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Federal Department of the Environment, Transport, Energy and Communication DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

Annual report 2021

Slurry-Store

Experimental and numerical investigations of ice slurry storages.

INSTITUT FÜR SOLARTECHNIK

OST Ostschweizer Fachhochschule

Date: December 21, 2021

Location: Rapperswil

Subsidiser:

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Section
CH-3003 Bern
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SFOE Contract number: SI/502063-01

1 Motivation

Solar-ice systems are becoming popular in Switzerland. However, state-of-the-art solar-ice systems have some disadvantages such as a usually higher cost compared to Ground Source Heat Pumps (GSHP) if the same performance is desired. Therefore, research is still needed to bring robust solar-ice systems to the market with comparable cost and higher efficiency compared to GSHP solutions.

A feasibility study carried out in the project Slurry-HP undertaken by SPF (Carbonell et al., 2017) has shown that solar-ice systems based on the ice slurry heat pump using the supercooling approach have a high potential for cost reduction, while having a high energetic efficiency, especially for ice storage volumes of at least 1 m^3 per MWh of yearly heating demand, which corresponds well to ice storage volumes used today for multi-family buildings. Moreover, an ice slurry storage would allow to use existing rooms of the building efficiently since any shape and room size could store slurries if properly distributed.

The supercooling ice slurry method is a concept for ice slurry production that does not rely on moving parts. It is based on supercooling water with a heat exchanger, the so-called supercooler, which allows one to supercool a liquid to a metastable state. This liquid is then pumped to the crystallizer where it undergoes nucleation to form an ice slurry mixture that is stored in the ice slurry tank. An important variable here is the degree of supercooling, defined as the freezing temperature minus the supercooled liquid temperature. This concept allows one to completely eliminate the heat exchangers from the ice storage and it also eliminates the efficiency lost by an insulating ice layer growing on the cooled surface. The solar ice slurry system is expected to have an installation cost reduction of 10 % respect to traditional solar-ice systems with ice-on-coil heat exchangers.

2 Project objectives

The overall goal of the Slurry-Store project is to experimentally investigate ice storages able to store and melt slurries with (solar) heat without using a stirring device. The specific objectives of the project will be:

- Design, construct and test an ice slurry storage tank capable of achieving 50 % ice slurry fraction
- Develop, construct and test an ice crystallizer for stable continuous ice slurry production of 6 hours
- Design, construct and test two concepts for loading (icing)
- Design, construct and test two concepts for unloading (melting)
- Develop a mathematical model for the ice slurry storage, implement and validated it with TRNSYS.
  Design, construction and testing of an ice storage facility capable of achieving 50

3 Status and work carried out

During the year 2021, parts for the previously planned experimental set-up have been ordered and assembled, as described in the yearly report of 2020. The first version of the set-up was tested and various alterations and improvements were found to be necessary. The different parts and alterations are described in chapter 4. The current ice slurry generator concept is able to operate with a 2 K supercooling degree at a mass flow of 1000 kg/h releasing its supercooling degree in the ice crystallizer. This supercooling degree leads to an ice slurry flow with a 2.5 % ice content that is pumped into the tank. We have operated this systems for more than two hours until the small tank was filled with ice. However, there are several limitations and new challenges that were found during this year and that have to be tackled and improved.

- **Inducing crystallization (ice crystallizer)**: Crystallization can be induced using several methods, as described in the theoretical chapter of the yearly report of 2020. The currently preferred method is the use of ultrasonic wave bombardment, which works reliably for the necessary operating conditions. The ultrasonic transducer provokes cavitation which in turns enhances crystallization due to the high local pressure change on the fluid flow. However, it requires a supercooling degree above 1 K and roughly

30 s of bombardment time to successfully induce crystallization. The pipe wall must not be heated at the position of the ultrasonic transducer to allow ice to attach to the wall. After the mentioned 30 s, ice is attached at the inner pipe walls and continues to grow along the walls. This device is described in section 4.2.

- **Prevention of upstream propagation (upstream ice barrier)**: As soon as ice grows at the inner pipe walls, it starts propagating towards the coldest points, i.e. towards the supercooling heat exchanger. The water velocity at the pipe wall has the no-slip boundary condition, i.e. zero velocity. This means that ice at this location is not flushed away by the water flow until its volume is large enough. Even then, it is not fully removed, and ice nuclei are still present at the rough spots of the inner pipe wall leading to a continuous ice growth. During this process, ice grows towards the supercooler until the heat exchanger or other obstacles are reached anywhere else between the supercooler and the crystallizer, both resulting in clogging the system. Thus, a mechanism is needed to prevent upstream ice propagating along the pipe walls. A design to accomplish this task, called *upstream ice barrier*, was proposed and tested successfully, but it still needs improvements regarding energy efficiency and reliability. The upstream ice barrier is described in section 4.3.

- **Ice pumping and distribution**: The currently used crystallization design has ice growing mainly at the pipe walls, resulting in a loosely connected, cylindrical ice shape. It is pushed away from the pipe by the water flow as soon as its resistance to the water is larger than its adhesion to the pipe wall. It is, however, strongly susceptible to blockage if there are obstacles on its path towards the tank. Experiments have shown that already edges of few mm on the pipe walls can be enough to lead to blockage of the entire pipe. A device, called *seeding mixer*, had been designed, built and tested to deal with this challenge. The current design, described in section 4.4, still needs improvement due to a narrow range of operation conditions.

- **Tank design, separation of ice and water**: A certain cause of blockage is the presence of ice at the entrance of the supercooler. If ice nuclei are present at this location, blockage is almost inevitable. This leads to the challenge that the feed water flow to the supercooler needs to be completely ice free, even though it is connected to the ice slurry tank. Other approaches address this challenge by simply pre-heating the water flow entering the supercooler until all ice particles are melted. Preliminary experimental results showed that the required energy input and reliability is linked to the amount of ice that is present at the tank outlet. The design of the tank and the way how the ice slurry flow is introduced into the tank influence the amount of ice present at the tank outlet and can be used to optimize energy efficiency.

4 Experimental set-up for supercooling ice production

4.1 Current status of the experimental set up

The target of the described installation is to continuously produce ice slurry with a 2 K supercooling degree. This will lead to a continuous ice slurry flow with an mass ice content of roughly 2.5 % of the flow rate at the tank inlet. Our goal is to achieve an ice fraction of 50 % in the tank itself. The design of the installation is based on the setup of a previous project, in which the supercooling capability of a coated flat plate heat exchanger was tested. The setup is schematically shown in Fig. 1. It consists of two separate piping loops: i) a loop with demineralized water (right) and ii) a glycol-water mixture loop with 30 % glycol content (left). The two loops are connected via a plate heat exchanger that acts as the supercooler.

The glycol loop is cooled using the air-cooled chiller Lauda IN 1030 T (left device on Fig .1). Its mass flow is achieved with a chiller pump controlled by an Endress+Hauser Promag 10H. The temperature is controlled by the chiller using the PT-100 temperature sensor TI-2 installed before (left part) of the heat exchanger. Temperatures are measured using several 4-wire PT100 temperature sensors. Temperature sensors TI-2, TI-5 and TI-6 are used to control the temperatures before and after the supercooling plate heat exchanger.

TI-5 is also used to control the heat generated by the electric heater (Heater 1). The temperature sensor TSH includes a mechanical safety switch to prevent overheating in case the heater would run without a fluid flow. The temperature at TI-4 is currently not used, but is shown to be able to predict icing inside of the pipe: a sudden increase of temperature while no system settings are changed strongly indicates icing. A temperature sensor can also be installed after the last piece of equipment, the so-called *seeding mixer* but poses an obstacle to the transported ice. It can be used to measure the successful removal of supercooling, but still needs improvement to not block the ice slurry flow. The electric current delivered to the pump together with data from flow measurement is used to detect blocked pipes. Once ice is detected, a melting program is initiated. In this program, the temperature is increased by the chiller reverting the cycle from cooling to heating to melt the ice formed on the heat exchanger.

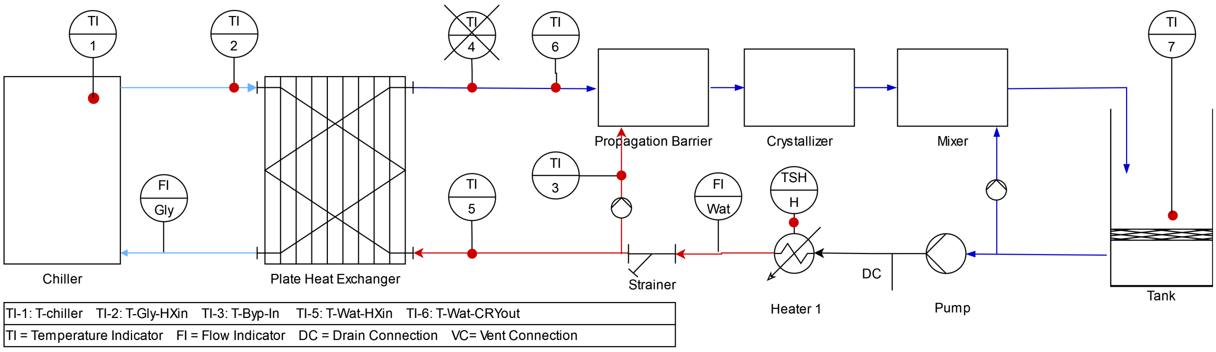


Figure 1: Piping & Instrumentation Diagram of the current set up.

On the water circuit, the water is pumped from the ice storage and heated up to 1.5 °C to ensure that no ice particles are pumped to the supercooler. Reduction of this temperature will be targeted during 2022. The fluid is pumped using a radial pump. After passing a static mixer that ensures the flow is well mixed, the mass flow rate is measured using a Coriolis mass flow meter. It then passes a filter with 5 μm mesh size to remove possible solid particles before it reaches the supercooler. In the supercooler, the water is cooled down to temperatures around -2 °C to -2.5 °C, where icephobic coated surfaces are expected to delay the formation of ice. With a 2 K supercooling degree an ice slurry mixture with around 2.5 % ice content will be fed into the slurry tank.

After the supercooler, the supercooling state is released in the ice crystallizer, which is a custom made device consisting of three parts. In the first part, a solution to avoid ice propagation upstream, the so-called "ice barrier", is installed. The ice barrier device consist on a low flow (roughly 3 % of the main flow) above 0 °C that is injected into the inner wall of the main flow to prevent ice from propagating towards the heat exchanger. After this, an ultrasonic transducer is mounted on the pipe to trigger ice nucleation. Ice is formed inside the piece containing the ultrasonic device. The ice particles are flushed away, but some of them remain attached on the inner side of the pipe wall. The third part of the ice crystallizer, the so-called *"seeding-mixer"* consists of a device that mixes a high flow (roughly 50 % of the main flow) of cold tank water to thoroughly mix the main flow. This speeds up ice formation, releases the remaining supercooling and removes ice from the pipe walls, rendering it pumpable. All of these parts are crucial to prevent formation of ice in unwanted places, where the ice could clog the pipe.

4.2 Inducing crystallization

Initial versions of the crystallization device used a peltier module that was introduced into the flow. It became obvious that the ice adhesion to the peltier was rather large and that the peltier itself was acting as obstacle while flushing ice away. No stable operation condition could be found using this method for any of the tested flow conditions and pipe diameters ($\dot{m}$ = 500 kg/h...4000 kg/h, d_{in}=27.4 mm...80 mm). This attempt is depicted in the left picture of Fig. 2. As next option, the peltier was used on the outside of the pipe, assuming that cooling of the pipe wall would cool down the inside of the pipe wall enough to trigger nucleation. This did

Table 1: Equipment and instrumentation planned for the experimental set-up

Description	**Identifier**	**Make**	**Model**
Electric Heater	El-H	Walser	RDL 70, 7 kW
Pump	P-W	Grundfos	CME
Coriolis Mass Flow Meter	FI-W	E+H	Promass 300, DN15
Filter	-		5 μm mesh
Plate Heat Exchanger	PHX	AlfaLaval	CBXP52
Chiller	El-C	Lauda	IN 1030 T
MID	FI-G	E+H	Promag H300
Temperature Indicator	TI-1 to TI-6	Transmetra	4-wire PT100
Flow Meter	Mixer	Gams	173940
Flow Meter	Barrier	Gams	212460E

not lead to any success, even with the reduction of pipe wall thickness to 0.5 mm. Then, the peltier module was inserted into the pipe wall, such that it replaced pieces of the wall. There, once again, the high adhesion of ice to the peltier prevented flushing out of ice and lead to blockage. It was found that attaching a peltier module to the outside of the pipe wall and connecting it with a 1 mm hole to the inside of the main flow lead to some success. This is depicted on the right picture of Fig. 2. Ice formation could be triggered successfully if the supercooled water was below $-1\,°C$. However, sealing the peltier module to the pipe seemed to be troublesome and cooling the outside of the peltier during operation might not be an easy task in a real system. Furthermore, for water flows above 1000 kg/h, it did not proof itself to be reliable.

Due to the above reasons, the method of ultrasonic bombardement was tested. A 45 kHz, 50 W ultrasonic (US) transducer (*The allendale group*) was clamped to the pipe wall using a custom made clamping plate. The transducer could also be screwed directly to the pipe, but the pipe wall is too thin to insert screws into it. Also, doubling up and increasing the pipe thickness hinders the effect of the ultrasonic bombardment. The transducer emits ultrasonic waves, leading to cavitation inside the fluid flow. The high pressure oscillation that occurs during cavitation result in nucleation inside the bulk water. This method successfully started nucleation with supercooling degrees of 1.25 K and higher for the tested mass flows of 500 kg/h and 1000 kg/h. The resonance of the tube due to the US waves helps to remove ice from the pipe wall during its operation, preventing ice from attaching and growing at pipe walls. Thus, ice growth is only observed further downstream once the waves are active. The advantage of this method is its flexibility and reliability. The transducer can be attached to almost any shaped pipe of duct without altering the container in which ice nucleation is desired.

4.3 Prevention of upstream propagation

During the experiments, it was found that ice mainly grows at the pipe walls and slowly grows upstream. As stated in section 3, a device is needed to prevent ice from reaching the heat exchanger or any other parts in the pipe that could lead to blockage. Initial experiments used a trace heating cable (make *HTS Systems, DEVIpipeguard 25*, 2 m, 25 W/m) that just heats the outside of the pipe wall, leading to an elevated temperature at the inside of the pipe. The heat tracing concept can be seen on the right of Fig. 2 (red cable). This was found to be working for low degrees of supercooling and low flows ($< -1.5\,°C$ and < 500 kg/s), but failed with higher degrees of supercooling. Insulation and a stronger heating cable (40 W/m) did not improve this method noticeably. Furthermore, it consumes electricity, which could reduce the overall efficiency of the system.

As an alternative of the heat tracing, Mito (2002) proposed a device that is supposed to form a barrier to the ice, and efforts were made to replicate such a device. The idea of this device is to introduce a low flow water stream that is slightly above 0 °C, in which ice does not grow. This water stream is currently taken

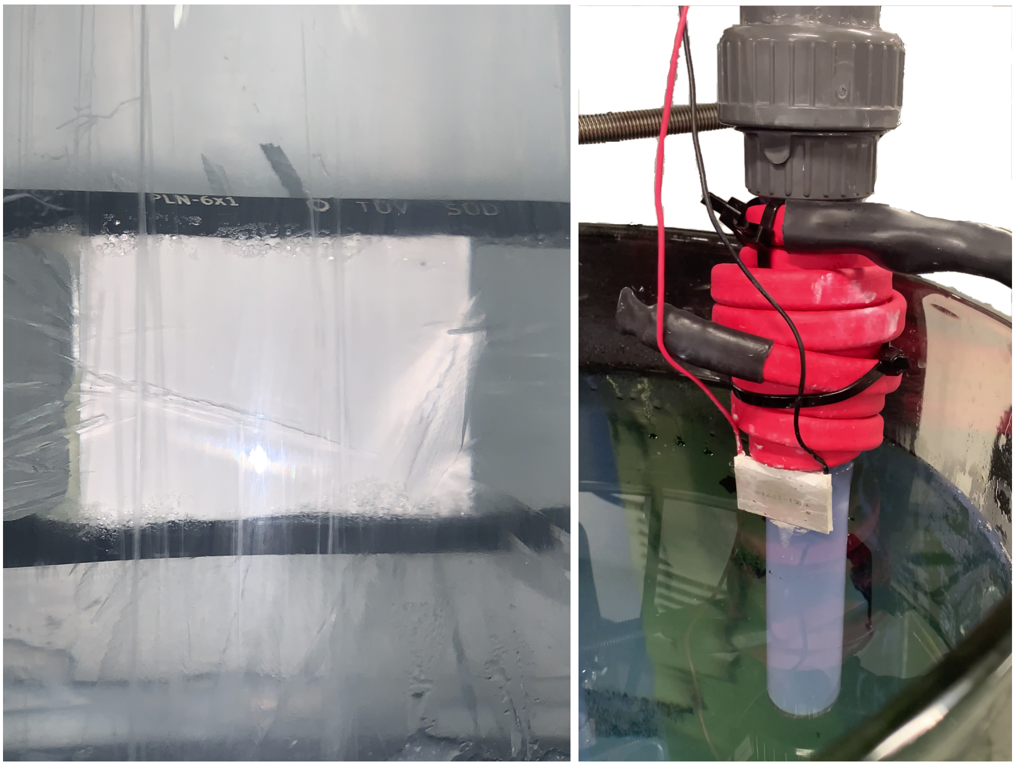
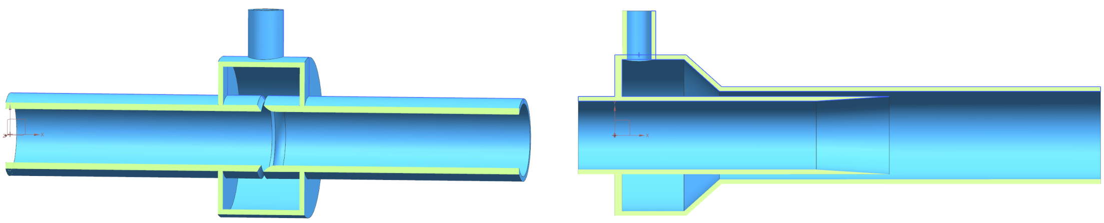


Figure 2: First version crystallization module. Left: a peltier module was introduced into the flow to start nucleation. Right: the peltier module (white plate) is on the outside of the pipe, connected with a 1 mm hole to the cold flow.

from the system after the installed filer (FI in Fig 1), thus by-passing the heat exchanger. With this concept, ice can not adhere to the pipe wall where this warm stream is injected, allowing the main flow to flush it away. Two different geometries are currently investigated, which are depicted in Fig. 3. The design shown in Fig. 3 (a) was constructed and tested. It allows to operate at conditions above 3 K supercooling degrees with a mass flow rate of the main flow of 1000 kg/h. Stable conditions were found with temperatures of 2.2 °C with 0.5 l/m, which corresponds to 3 % of the main flow. Design shown in Fig. 3 (b) is currently being tested and operated at conditions of up to 2.25 K supercooling degree and 1000 kg/h main water flow. Efforts are currently made to reduce the mass flow and temperature of the barrier flow in order to improve the energy efficiency.



(a) (b)

Figure 3: CAD drawings of two proposed ice barrier designs. Slightly warm water above 0 °C is fed into the main stream from the top and through a narrow annulus gap in the pipe wall, preventing ice from growing upstream (from right to left). Main water flow direction is from left to right.

4.4 Ice pumping and distribution

In the first design of the ice slurry generator, ice was pumped into the tank using only a straight piece of piping after the crystallizer. Afterwards, it was observed that slight changes in the piping after the crystallizer (e.g. elbows, reductions, fittings) could lead to blockage. This study made clear that a close proximity between crystallizer and tank would be necessary if the supercooling degree would not be completely released. This might not be always possible on a future system design and a solution was needed. The goal is to be able to pump the ice slurry flow trough a certain distance of piping with valves and other devices.

In the used device, a water/ice mixture from the ice slurry storage is fed into the main flow after the crystallizer with a flow of 50 % respect to the main flow. The inlet of the second flow is drilled tangentially, such that a vortex is created inside of the main pipe. This strongly mixes the main water flow and promotes ice growth. Since the mixed flow contains ice particles this device is called *seeding-mixer*. After the seeding-mixer, the supercooling degree is almost completely released featuring a water temperature of $\pm$ 0.1 °C after its use. Currently, the required amount of water fed into this device is roughly half of the main mass flow. It was successfully tested with supercooling degrees and main water mass flows of up to -2 °C and 500 kg/h respectively. The ice slurry could be led through multiple consecutive elements such as elbows, reductions, PT-100 sensors and even a rough hose. However, further studies are required to improve the energy efficiency (reducing the required water flow) and increase the reliability at higher main flow velocities and higher ice fractions.

4.5 Tank design: separation of ice and water

The stability of the ice generator is dependent on the ability to completely eliminate ice slurry particles pumped into the entrance of the supercooler. If any ice particle enters the supercooler, ice will grow rapidly and a blockage of the supercooler will be inevitable. This means that the feed water to the supercooler needs to be completely ice free, even though it is connected to an ice filled storage tank. Most publications heat the inlet flow to the supercooler to 0.5 °C to reduce the probability of pumping ice particles into the supercooler (Tanino and Kozawa, 2001). In the present setup, this temperature was not sufficient to keep the heat exchanger from blocking. Tests have shown that at least 0.75 °C was necessary, so currently, a higher setpoint of 1.5 °C is used as a form of safety. This requires more energy for heating and cooling and thus decreases efficiency, but allows us to test the other devices with confidence. Our aim is to separate the challenges and tackle them one by one. The current design heated by an electric rod is not completely heating the entire flow evenly. Thus, one way to reduce this temperature will be to have a more efficient heat exchanger for preheating water that would ensure a fully mixed flow. A second approach is based on the ability to filter ice particles. As an attempt of improvement, the previously used strainer with 0.5 mm mesh size was replaced with a filter using 5 μm mesh size. This did not lead to a noticeable effect. As a third measure we are working on the storage design. Ideally a proper design that would allow a high level of ice slurry stratification would help to reduce/eliminate ice particles pumped to the supercooler. In this regards, the first 150 l glass tank was replaced by two 1000 l IBC tanks. They are currently installed as a daisy chain, where the ice slurry mixture is stored in the first tank and ice free water is extracted from the second. This setup also allows to interrupt the connection between the two tanks, giving the possibility of a non-circular, independent operation of roughly one hour time, in which introduction of ice into the supercooler from tank side is impossible. This allows us to separate effects and reduce challenges on specific experiments. Having a bigger storage volume also leads to longer residence time of water in the tanks and to lower velocities, both leading to a more stratified behavior of the ice-water mixture in the tank and thus reducing the likelihood to have ice in the outflow of the tanks.

5 National / International cooperation

We have started a collaboration with Echogen, a company from US for which an ice slurry generator would be a great benefit for their electro-thermal energy storage (ETES) concept. This collaboration has the potential to allow us to improve and scale-up the current designs of an ice crystallizer for their application.

5.1 Publications and presentation in conferences

No publications are available yet

6 Evaluation 2020 and Outlook 2021

During 2021, the first experimental design to produce ice slurries has been finished. This includes a supercooler and an ice crystallizer. Originally, the ice crystallizer was meant as a device that would trigger nucleation only. After this year of research, our current understanding of the ice crystallizer includes a method to avoid upstream ice propagation and one that ensures that the slurries are pumpable after the crystallizer, using the so-called ice seeding-mixer. Thus, our cystallizer concept considers three devices that are strongly interlinked. If one fails, the whole system collapses, thus we consider these three devices as a whole unit. We have shown that we can superocool water by about 2.5 K in steady state for two hours when all the devices described below are in place. An example of a two hour running test run can be seen in Fig. 4. The sensor T-Wat-CRYout shows the supercooling degree achieved after the supercooler. T-WAT-Surface is placed directly above the upstream ice propagation barrier. T-WAT-Bypass is the water temperature injected by the ice propagation barrier device into the main flow. In this experiment, a chiller set point of −2.5 °C, a main supercooled flow of 960 kg/h with a by-passed flow on the propagation barrier of 39.6 l/h were used. The upstream ice propagation barrier from Fig. 3(a) was used. The test was stopped since ice was detected originating from the supercooling heat exchanger. This can be determined from the temperature data: the temperature in T-Wat-CRYout rises earlier than the temperature in T-WAT-Surface, which is located somewhat downstream from the first sensor. The tank temperature fluctuates since ice had to be removed manually to prevent overfilling of the tank. T-WAT-Bypass fluctuates initially since it was manually set.

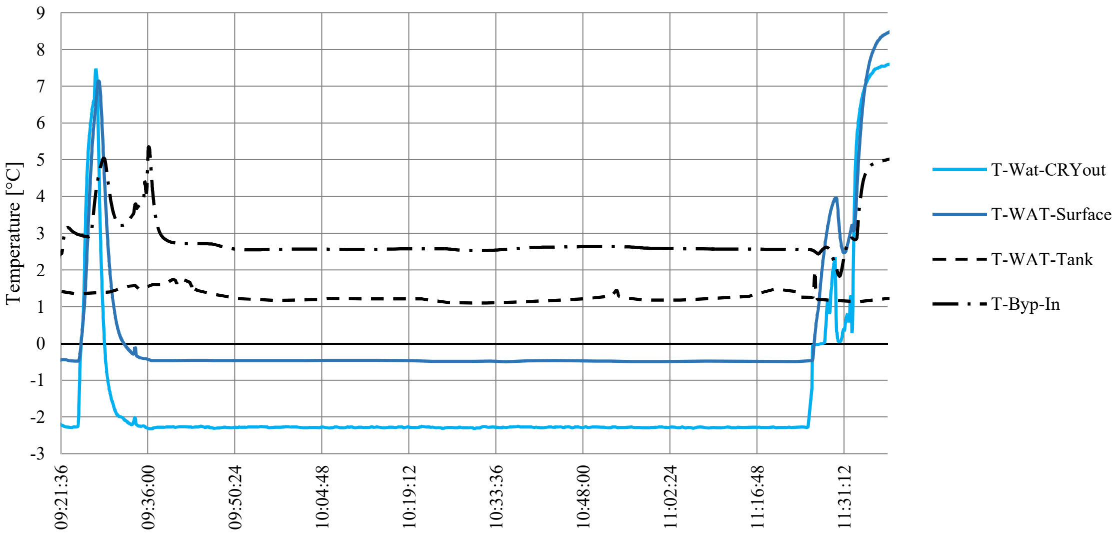


Figure 4: Temperature measurement data of a 2-hour long test run, measured on 30.11.2021.

For 2022 we are planning to carry out the following work:

- Optimize the design of the downstream ice propagation barrier by quantifying the effects of injected temperature and mass flow rate respect to the supercooling degree and mass flow rate of the supercooled flow. This will be supported by Computational Fluid Dynamics (CFD) simulations to analyze the most promising geometry.
- Optimize the design of the seeding-mixer by quantifying the effects of injected mass flow rate respect to the supercooling degree and mass flow rate of the supercooled flow.

- Analyze stratification measures to ensure injected ice slurries in the storage are not pumped to the supercooler. This will include tank inlets designs and velocity reduction measures. If possible, this will be supported by CFD simulations as well.
- Proper arrangements of inlet and outlet of the tank and different kinds of heaters and filters have to be tested to improve the reliability and energy consumption.
- Different ways to melt ice slurries from a heat source will be investigated.

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