Highest Efficiency Ice Storage for Solar Cooling Systems – Experiences with a Vacuum Ice Slurry Cold Thermal Energy Storage

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Abstract

With an increasing share of renewable energies efficient storage technologies are in high demand. Due to the high specific enthalpy of fusion pumpable water-based ice slurry represents a thermal storage medium which is ecological as well as economical advantageous. A further need for research can be seen in the increase of efficiency for ice slurry generation processes. The high efficient process of ice slurry generation by direct evaporation under rough vacuum conditions including its potential for solar cooling systems is presented in this paper. After installing a first pilot of an integrated ice slurry generation and storage system based on the R718 turbo vapour compression technology a new facility concept for higher capacities has been developed and commissioned. Findings from recent research projects flowed into the conceptional work and have been implemented. The facility has a nominal ice generation capacity of 180kW, a storage capacity of 1MWh and a discharging capacity of max. 300kW.

Keywords: Thermal Energy Storage, Vacuum Ice Slurry, Solar Cooling, water as refrigerant (R718), Natural Refrigerants, Secondary Refrigerants, Load Management, District Cooling

Introduction

In fields of refrigeration and air conditioning technologies the current research focus lies on the transition towards natural refrigerants combined with an increase of efficiency for the whole compression cycle, e.g. development of new compressors with higher efficiencies especially for part load conditions (Heinrich, 2012). In the near future an increasing expansion of the renewable energy sector will gradually challenge us worldwide to use generated power when it is made available. A main question will be how to store energy that is not immediately needed at time of generation. The reduction of peak loads and the compensation of fluctuating availabilities of renewable energy sources requires a comprehensive planning approach. With the integration of a thermal storage system energy demand and availability can be adapted. For refrigeration and air conditioning systems several approaches to store cold thermal energy are applicable. Fig. 1 gives an overview of available storage technologies according to the type of storage media (Urbaneck, 2012).

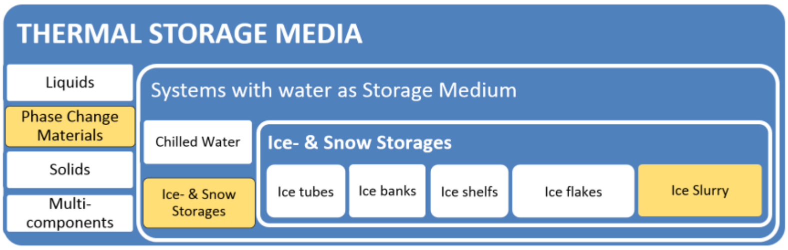

Fig. 1: Technologies for water-based cold thermal storage systems

From an economical as well as ecological perspective systems with water as storage medium represent a safe, environmentally friendly and efficient approach to store thermal energy (Kauffeld et. al, 2005). The synergy effect of a pumpable secondary refrigerant with the characteristics of a phase change material are the key argument for the usage of water-based ice slurries (see Fig. 2). Besides the high enthalpy of fusion (transport capacity) higher heat transfer coefficients can be achieved. Hence, the dimensions of cooling distribution networks and related pump capacities can be reduced significantly (Kauffeld et. al, 2010).

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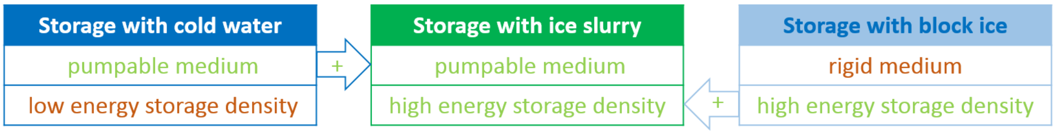
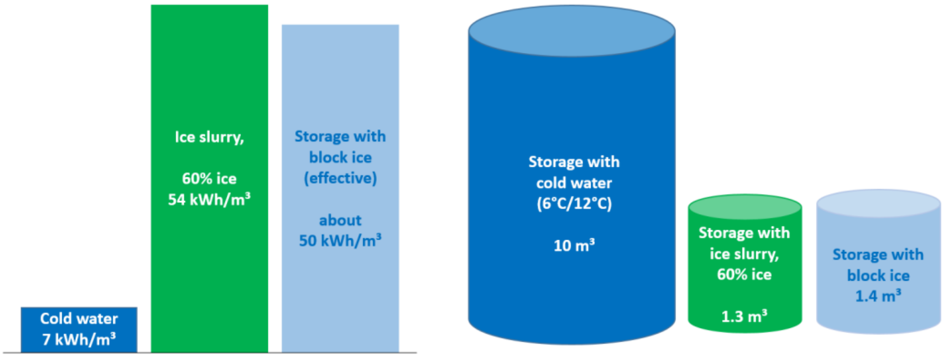


Ice slurry storages combine the advantages of cold water and ice block



Comparison of volumetric energy storage density

Comparison of storage volume for the same capacity

Fig. 2: Synergy effects of ice slurry as thermal storage medium

To date ice slurry based cooling systems are mainly applied in cooling processes for food products, e.g. breweries, fishing and refrigerating counters. In Japan first air conditioning applications were installed by using ice slurry only as storage medium (Snoek, 1993).

For the production of ice slurry various processes have been developed and are available on the market (Kauffeld et. al, 2010). From an energetic perspective vacuum ice slurry technology is a promising approach in terms of efficiency of cold generation for all traditional applications of industrial refrigeration processes and air conditioning of buildings (Albring, 2009). The system can be integrated for cold thermal energy storage in larger PV driven cooling systems to increase efficiency, availability and comfort or to minimize back-up needs. The current research work focuses on the optimization of the vacuum ice generation process as well as investigating new fields for ice slurry applications, e.g.:

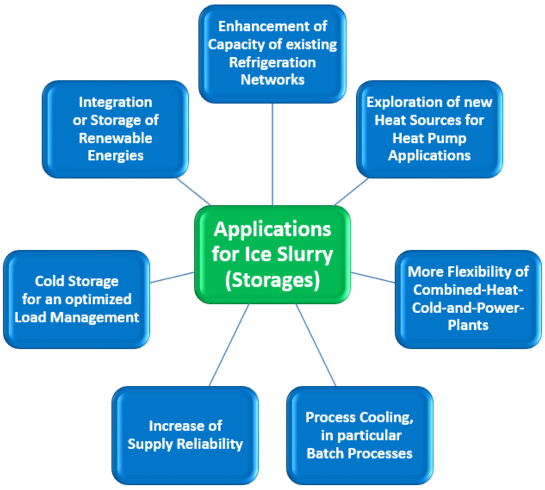


Fig. 3: General fields of application for ice slurry as secondary refrigerant and storage medium

Vacuum Ice Slurry Technology

2.1. Process description

The process of ice generation by direct evaporation in a rough vacuum runs at low pressure conditions below the triple point of water (p_{Tr}=611 Pa, ϑ_{Tr}=0.01 °C). Within a vessel which is initially pre-evacuated down to saturation conditions water is cooled sensibly by heat loss through evaporation (Figure 1). Below triple point conditions water cannot cooled down anymore. Thus, the energy for evaporation must be provided by a further phase change – the generation of ice particles within the sump of the evaporator. The quotient between enthalpy of fusion ($h_{lg} \approx 2500\,kJ \cdot kg^{-1}$) and the freezing enthalpy ($h_{ls} \approx 333.4\,kJ \cdot kg^{-1}$) provides the mass relation between evaporated vapor and the amount of produced ice particles. Hence, evaporating one kilogram of water would lead to a generated ice mass of 7.5 kg. Under vacuum conditions the corresponding volume flow is high due to the low density of water vapor ($\rho_g \approx 0.005\,kg \cdot m^{-3}$). The driving thermodynamic potential in the evaporator is given by the pressure difference between saturation pressure (p_{lg}) and the pressure (p_g) in the gas phase above. High energy efficiency can be achieved because of a minimal thermal resistance through direct evaporation. Direct contact between storage medium and refrigerant requires low subcooling temperatures in comparison to other ice slurry generation processes. By increasing the evaporating surface A_O and the heat transfer coefficient α the evaporating performance can be further increased. In order to achieve stable ice generating conditions in the sump of the evaporator the pressure difference must be kept stable, e.g. by using a vacuum pump. Higher water vapor volume flows can be conveyed by applying a centrifugal compressor technology.

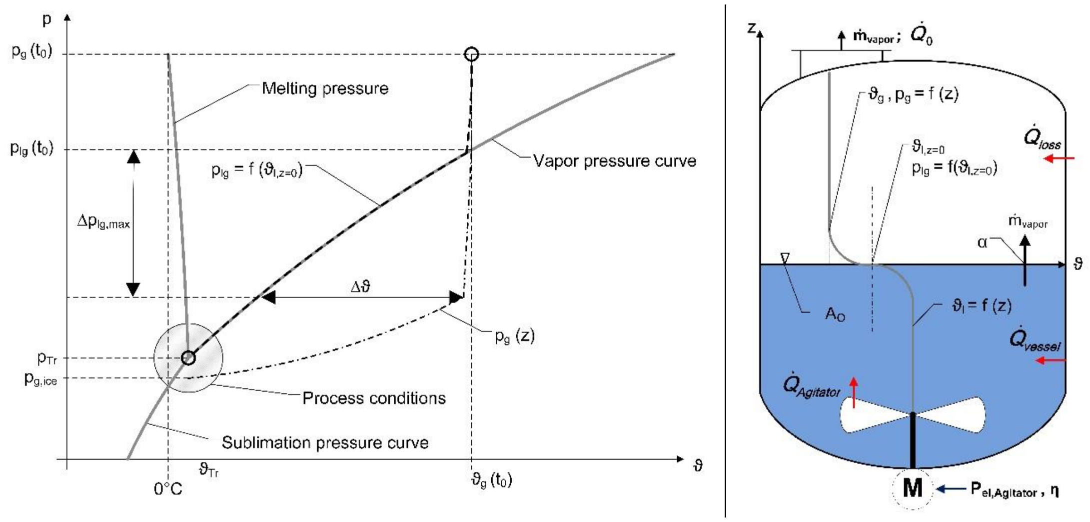


Figure 1: Ice slurry generation by direct evaporation in a rough vacuum

2.2. Efficiency comparison

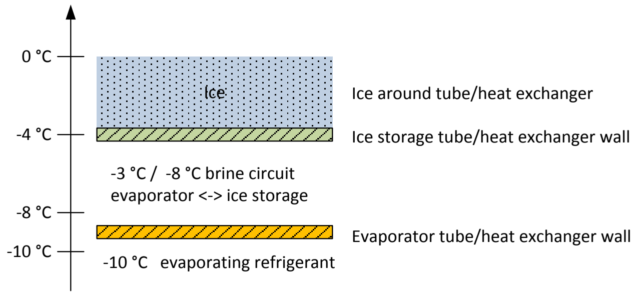


Fig. 4: Exemplary temperatures during charging of a block ice storage using a cold brine circuit

One major disadvantage of conventional ice generators (e.g. in block ice storages) is the low effective evaporation temperature of the cooling cycle which is often operated in the range of -10 °C to -13°C. The low evaporation temperature is caused by the temperature differences necessary for heat transfer between the evaporator of the chiller and the heat exchanger inside the ice storage/ice generator, see Fig. 4. Hence, the low evaporation temperature results in a lower efficiency of the ice generation process. Generating ice slurry by direct evaporation of water the heat exchanger between the refrigerant and the phase change material water/ice can be eliminated. Here, the water itself is used as refrigerant. The effective evaporation temperature is as high as -0°C which leads to highest efficiencies for ice generation using the direct evaporation process.

Tab. 1: Calculation scenarios and results

Process	t_0 [°C]	t_C [°C]	EER	Specific energy demand [kW_{el}/kW_0]
1) On-time chilled water generation 6/12 °C (chiller with R717; η_{is} = 0,7)	4	34	5.71	0.175
2) Ice slurry generation by direct evaporation (refrigerant R718, η_{is} = 0,65)	-0.5	6	26.2	0.038
3) Combined (cascaded) ice slurry generation using the conventional chiller for condensing the compressed water vapour of the vacuum ice process -> combination of 1) and 2)	-0.5	34	4.69	0.213
4) Combined (cascaded) ice slurry generation at nighttime conditions with reduced condensation temperature	-0.5	24	6.67	0.150
5) Conventional ice slurry generation (scraped surface) or block ice storage (chiller with refrigerant R717, compressor η_{is} = 0,7)	-10	34	3.49	0.287
6) Conventional ice slurry generation (scraped surface) or block ice storage at nighttime conditions with reduced condensation temperature	-10	24	4.71	0.212

Tab. 1 shows a comparison of thermodynamic efficiencies of two different approaches for ice slurry generation. Here only the required electrical capacity for the compressor is taken into account. Necessary capacities for mixing or scraping devices and auxiliary systems, e.g. initially or sequentially operating vacuum pumps should not be part of a general comparison and have to be evaluated case by case. Using the method of direct evaporation additional energy demand for ice production compared to chilled water generation can be reduced significantly. If ice generation (charging of storage) can be done during nighttime the efficiency can be further increased by taking advantage of lower ambient temperatures, see #4 and #6 in Tab. 1. The comparison between case 1 in (on-time chilled water generation) and case 4 (vacuum ice slurry generation during nighttime) shows that additional energy demand for ice generation can be overcompensated by saving that results from the decrease of the condensation temperature.

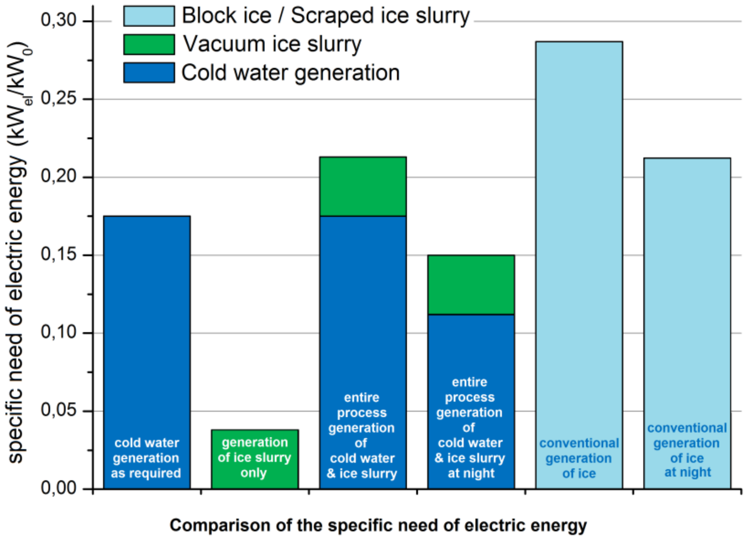


Fig. 5: Efficiency comparison

2.3. Facility Scheme

At Göttingen University a second pilot facility of a vacuum ice slurry thermal storage system has been installed. The system is integrated in the chilled water network of a chemistry building in order to reduce peak loads. An overall scheme of the facility is shown in Fig. 6. The chilled water network is run at 6°C/12°C. The conveyed and compressed water vapor is condensed by a direct condenser which is supplied by an intermediate cold water circuit. The produced condensation heat is transfered to the subordinate chilled water network. This is done by HX2.

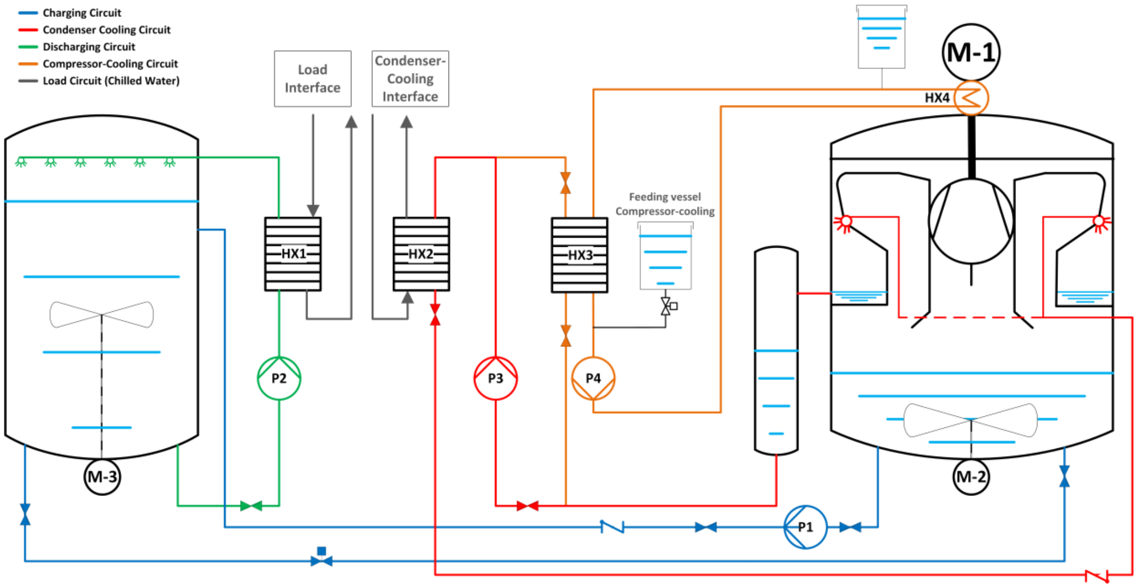
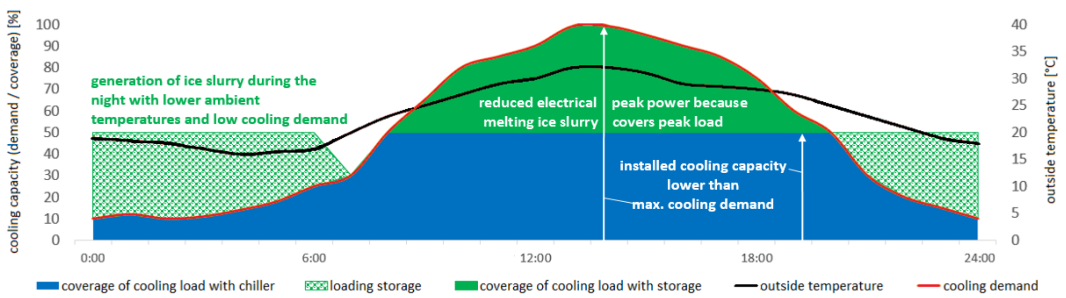


Fig. 6: General scheme of the pilot facility at University of Göttingen

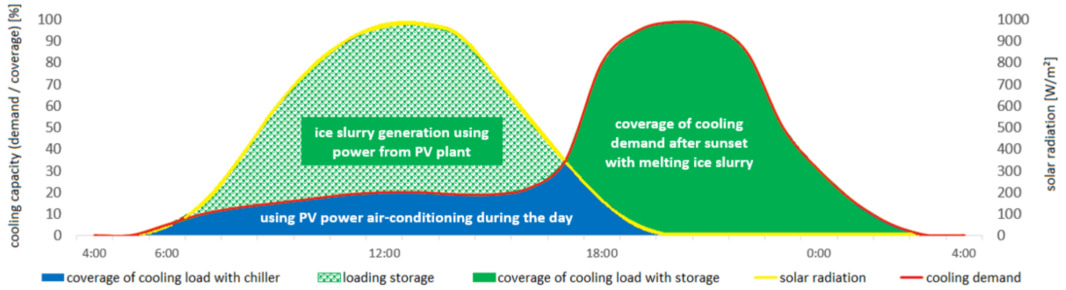
A small fraction of the volume flow (condensed vapor, destillate) is used as return flow to the sump of the evaporator. For cooling parts of the compressor (contour plates, rotary shafts and seals) chilled water from the condenser cooling circuit is used. An agitator in the sump of the evaporator was installed in order to increase evaporation surface and thermal heat transfer coefficients for maximizing the evaporation performance. For discharging the storage a 300kW plate heat exchanger (HX 1) tranfers heat from the chilled water network to the ice slurry. The storage vessel has a diameter of 3 m and takes 28m³ of water. The fully charged storage reaches a capacity of 1.000 kWh which correlates with a mass fraction of 50 % ice produced. As well as for other ice slurry generating processes a freezing point depressant additive has to be used in order to reach smaller crystal sizes and minimizing the risk of frozen evaporation surfaces. At ILK’s vacuum ice slurry generators sodium-chloride-solution (1%) is applied which lowers the initial saturation temperature by 0.61 K. The demonstration facility is fully-integrated within the subordinate control system. With an installed data logging and the access via remote control error messages and failure reports can be analyzed. An additional LabVIEW-programme is used for monitoring and data analysis.

2.4. Solar Cooling with Vacuum Ice Slurry

Using solar energy fluctuating availabilities lead to high requirements in order to level supply voltages in power grids. Besides electrical storage technologies peak availabilities can be used to converse and store effective energy for a delayed use, e.g. for cooling purposes. Even conversion losses can be shifted. Consequently energy consumption for the provision of cold thermal energy during trough periods can be minimized significantly. Nevertheless cooling load and energy availability curves has to be analyzed. In Fig. 7 two generic charts for load shifting describe the main approaches for the use of cold thermal energy storages. The upper chart shows an efficiency orientated approach with focus on ideal condensing conditions at times with low ambient temperatures. For instance in continental climate areas (e.g. deserts) high day / night temperature differences resulting in high efficiency values. For the application of solar cooling an availability orientated approach has to be applied. Mainly, this approach can be reasoned by a higher reliability of supply (autonomous energy provision) or overcapacities of solar energy. As a result, financial aspects play more and more an important role. When it comes to troughs in energy availability market prices for energy provision tend to increase. In times of higher availabilities or even overcapacities low market prices or negative market prices can be achieved.



Coverage of peak load with ice slurry
Example: coverage of cooling demand of an office building or production site



Decoupling of cold generation and cooling demand increasing the self-consumption of PV power
Example: theater with performance in the evening

Fig. 7: Schematic charts for load shifting of cold thermal energy

Outlook

The paper presents a comprehensive approach for using water as refrigerant. Taking into account further requirements to integrate renewable energy sources into innovative refrigeration concepts cold thermal energy storages based on ice slurry are a preferable solution. Thermodynamically the process of direct evaporation under triple point conditions reflects a high efficient approach to generate a pumpable ice slurry solution which can be isochronously used as secondary refrigerant and storage medium. At ILK Dresden a further pilot facility was developed and has been tested under laboratory conditions. Due to a delay at customers chilled water system practical experiences cannot be discussed so far. Final commissioning is terminated for the first quarter 2018 and operational data will be presented.

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