the latent heat storage serves as additional heat storage if a low-exergy heating system is installed into the building. Measuring data as well as in-situ measurements show the general feasibility of the concept under different European climatic conditions. A significant positive effect on the key figures seasonal energy efficiency ration (SEER) and solar fraction is identifiable.

The therefore developed latent heat storage has passed through extensive cycle tests concerning thermal performance and long-term durability. After more than 800 completed cycles in several storage samples no degradation or separation has been detected. A promising attempt of an improved state of charge detection for latent heat storages may allow further improvements of the system concept.

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