# IceCO2

## Ice Slurry Generation from Supercooled Water for a Pumped Thermal Energy Storage

As part of the Ice-CO2 project, SPF is developing a novel ice slurry storage system intended to serve as a cold reservoir in a pumped thermal energy storage facility: our partner, the American company Echogen Power Systems, utilizes a $CO_2$ heat pump they have developed, along with two thermal storages at different temperatures (320 °C and 0 °C), to build a "Carnot battery". This system efficiently stores surplus electricity as thermal energy and later converts this thermal energy back into electricity when needed, feeding it into the grid.

### Novel ice storage using the supercooling approach

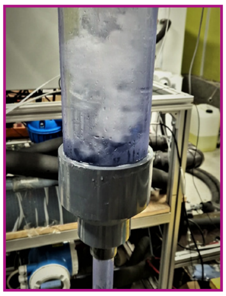
Using ice slurry produced from supercooled water with an in-stream crystallizer opens a new path for ice storages, increasing efficiency and reducing investment cost compared to ice-on-coil systems.

- Power needs (heat exchanger) decoupled from stored energy (storage size) since the heat exchanger for supercooling is the evaporator of the heat pump.
- Constant efficiency, since heat exchanger is always free of ice.
- Low maintenance cost compared to scraper technique, since no movable parts are involved.

### Working principle (see scheme below):

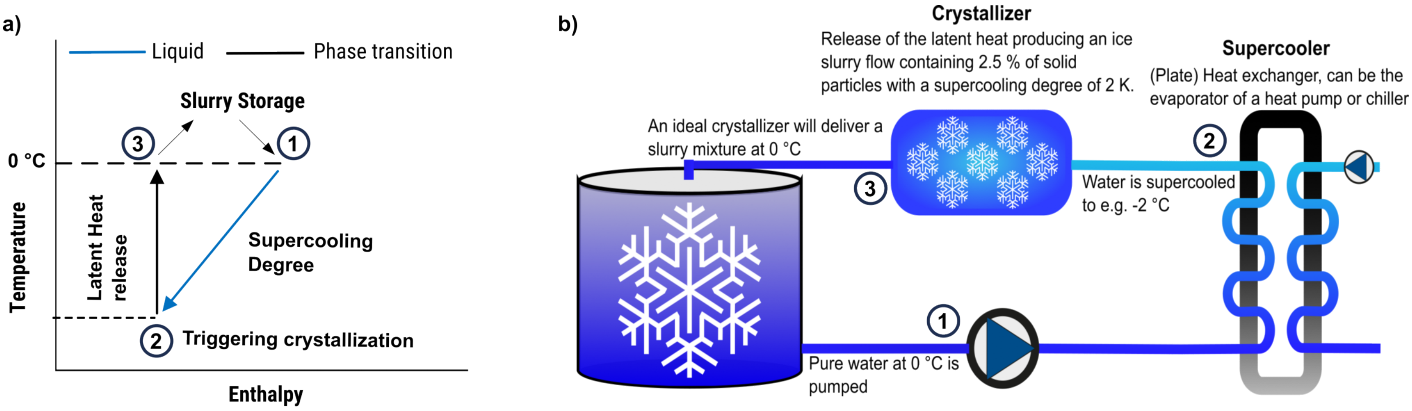
- Liquid water at a temperature of 0 °C is pumped from the storage vessel (state point 1) into a standard plate heat exchanger - the supercooler - where it undergoes supercooling, e.g. to a temperature of −2 °C.
- Water stays in a metastable liquid phase (state point 2).
- Stored sensible heat is transformed into latent heat triggered by the nucleation mechanism placed in-stream inside the crystallizer. Slurry will leave the crystallizer with a temperature of 0 °C (state point 3), i.e. all sensible heat is converted into latent heat during the phase change from supercooled water to ice inside the crystallizer.
- Slurry is pumped into the storage vessel.

Gasketed heat exchanger (supercooler) used to superccol water.

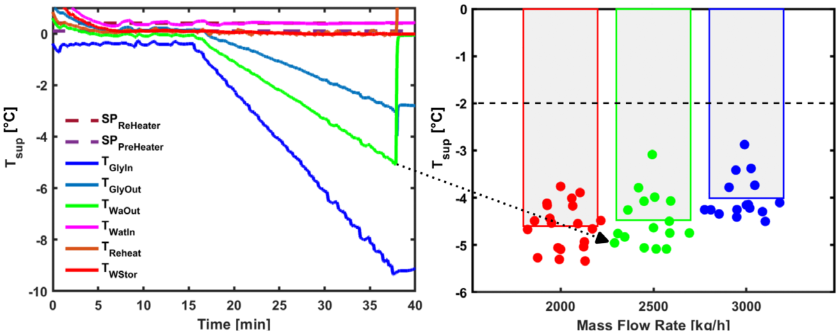


Crystallization of supercooled water in crystallizer initially triggered by ultrasound.

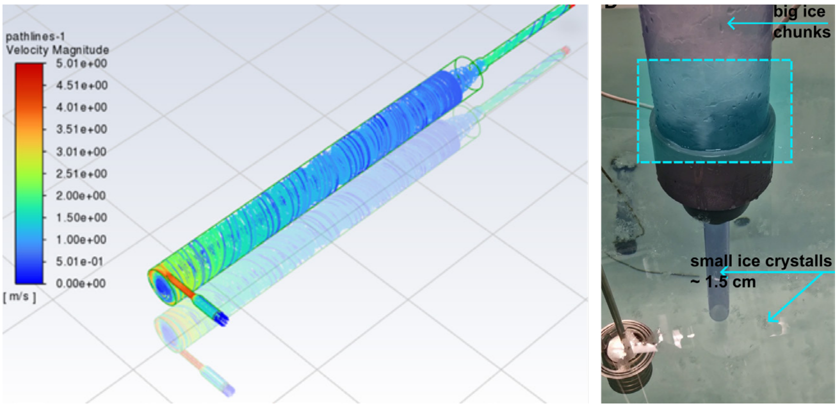
Ice slurry stored with high mass ice fraction avoiding ice particles from being sucked into the supercooler.



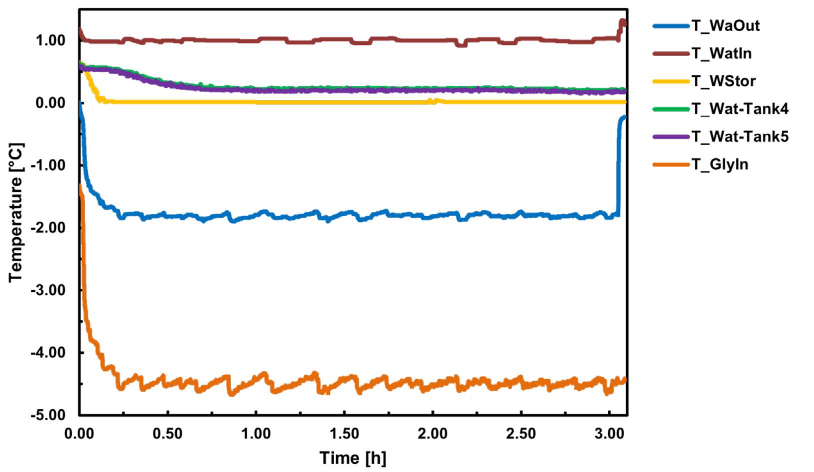

Temperature as a function of enthalpy using supercooling for ice slurry production. b) Conceptual visualization of the supercooling concept. a) and b) are linked via points 1 to 3: Pure liquid water at a temperature of 0 °C (1), is pumped into the supercooler, where it is supercooled and remains in a metastable liquid state (2). The supercooled water is crystallized in an in-stream crystallizer, releasing sensible heat into latent heat, and is pumped into the storage vessel as slurry (3).




**Left: Supercooler test-run at a water mass flow rate of 2500 kg/h with the decrease of the glycol temperature (blue line) in steps of 0.2 K per 0.5 min. The minimum supercooling temperature, at the outlet of the supercooler (TWaOut, green line) is one of the points in the bar plot (right) summarizing the reached supercooling temperatures for three evaluated different mass flow rates. The bar heights give the average supercooling temperature achieved per mass flow rate.**




**Left: CFD simulation of a single-phase fluid (water) inside the crystallizer, showing a velocity profile of the flow (velocities given according to color bar). Right: Photograph of the crystallizer with mounted outlet reduction and pipe, slurry fed into the storage. The cyan marked area is the area of suction effect causing a trenching of the ice crystals into smaller particles.**




**Measured temperature data for a successful 3 h test run at an average supercooling temperature of -1.75 °C (blue line, TWaOut). Water is pre-heated to 1.0 °C before entering the supercooler (red line, TWatIn). The temperature in the storage vessel filled with slurry is very close to zero during the whole test run (yellow line, TWStor).**

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## Results of Heat Exchanger Testing

Gasketed plate heat exchangers with and without coatings were tested with regard of the achievable supercooling temperature when operated with water and glycol as the heat transfer fluid. The glycol inlet temperature was decreased in steps of 0.2 K/ 30 s, followed by a decrease in water outlet temperature until a freezing inside the heat exchanger occurred. These tests were repeated at least 15 times each for different water mass flow rates.

- For high and constant water quality icephobic coatings could not improve reached supercooling temperature.
- With large enough heat exchanger surface area, operation at a reasonable supercooling temperature of - 2 °C is possible with pure stainless steel surface.

## Crystallizer Development

An in-stream crystallizer made from PVC-U has been developed. It is capable of releasing the whole supercooling potential due to its dimensions within the crystallizer such that a slurry, consisting of ~ 2.5 % ice and water at 0 °C is pumped into the storage vessel.

- Initially, nucleation is reliably triggered inside the crystallizer by ultrasound. Afterwards, the nucleation process is self-sustaining due to the adhesion of very small ice crystals to the upper part of the crystallizer pipe wall, serving as nucleation centers for new crystals to build.
- Supercooling is released completely thanks to the length and rotational movement of fluid inside the crystallizer.
- Prevention of upstream ice propagation in direction of the supercooler due to high velocity in the crystallizer inlet.
- Power of the crystallizer developed at SPF: 12 kW (tested at Echogen power systems).

## Crystallizer Test Results

- Temperature measurements of a successful test-run of the crystallizer with a supercooling power of 6.5 kW, operated for 3 h, at a water mass flow rate of 3200 kg/h are shown in the left figure.
- Crystallizer produced at SPF was tested in Echogen facilities with a supercooling power of 12 kW (supercooler inlet temperature +0.3 °C, supercooler outlet temperature -2.3 °C).

## Storage Vessel Design

- Storage vessel with a volume of 1 m³ was filled with 23 % ice during the test-run presented.
- Phase separation between solid and liquid must be guaranteed in the storage vessel, as no ice crystals should be pumped into the supercooler, where they would cause a freezing event immediately.
- Further development in the storage vessel design is required to increase the ice mass fraction inside the storage vessel to close to 50 %.

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