SOLAR HEATING AND COOLING WITH ABSORPTION CHILLER AND LATENT HEAT STORAGE

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Abstract: Performance figures and control strategies of an innovative solar heating and cooling system (SHC-System) composed of an aqueous lithium bromide-water single-effect absorption chiller with 10 kW cooling capacity, a dry heat rejection system and a low phase change temperature (28-29°C) latent heat storage based on salt hydrates are given. During cooling season the latent heat storage serves as a secondary heat sink supporting the dry air cooler at high ambient temperatures to ensure 32°C coolant to the absorption chiller at any time. In the heating season the latent heat storage buffers heat surplus of the solar collectors latently by melting the phase change material (PCM) calcium chloride hexahydrate. As a result of the constant temperature during charging, solar thermal collector efficiency is increased and furthermore the overall heat dissipation is reduced. The results on the one hand show a positive effect on the cooling capacity, electrical and thermal Coefficient of Performance (COP) of the absorption chiller, which are significantly increased especially at hot days compared to solely dry air cooled systems. On the other hand a high solar fraction in the heating period, due to constantly low storage temperatures, is achieved.

Key Words: dry air cooler, low temperature latent heat storage

1 INTRODUCTION

In SHC-Systems, solar heating as well as solar cooling are provided synergistically yielding a complete annual utilisation. The solar gain during the cold season serves for space heating. In order to cope with the mismatch of solar gain and building heat demand voluminous heat storages with up to 100 litre per square meter collector area are necessary. Increasing storage temperature during the loading process results in high thermal losses of the collector system and reduced system efficiency.

During the warm season the solar heat is converted into useful chilled water for air conditioning by means of sorption cooling devices. These devices typically require an open wet cooling tower to dissipate the reject heat to the ambient. Yet, water consumption, the need for water make-up and cleaning, formation of fog, and the risk of legionella bacteria growth are hindering factors for their use. If a dry air cooler is applied, the chilling capacity of the same sorption machine decreases up to 40 % due to significant higher coolant temperatures.

To overcome both problems a low-temperature latent heat storage based on phase-change-materials (PCM) can be applied to cope with the given system requirements: During heating operation the storage temperature of the latent heat storage remains constant while gathering solar surpluses. Thus a low operating temperature of the solar thermal system is accomplished yielding efficient operation with optimum solar gain. In cooling mode the latent heat storage serves as an additionally reject heat sink for the absorption chiller in addition to the dry cooling system and allows a staggered reject heat dissipation. By that means a part of the heat rejection of the chiller is shifted to periods with lower ambient temperatures, i.e. night time or off-peak hours, and thus the necessity of a wet cooling tower is eliminated allowing for a substantial reduction in operational effort, water consumption and cost.

2 INNOVATIVE CONCEPT

Open wet cooling towers are designed for coolant supply/return temperature 27/35°C. When a dry air-cooler is to be used, cooling water temperature increases to 40/45°C in Mediterranean climate. As a consequence of the increased cooling water temperature, the temperature level of the driving heat supplied to the regenerator of the absorption chiller has to be increased to about 105°C accordingly. Finally, the low collector efficiency at this temperature has to be compensated for by installing more than 20% additional collector area. Otherwise the cooling capacity of the chiller decreases by about 40%. The application of a latent heat storage supporting the dry air cooler allows a reduction of the coolant temperature to 40/32°C, avoiding a major decrease of the chiller's capacity during hot ambient conditions. At ambient temperatures of 32°C the dry air cooler provides a coolant temperature of 36°C and the latent heat storage serves for additional cooling of the cooling water from 36°C down to 32°C. Independently from the operation of the latent heat storage, the dry air cooler may provide a further reduction of the coolant cycle temperatures during off-peak hours with moderate ambient air temperatures. The stored reject heat is then discharged during off-peak operation or night time when more favorable ambient temperature conditions are available. A simplified system structure for a solar cooling system with a latent heat storage supporting a dry air cooler in the reject heat cycle is given in Figure 1.

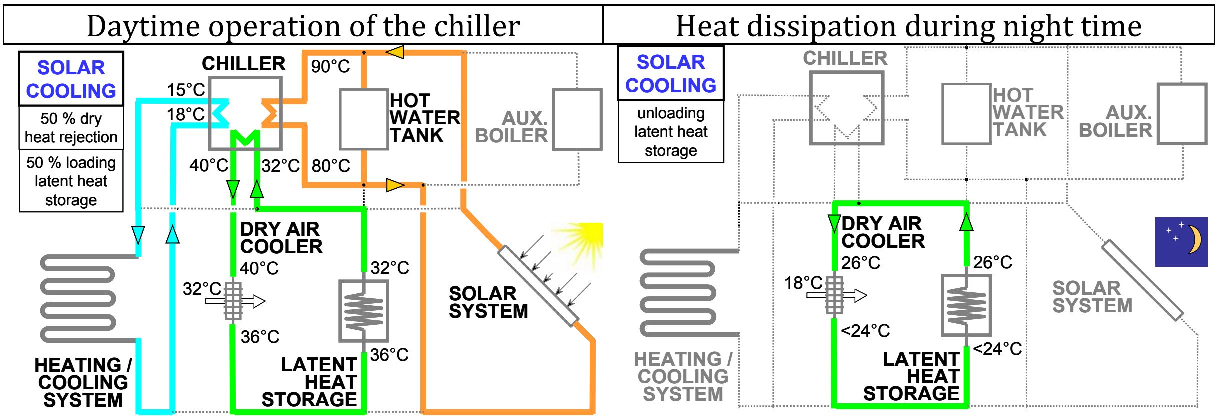

Figure 1: System scheme for solar cooling supported by a latent heat storage

During the heating season, the latent heat storage buffers the solar surplus heat and balances the heat supply to the consumer by boosting the return temperature of the heating system (see Figure 2). The design of the latent heat storage is based on an internal phase-change temperature of about 29°C. Thus, a low operating temperature of the solar thermal system is accomplished yielding efficient operation with optimum solar gain.

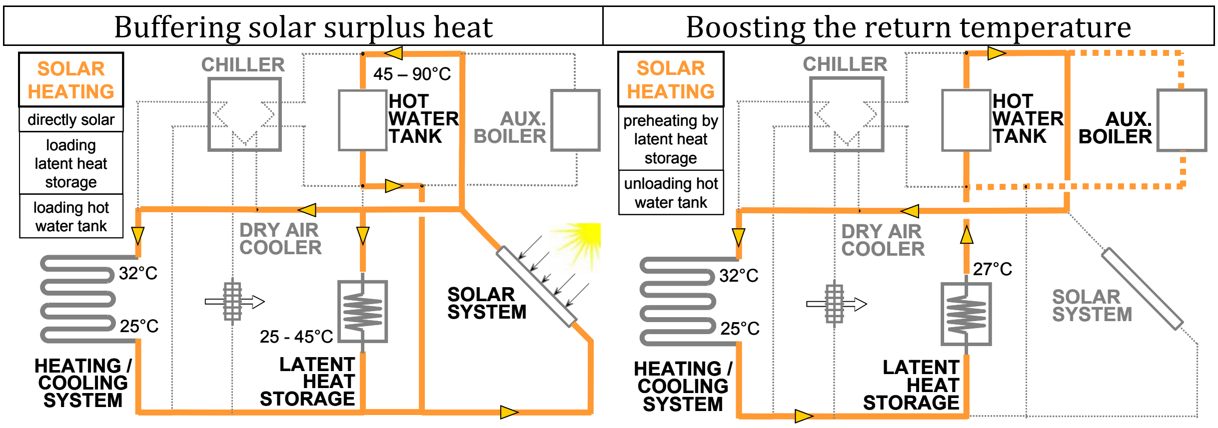

Figure 2: System scheme for solar heating with latent heat storage

3 PILOT INSTALLATION

Within the framework of the German “Solarthermie 2000plus” Program a pilot installation of an innovative solar heating and cooling (SHC-System) has been erected at the office building of the Bavarian Centre for Applied Energy Research (ZAE Bayern) in Garching (near Munich), Germany in 2007. The installation simultaneously serves as a field test project for a compact water/LiBr absorption chiller with 10 kW nominal capacity designed by ZAE Bayern in collaboration with SK Sonnenklima and TU Berlin (Schweigler et al. 2002, Kühn et al. 2005). Furthermore, the performance, cycle stability and the material's chemical resistance/durability of a new developed low temperature latent heat storage based on the salt hydrate calcium chloride hexahydrate is tested.

The two-floor office building (see Figure 3) was completed in the year 2000. At this time its wooden wallboard construction exceeds the prevailing German low-energy standard. The thermal insulation for the building envelope is dimensioned to U = 0.18 to 0.20 $W \cdot m^{-1} \cdot K^{-1}$. The glazing has insulating properties of U = 0.4 and 0.9 $W \cdot m^{-1} \cdot K^{-1}$. Passive utilization of solar energy is done by storing heat from solar radiation in the concrete core and in the insulated base plate. Therefore, the building heat demand is comparable to the German "3-liter-house" class, which limits the annual correspondent domestic fuel oil consumption for space heating to 3 liters per square meter living area.

Figure 3: ZAE Bayern office building and solar thermal flat plate collectors on the rooftop

As heating and cooling equipment, for the in total 400 square meters of office space, activated ceilings are installed. This allows moderate system temperatures in both modes. In the heating season the maximal supply temperature is set dependently on the ambient conditions based on a characteristic heating curve gradient of 0.5 and in cooling mode to 15°C by default, but at least 1.5 K above dew point temperature. As backup system in times of insufficient solar energy a pellet boiler for heating and a well for additional chilled water during the cooling season are available.

The pilot installation provides solar assisted heating and cooling with a total of 57 square meters of aperture area consisting of 24 anti-glare coated flat plate collectors oriented +10° to the south with 40° inclination.

The solar-driven single-stage absorption chiller with working pair aqueous lithium bromide as sorbent and water as refrigerant with a nominal chilled water capacity of 10 kW is designed to cover a base load coverage of 50% referred to the maximum cooling load of the building (20 kW). The chiller provides chilled water supply/return temperatures 18/15°C in full load, driven by solar heat gained from the flat plate collectors at supply/return temperatures of 90/80°C. The occasional fluctuations in radiation and heat consumption are buffered by a hot water tank connected in parallel to the solar thermal collectors.

In conventional absorption cooling installations, wet cooling towers designed for coolant supply/return temperature 27/35°C are applied as heat rejection system. Water consumption and high maintenance costs as well as the risk of bacteria notably legionella growth and legal restrictions are hindering facts for an extensive use of this kind of solar cooling. When an almost maintenance-free dry air-cooler is to be used, cooling water temperature has to be increased above ambient air temperature for sensible heat dissipation.

Having regard to an economic size of the heat exchanger area of the dry air cooler (195 m²) a driving temperature difference of 8 K between cooling water outlet and ambient air temperature is required. In view of this fact and considering the hottest weather data for the location Garching (Munich) of +32°C the temperature level in the reject heat circuit rises to 40°C. This increase of the cooling water temperature negatively affects the performance of the chiller especially on days with high cooling load.

By integrating a latent heat storage with a phase change temperature between 28°C and 29°C in serial to the dry air cooler a second heat sink is available to ensure a constant coolant temperature level of 32°C yielding constant chilling capacity even at rising ambient temperatures. The latent stored reject heat can be discharged during off-peak operation or night time when more favorable ambient conditions, i.e. lower ambient temperatures or electricity tariff, are available. The melting temperature of the aqueous salt solution calcium chloride hexahydrate ($CaCl_2$•$6H_2O$) fits perfectly for the given application (see Figure 4). This low-cost technical phase change material (PCM) provides a latent heat of about 150 J/g or 240 J/L and is used in food industry, medicine and farming for several purposes as well.

The heat storage capacity is set to cover 50 % of the nominal reject heat capacity of the chiller and a heat content of 120 kWh in the temperature range between 22 °C and 36 °C. Within the current project a matrix of polypropylene capillary tubes with an outer diameter of 4.3 mm serves as heat exchanger between the polypropylene glycol coolant and the phase change material. Despite the total heat exchanger area of more than 30 m² the capillary tubes occupy less than 5% of the whole storage volume.

Melting range	28... 29°C
Melting Enthalpy (by weight)	150 kJ·kg^{-1}
Melting Enthalpy (volumetric)	240 kJ·Litre^{-1}
PCM costs	0.30 €·kg^{-1}
Volume	1.4 m^{-3}
Mass	2.2 tons

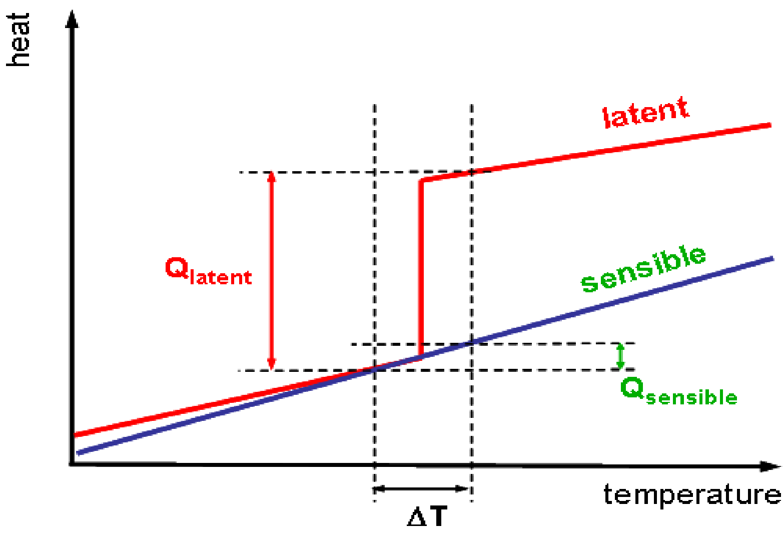

Figure 4: Selected storage data and principle of latent and sensible heat storage

The heat exchanger is finally enclosed by a modified PVC plastic bag and immersed in a cubic sandwich-panel structure which contains 1400 liters of phase change material (see Figure 5). Based on the low specific cost of 0.30 Euro per kilogram calcium chloride hexahydrate the investment costs for the complete filling does not exceed 500 Euro.

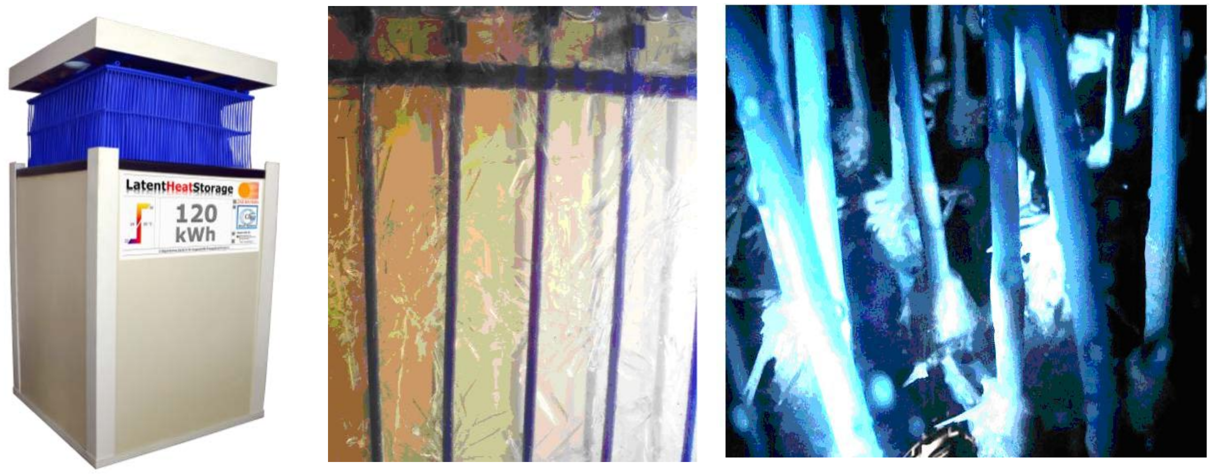

Figure 5: Latent heat storage and capillary matrix surrounded by crystallized salt hydrate

In heating mode the available solar thermal energy is used for direct heating or preheating of the building's heating system. Solar surpluses are primarily stored at constant low temperature (29°C) in the latent heat storage. Thus a low operating temperature of the solar thermal system is accomplished yielding efficient operation with optimum solar gain. In addition to the latent heat the phase change material can be heated up sensibly to 45°C. Further solar surpluses are stored in the buffer tank by increasing the water temperature from 45°C to 90°C. Due to the low return temperature of the activated ceilings (~25°C) and the constant latent storage temperature (29°C) the heat pump mode of the absorption machine in combination with the solar thermal collectors as heat sink only affects the solar coverage ratio negligibly and is therefore not implemented. A detailed hydraulic scheme including all main components and sensors of the system is given in Figure 6.

4 CONTROL STRATEGIES

Depending on the three days average of the ambient temperature (TIC001) the building management system (BMS) of the ZAE Bayern office in Garching chooses cooling or heating mode (see Figure 6). When ambient and certain room temperatures exceed the set point values the main distribution pump starts and the individual control equipment conditions each single room to custom settings by regulating the mass flow rate through the activated ceilings. Notwithstanding the above, a pellet backup boiler keeps the buffer tank (TIC406) on a temperature of 60°C for hot water preparation at any times. If the upper buffer tank temperature (TIC406) falls below 60°C the pellet boiler starts firing and continues until the lower buffer tank temperature (TIC410) reaches 60°C.

The SHC system itself is controlled by a low-cost (600 €) universal programmable logic controller. Except the chillers internal processes, which are regulated by a PLC (Beckhoff), all valves, pumps, fan etc. of the whole system are connected to this device.

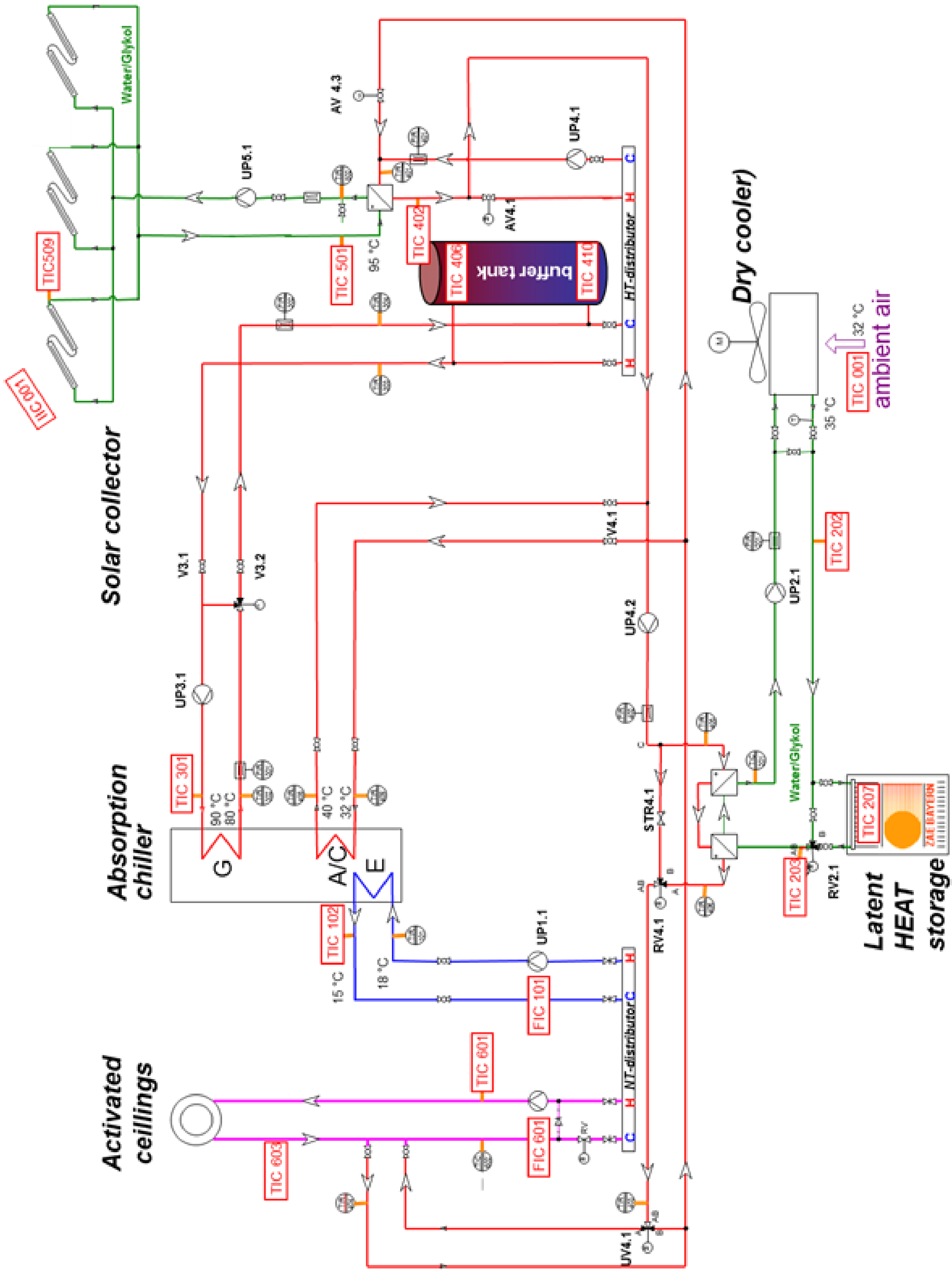

Figure 6: Piping and instrumentation diagram (P&ID) of the solar heating and cooling system

Winter Period:
In heating mode the current supply temperature (TIC601) to the activated ceilings is calculated with a heating curve gradient of 0.5 referred to the ambient air temperature (TIC001) and adjusted by injecting hot water from the buffer tank into the heating circuit. Due to the low return temperatures around 25°C the absorption machine is not used as a heat pump. Thus, Evaporator (E) and Absorber/Condenser (A/C) hydraulic circuit are shut off and solar energy is directly used to preheat the return flow of the heating system in several steps. When the collector aperture temperature (TIC509) exceeds the return flow temperature (TIC603) +3 K with a hysteresis of -1 K the solar primary pump (UP5.1) starts with a rotary speed directly proportional to the insolation on the solar plant (IIC001). After the required temperature at the solar heat exchanger (TIC501) is reached, one of the solar secondary pumps (UP4.2) feeds the heating system with the corresponding flow (FIC601). In the case that the solar gain exceeds the building heat demand, the latent heat storage circuit (UP2.1) is activated to store heat at all times the internal phase change material temperature (TIC207) is 5 K lower than the collector temperature (TIC509) with a hysteresis of -2 K. This stored heat is delivered to the heating system during night-time or insufficient insolation if the storage temperature (TIC207) is 2 K higher than the return flow of the building (TIC603). Thereby the pumps UP4.2 and UP2.1 generate a flow corresponding to the circulating water in the activated ceilings. The adequate supply temperature (TIC601) is ensured by the mixing valve (UV4.1) in both cases.

If the temperature in the solar circuit (TIC501) exceeds 65°C due to minor heat demand and/or full loaded latent heat storage (TIC207=50°C) the system switches to load the high temperature buffer tank via the HT-distributor and the pump UP4.1 with the current buffer tank temperature (TIC406), but at least 60°C. Buffer tank charging stops when its bottom temperature reaches 85°C (Hysteresis -5 K).

An overheating of the collector plant is avoided by dissipating any surplus heat to the ambient air. In this rare case the pumps UP4.2 and UP2.1 operate at maximum speed, the mixing valve RV4.1 limits the temperature in the solar secondary circuit (TIC402) to 90°C and the dry air cooler cools the brine (TIC202) to 50°C.

Summer Period:
In the cooling season chilled water at 15°C and 1.5 K above dew point respectively is provide to the building from 8 a.m. to 7 p.m. A well as backup cold source ensures continuous chilled water for the activated ceilings in times of insufficient solar energy necessary to drive the thermally driven chiller, which is design to operate in base load with a capacity (10 kW) of 50% of the maximum cooling demand (20 kW).

During the cooling mode the switching valves AV4.3 and UV4.1 separate the reject heat circuit from the solar and the building circuit respectively.

When the collector aperture temperature (TIC509) exceeds 65°C and the upper buffer tank temperature (TIC406) +2 K the solar primary pump (UP5.1) starts with a rotary speed directly proportional to the insolation on the solar plant (IIC001). After the required temperature at the solar heat exchanger (TIC501) is reached, the solar secondary pump (UP4.1) feeds the buffer tank via the HT-distributor. Thereby the maximum flow rate is limited to 1 m³/h, which corresponds to the generator flow rate of the chiller. This improves the chiller performance at startup, due to higher driving temperatures up to 92°C. There over, the limitation is negated and the hot water surplus charges the hot water buffer tank.

In case of cooling demand the chiller and chilled water pump (UP1.1) start, but only when the upper buffer temperature (TIC406) or the solar collector temperature (TIC402) is higher than the minimum driving temperature; here 65°C. The generator pump (UP3.1) operates at constant speed and the mixing valve RV3.1 reduces the heat flow from the buffer to the chiller in part load conditions to ensure 15°C chilled water.

The variable rotary speed of the reject heat pump UP2.1 is linked to UP4.2, which operates as a function of the difference between driving and ambient temperature. In a first step the coolant is cooled by the activated dry air cooler to 32°C. Above 24°C ambient air temperature the valve RV2.1 opens proportionally and the latent heat storage is used as a secondary heat sink to guarantee 32°C coolant, if the phase change material temperature (TIC207) is lower than the outlet temperature (TIC202) of the dry air cooler.

Chilled water preparation stops at 7 p.m. or insufficient driving heat from the solar plant or buffer tank. Due to the low internal lithium bromide concentrations a solution dilution procedure is not required for indoor applications.

If energy has been stored in the latent heat storage in the course of cold production the discharging of the latent heat storage is activated at 12 p.m. at the earliest when ambient temperature falls below 22°C and continued until the phase change material temperature is cooled down to 2 K below phase change temperature. In the process the pump (UP2.1) and fan operate at constant speed to ensure a economic discharging with high heat transfer rates and low auxiliary power consumption, which have been determined earlier on a test rig.

In the near future a new developed energy meter for the stored latent heat replaces this algorithm. Then discharging starts depending on the current latent energy content, weather forecast, ambient temperature and available timeframe in the night. By doing this, reject heat dissipation is shifted in times of lowest ambient temperatures and the electricity consumption for discharging is reduced to a minimum.

5 PERFORMANCE EVALUATION

The system has been operated and monitored for four complete years (2008-2011). Due to the low system temperatures for heating and moderate chilled water temperatures supplied to the activated ceilings in summer a high collector yield of about 400 $kWh \cdot m^{-2} \cdot a^{-1}$ is obtained. The absorption chiller itself operates about 600 hours each year, producing cold at 15°C by means of solar heat about 90°C with an average thermal Coefficient of Performance of 0.70.

By replacing some ineffective pumps with high efficiency components in spring 2009 the overall seasonal electrical COP increased significantly (about 20%) and reaches values above 10 at the moment. Almost 60% of the primary energy has been saved compared to a conventional compression cooling system supplying the same amount of cold.

During the monitoring period 2008 until 2011 (Helm et al. 2009) the two latent heat storage prototypes have undergone over 800 charging and discharging cycles under real conditions. In 2011 these two modules were replaced by a single module with improved compact design. Since then a total of over 300 charge- and discharging cycles have been completed without any indication of degradation in capacity and heat content. Figure 7 and 8 show inlet and outlet temperatures of the latent heat storage during charging at 36°C and discharging at 22°C with a flow rate of 3 $m^3 \cdot h^{-1}$. The quarterly measured constant temperatures clearly show the effect of latent heat storage over a long period where the phase change material melts and solidifies, respectively. Subcooling of the phase change material is observed during discharging by only about 1.5 K below the phase change temperature of 28…29°C, facilitating a reliable operation of the system.

In heating mode about one third of the overall heat demand had been covered by solar energy. Due to the use of the latent heat storage in cooling mode the cooling water return temperature did not exceed 32°C despite the dry heat rejection at ambient temperatures above 32°C.

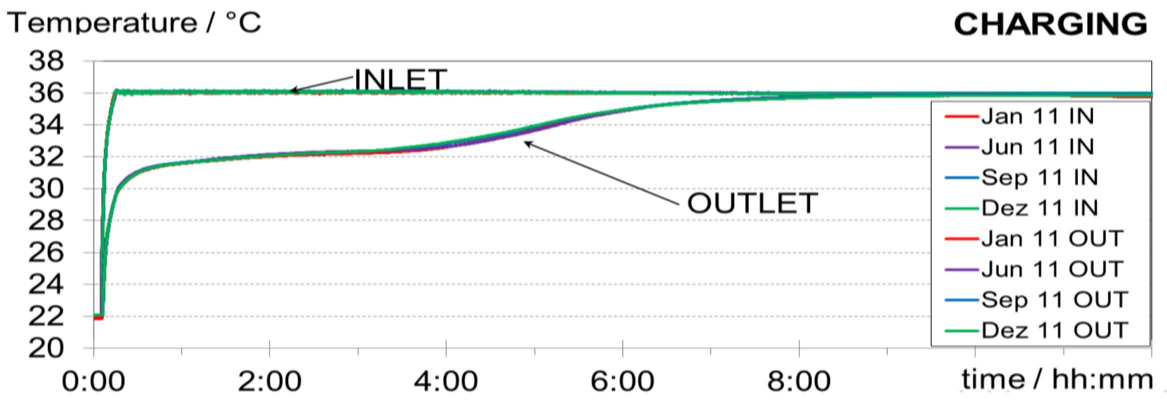

Figure 7: Quarterly reference measures of the latent heat storage while charging at 36 °C

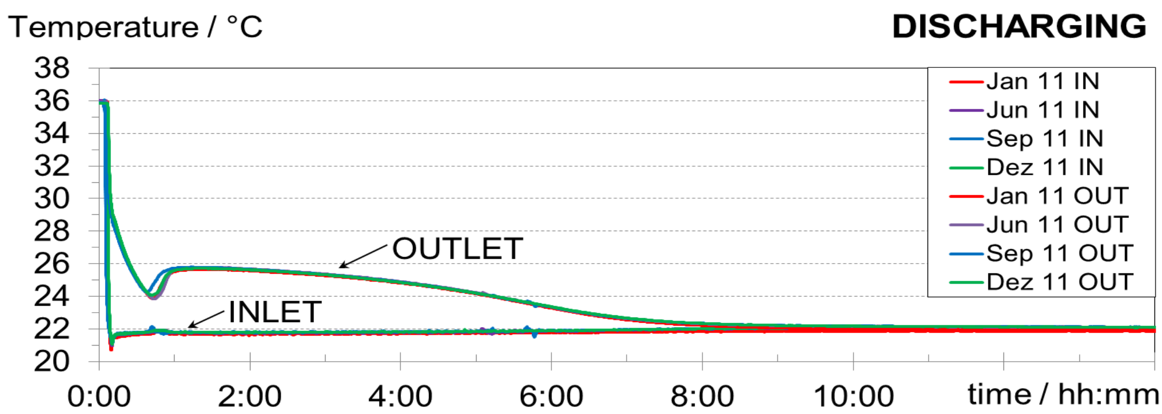

Figure 8: Quarterly reference measures of the latent heat storage while discharging at 22 °C

Figure 9 shows a typical temperature chart in the course of a day when the latent heat storage supports the dry air cooler and ensures constant cooling water temperatures to the absorption chiller below 32°C even at higher ambient temperatures. During hot (34°C) ambient conditions up to 50% of the daily reject heat load is covered by the latent heat storage (see Figure 10). During night time the lower ambient temperatures down to 15°C suffice to regenerate the latent heat storage within 6 hours.

6 CONCLUSION

A new innovative and patented concept of a solar cooling and heating system comprising an absorption chiller (10 kW chilled water capacity, $COP_{thermal}$ ~ 0.72) with dry air cooler and a latent heat storage has been observed over a period of four years. In cooling mode the latent heat storage stabilizes the cooling water temperature at 32°C independently from the ambient temperature. During the heating period a significant increase of the solar gain has been observed, due to the lower collector temperature compared to sensible heat storages. It has been proven that despite the low storage temperature, the buffered solar heat can be transferred efficiently to the building heating system. It may be concluded, that especially in low capacity applications the absence of a wet cooling tower substantially facilitates the introduction of absorption technology and contributes significantly to the performance of the solar heating system.

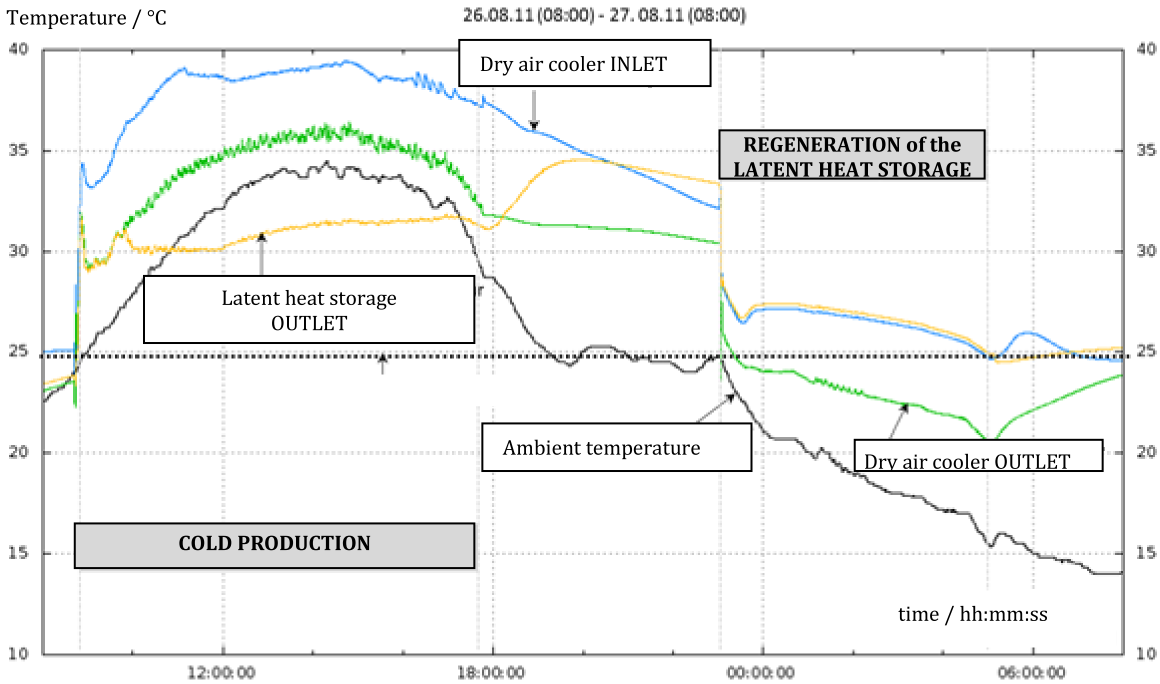

Figure 9: Temperatures of the dry air cooler and latent heat storage in the course of a day

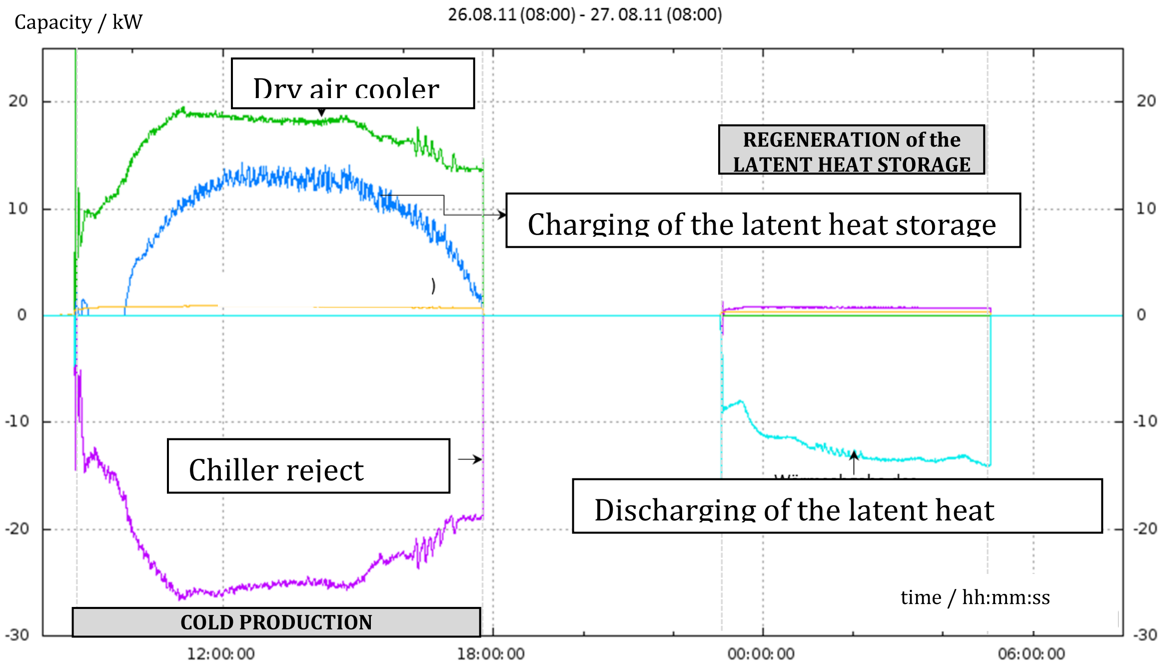

Figure 10: Power of the dry air cooler and latent heat storage in the course of a day

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