DTU Civil Engineering
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Exploring Ice-source Heat Pump Solar Heating Technology

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Summary

This project studied a new technology of heat pump - ice source heat pump (ISHP) for space heating that utilizes both solar heat and low temperature heat from ambient air in winter season. The project conducted the development of the technology from the design and laboratory experiment to the field validation. The results showed that the ice source heat pump solar heating system developed in this project was very successful. Combined with radiant heating system with 40°C of hot water supply, the minimum COP of the heat pump is 3. The technology has two significant advantages compared to any other heat pump technologies, i.e. (a) It can used the heat sources with the temperature as low as above 0°C. (b) It can extract heat from phase change of water freeze into ice. The first advantage makes it possible to use low temperature heat of both solar and ambient air. It is particular suitable for the Danish winter application where most of the days are cloudy and mild. The second advantage can significantly reduce the size of the heat storage tank of heat pumps. Coil freeze problem for air source heat pump can be avoided by using ISHP. The ISHP technology may also combined with cross-seasonal solar heating system to extend the heating period or combined with seawater heat pump heating system to avoid freezing problem. The application prospect of the ISHP is huge. This report summarized the details of the principle, the design and the results of both laboratory and field tests on the technology.

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1. Background of the research

Solar irradiance is a clean and renewable energy source. Solar heating technology has been well developed and widely used. However, solar heating in Denmark encountered a problem in winter when space heating is needed. The problem is due to the frequent and long cloudy sky in winter that blocks most of the direct normal irradiance (DNI) results in too low temperature (e.g. lower than 20 °C) of heat collected for space heating. One solution is using heat pump to raise the temperature for space heating [1]. The problem is that a big water tank is required for the storage of sufficient heat to be pumped into the heating space. For a single family house, a water tank of about 0.8 m3 volume or bigger maybe required for storing the heat, which is too big for the installation in a house. Furthermore, the water temperature in the heat storage tank decreases with the extraction of heat by heat pump, which decreases the COP of heat pump and results in higher and higher heat pump power consumption.

Heating in Danish winter using heat pump has also problems. The major barrier is where to find heat sources? Air source heat pump takes heat from outdoor air. However, the Danish winter is cold and humid. The evaporating temperature of air source heat pump has to be well below outdoor air temperature in order to extract heat from outdoor air, which decreases the COP of the heat pump. Furthermore, evaporator of the heat pump needs to be defrosted from time to time due to the humid outdoor climate. These make the operation of air source heat pump at low energy efficiency. Ground source heat pump takes heat from soil underground. However, the mild Danish summer climate does not need cooling in buildings. Therefore, ground source heat pump encounters a problem that the temperature of the soil cannot be recovered in summer by reversing operation of the heat pump. With a continuous extraction of heat from underground soil, the temperature of soil will decrease and thus decrease the COP of heat pump resulting low energy efficiency of ground source heat pump. Besides, the initial investment of ground source heat pump is also very high.

A new concept called ice-source heat pump brings a solution to solve all above mentioned problems in Denmark. The concept of ice-source heat pump is created based on a newly developed ice-crystal diffusion interrupting technology that can prevent diffusion of ice crystal in subcooled water flow. This technology was released by KOLIN M&E in 2017 [2, 3]. With this technology, a normal plate heat exchanger can be used to generate subcooled water at -2 °C without freezing (no antifreezing agent in water). When the subcooled water leaves the heat exchanger, it freezes in the form of ice slurry and releases its phase change heat of 80 kcal/kg. Combined this technology with a heat pump, the evaporator of the heat pump can produce subcooled water into a heat storage tank. The subcooled water will freeze into ice slurry in the tank and release its phase change heat to keep the temperature in the tank at 0 °C. The heat pump continuously suck the 0 °C water from the tank and pump the heat released form phase change heat of ice formation until all water in the tank freezes into ice. In such a process, the heat source of heat pump is the phase change heat of water freeze into ice and, therefore, a name of ice-source heat pump (ISHP) is given to the technology.

An ice-source heat pump has basically no difference from a conventional heat pump except for a special ice-crystal diffusion interrupter is installed at the outlet of the evaporator (④ in Figure 1) that produce subcooled water to prevent ice from being formed inside the evaporator of heat pump. When evaporating temperature is higher than 0 °C, the heat pump will function just like a normal heat pump. Only when the evaporating temperature goes below 0°C, will the heat pump start its ice-source operation mode.

Based on the principle of ice-source heat pump, a new concept of ice-source heat pump solar heating system is designed. Figure 1 shows the schematic diagram of the ISHP solar heating system.

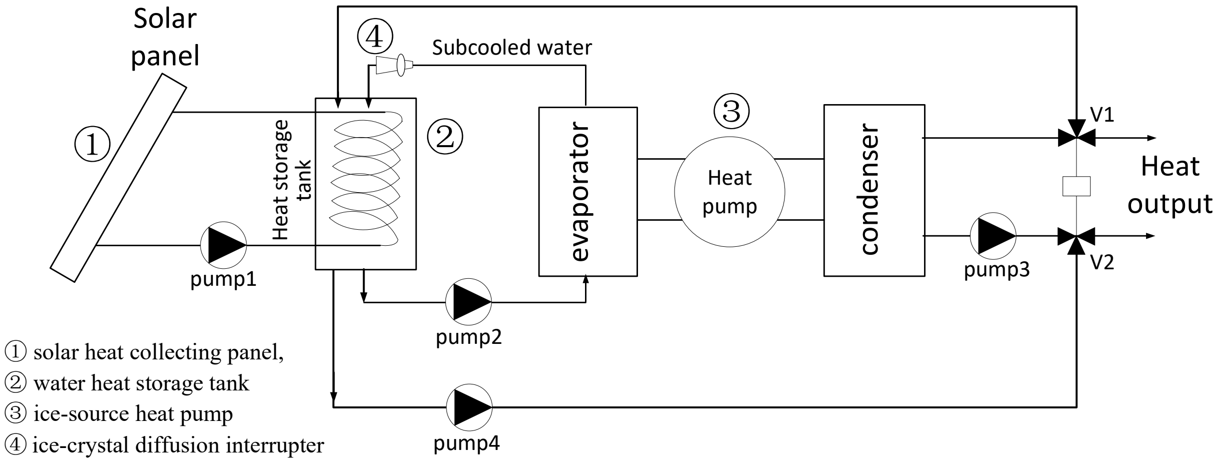


Figure 1. Schematic diagram of ice-source heat pump solar heating system.

The ISHP solar heating system consists of three major parts - a solar heat collecting panel ①, a water heat storage tank ② and an ice-source heat pump ③. The solar panel ① collects solar heat and store it into the heat storage tank ②. When the water temperature in the tank ② is above 40 °C (40 °C is sufficient for most of the radiant heating system), the hot water is used directly for space heating without starting the heat pump. When the water temperature in the tank ② goes below 35 °C, the heat pump will start to provide space heating. The heat pump will first run in a normal operation mode to pump heat from tank ② to the heating space. The water temperature in tank ② will decrease with the operation of heat pump. When the water temperature in the thank drops down to 0 °C, the ice-source heat pump mode will be initiated to generate subcooled water to the heat storage tank and ice slurry will start to form in the heat storage tank. In the ice-source heat pump operation mode, ISHP pumps latent heat released from the ice formation in tank ② to the heating space. Before all the water in the heat storage tank freezes into ice, the temperature of the water in the heat storage tank remains at 0 °C. The COP of the heat pump will first decrease with the decreasing of water temperature in the heat storage tank. When ice is formed in the heat storage tank, temperature in the tank remains constant at 0 °C and the COP of the heat pump will also remain constant without further decrease.

The ISHP solar heating system has the following significant advantage compared to the existing solar heating and heat pump heating systems:

a. It can be used to collect and store solar heat in both sunny and cloudy days. In cloudy winter days, as long as the temperature of water from solar panel is higher than 0 °C, the heat can be stored in the heat storage tank as latent heat by melting ice.
b. The heat storage tank stores not only the sensible heat but also the phase change latent heat of the water. Since the latent heat of phase change between water and ice is 80 kcal/kg (equivalent to the heat of 80 °C temperature change in the same amount of water), the heat storage capacity of the tank increased dramatically. Using an ice-source heat pump, the size of the heat storage tank is only 1/4 of the volume as required in normal scenario of solar heating + heat pump. This makes it possible to install an ISHP solar heating unit in house.
c. Due to water phase change, the low limit of temperature in a heat storage tank is 0 °C. Thus maintains high COP of the heat pump for heating. Compared to the existing air source heat pump, the ice-source heat pump has higher COP (due to higher evaporating temperature) and does not have defrost problem. Compared to the ground source heat pump, the ice-source heat pump is much simple and low cost, and is especially suitable for the Nordic countries where no cooling season can be used to balance the ground heat source.
d. The ISHP solar heating system perfectly solved the problem of solar heat storage for space heating at night with a simple, compact and energy efficient solution. It can most likely be the technology for the future heat pump heating system using solar energy.

2. Research methodology and results

According to the plan, the research project includes three tasks, i.e. 1. design and develop an ice-source heat pump, 2. develop a small ISHP solar heating system and test its performance and control strategy in laboratory and 3. field validation. This report documents the research and development of all three tasks and the results obtained.

2.1 Task 1. Design and develop an ISHP

2.1.1 Method

An ISHP was first designed based on the requirement of space heating using the technology developed by KOLIN M&E Co. Considering COP of the heat pump, the temperature of hot water supply of the heat pump was design at 40°C which is suitable for radiant heat system that is the most popular space heating system in Denmark at the moment and will also be in the future. Figure 2 shows the drawing of the ISHP design that was manufactured by Kolin M&E Co. The design used the patented technology of ultrasonic crystallizer and crystallizing interrupter that is owned by Kolin M&E Co. DTU got the permission of using these technologies for research purpose.

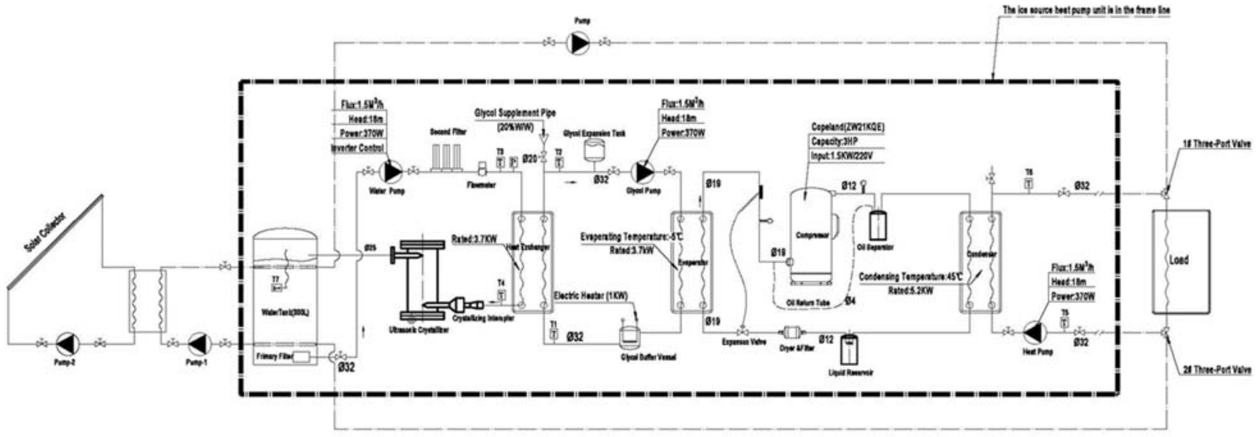


Figure 2. The design of the ISHP developed for this project.

Table 1. Performance of the ISHP tested in the lab.

Temp. in heat storage tank (°C)	Temp of the hot water output (°C)	Flowrate of hot water output (L/min)	Power of the compressor (kW)	Heat output (kW)	COP of the ISHP
0	50	13.08	1.88	4.56	2.40
0	45	13.17	1.68	4.68	2.79
0	40	13.15	1.49	4.58	3.07
0	35	13.18	1.35	4.59	3.40
0	30	13.20	1.27	4.51	3.55

2.1.2 Results

The manufacture of the designed ISHP was completed by Kolin M&E Co. in October 2018 and the ISHP was shipped to DTU in December 2018. The tested performance of the ISHP is shown in Table 1. Using R134a as refrigerant and extracting heat from 0°C of cold water, the temperature of hot water output can reach over 50°C and the measured COP of the ISHP is over 3 when output hot water at 40°C. The ISHP can generate ice slurry automatically in the cold side when temperature of the cold water goes down to 0°C. The min temperature of the cold water that used as the heat source of the ISHP is 0°C so that the COP of the ISHP remains constant during ice operation mode. When the temperature of the cold water goes up to higher than 0°C, the ISHP can automatically switch to the normal heat pump mode and the COP will increase with the increasing of cold-water temperature. Figure 3. Shows the developed ISHP and Figure 4 shows the ice generated by the heat pump.

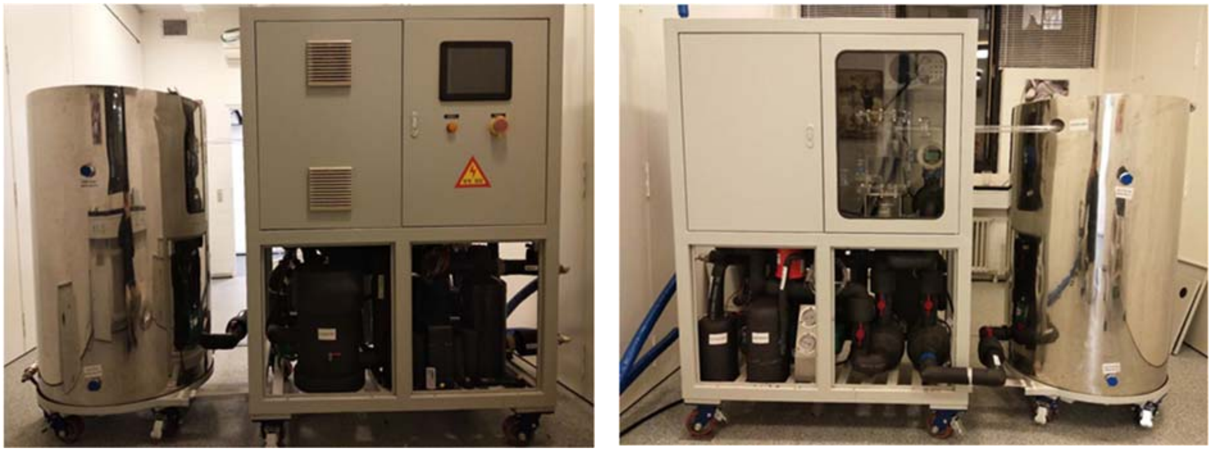


Figure 3. The ice-source heat pump developed for the solar heating application.

Figure 4. Ice slurry generated by the ISHP.

2.2 Task 2. Development of a small ISHP solar heating system and test its performance and control strategy

In task 2, a small ISHP solar heating system was constructed. Using an electric heater simulating a solar panel and chilled water supplied from the cooling system of the lab simulating heating load, the functions of the designed ISHP solar heating system was tested in an indoor climate laboratory. A control program was developed to control operation of the ISHP solar heating system. The control program was tested in the lab based on different simulated climate conditions. A master student conducted the experiment as his master project.

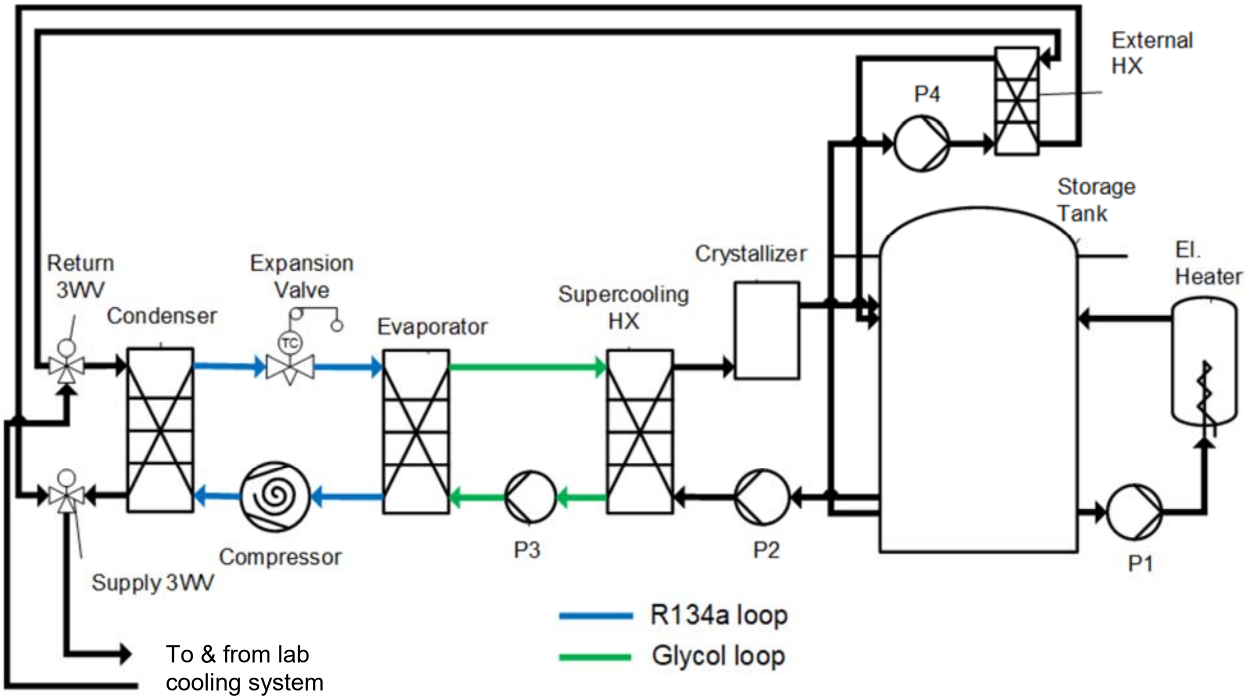
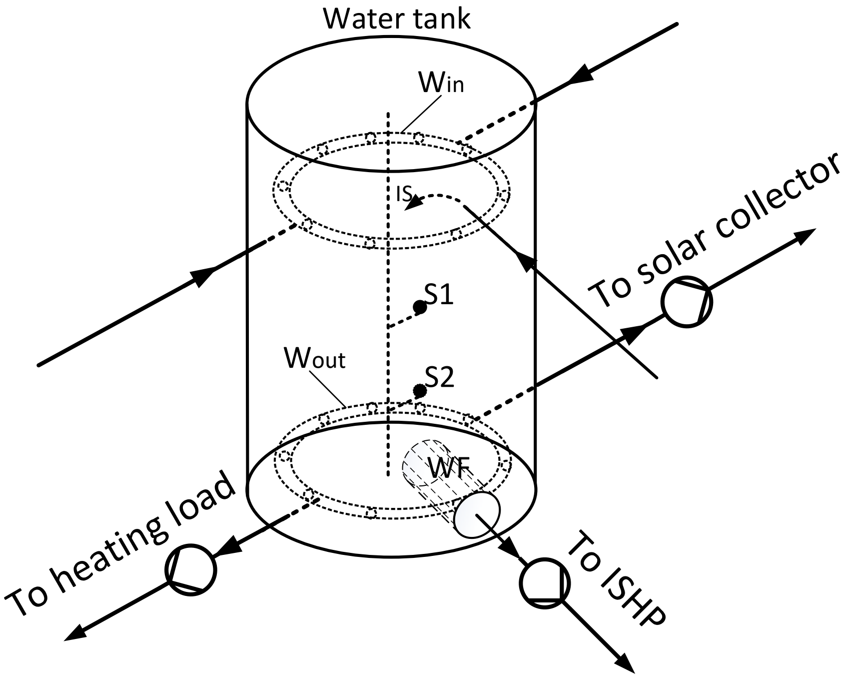


Figure 5. The principle of the developed ISHP solar heating system for the simulation test in the lab using an electric heater simulating a solar panel.

2.2.1 Method

Design of the ISHP

Figure 5 shows the principle of the ISHP solar heating system developed using an electric heater simulating solar panel for the laboratory test. The working principle of the ice-source heat pump is identical to that of any other heat pump only differing in the source of heat. The ISHP used for this study has a capacity of 3.5 kW and uses R134a as a refrigerant. The compressor used is a hermetic single stage, single speed scroll compressor. Both, the evaporator and the condenser used in the ISHP are plate heat exchangers. The ISHP also consists of an intermediate glycol loop which circulates between the evaporator and the supercooling heat exchanger. The glycol in the intermediate loop absorbs heat from the supercooled water in the heat exchanger and rejects it to the refrigerant in the evaporator. The supercooling HX cools the incoming water which then proceeds towards the ultrasound crystalliser. In the case that the water is cooled to a temperature below 0°C, the crystalliser induces nucleation in the flow leading to the formation of ice slurry which flows to the heat storage tank. Figure 6. shows the design of the heat storage tank. The heat storage tank, made of stainless steel, is a 300L cylindrical tank with 0.6m in diameter. It contains 4 ports at the side which can be used as inlet and outlet ports for the solar collector loop and inlet and outlet for the direct heating loop to the demand side, respectively. A port at the bottom of the tank allows for drainage. The outlet for the flow of water into the supercooling HX is located at the bottom of the tank which follows the filter, also present at the bottom. The water flowing into the supercooling HX is drawn from the bottom of the storage tank through two filters. First filter at the bottom of the tank prevents the flow of impurities or foreign particles along with the water and the second filter prevents the infiltration of ice crystals into heat exchanger. A pump insdie the ISHP maintains the flow rate of the water going into the heat exchanger at about **3 m^3/hr**. This flow rate helps maintain the stability of the supercooled flow and prevents freezing inside the heat exchanger.



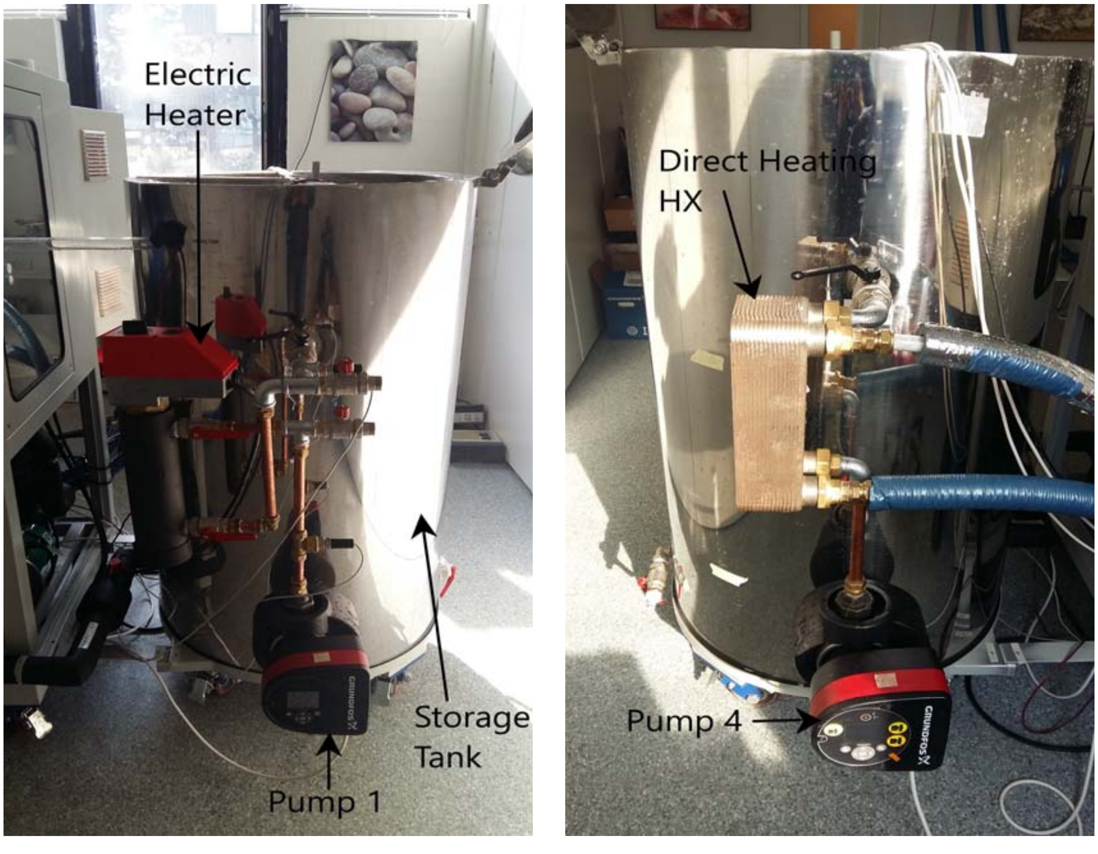
W_{in}: water inlet, W_{out}: water outlet, WF: water filter, IS: ice slurry inlet, S1 and S2: ice level sensors

Figure 6. Design of the heat storage tank.

Design of the ISHP solar heating system

The external heat exchanger facilitating heat transfer between the storage tank and the direct heating loop was a plate heat exchanger manufactured by SWEP. The heat exchanger to be used for this loop was selected using the app, Hexact 5, developed by Danfoss. Based on the operating conditions and the application, Hexact proposes a list of suitable heat exchangers from the Danfoss catalogue.

A mean temperature difference of 1 K for an outlet temperature of chilled water of 30˚C and a design heating load of 3.5 kW were used as the parameters for the selection of the heat exchanger. The model proposed by the application for these conditions was a D22-36, which is a micro-plate heat exchanger with 36 plates. Although an electric heater was used to simulate a solar collector in these experiments, another heat exchanger from Danfoss was procured for when the system would use a real solar collector with a glycol-water mixture on the solar side and water on the tank side. In this case, a flow rate of 0.3 kg/s and a mean temperature difference of 2K for a collector outlet temperature of 10˚C was assumed. The D22-20 was proposed by the application as the standard heat exchanger for these specifications with 20 micro-plates. The electric heater used as a simulator for a solar thermal collector was manufactured by Backer AB and is shown in Figure 7a, along with Pump P1. The heating capacity of this heater was 2.85 W, and was controlled based on the heating schedule observed in a day. Besides the circulating pumps used in the heat pump, external pumps to control the flow of water in the solar loop and the direct heating loop were also used. The pumps chosen for these loops were Grundfos Magna3 25-40 and Magna3 25-80 on each side. These pumps maintained a minimum flow of 1.1 m^3/hr with a rated flow of 4.1 m^3/hr and 5.4 m^3/hr respectively. The maximum operating pressure was 10 bar for both the pumps. The two pumps namely, P1 and P4 are shown in Figure 7 on the left and right respectively.



(a) Loop simulating the solar collector

(b) Direct heating loop

Figure 7. External pumps, Direct Heating HX & Electric Heater

Due to the possibility of direct heating depending on the temperature in the storage tank, controlling the flow of chilled water to the respective heating system was essential. This was facilitated by the use of 3-way valves switching the direction of the chilled water between the heat pump or the storage tank based on the storage tank temperature. The 3 way valves used for this setup were controlled by rotary actuators from Belimo. The supply flow was controlled using the Belimo TR24-SR, while the return was controlled using the Belimo TRC-24A SR. Both valves were controlled using one signal from the relays connected to the data acquisition interface. It must be noted that the switching time for both valves were considerably different, with the supply valve switching much slower than the return valve. This delay has been accommodated for in the control program. The supply and return 3-way valves can be seen at the top and the bottom, respectively, in Figure 8.

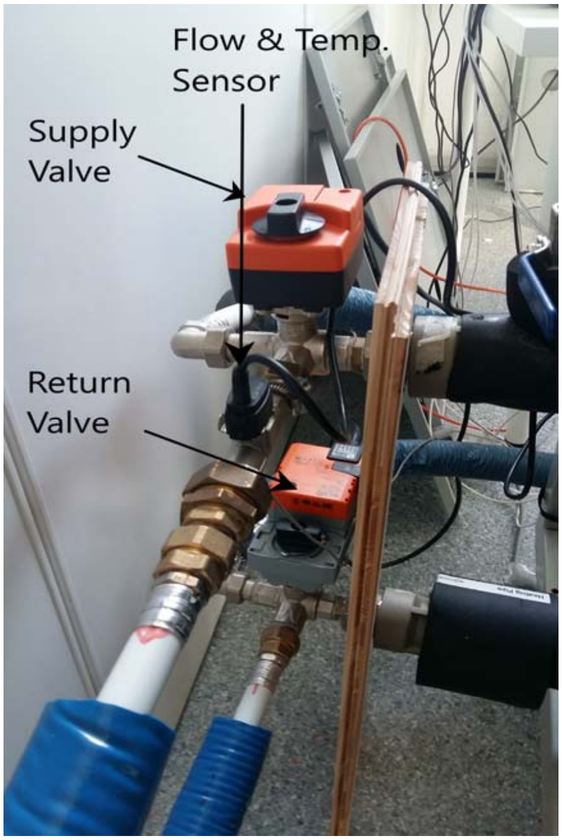
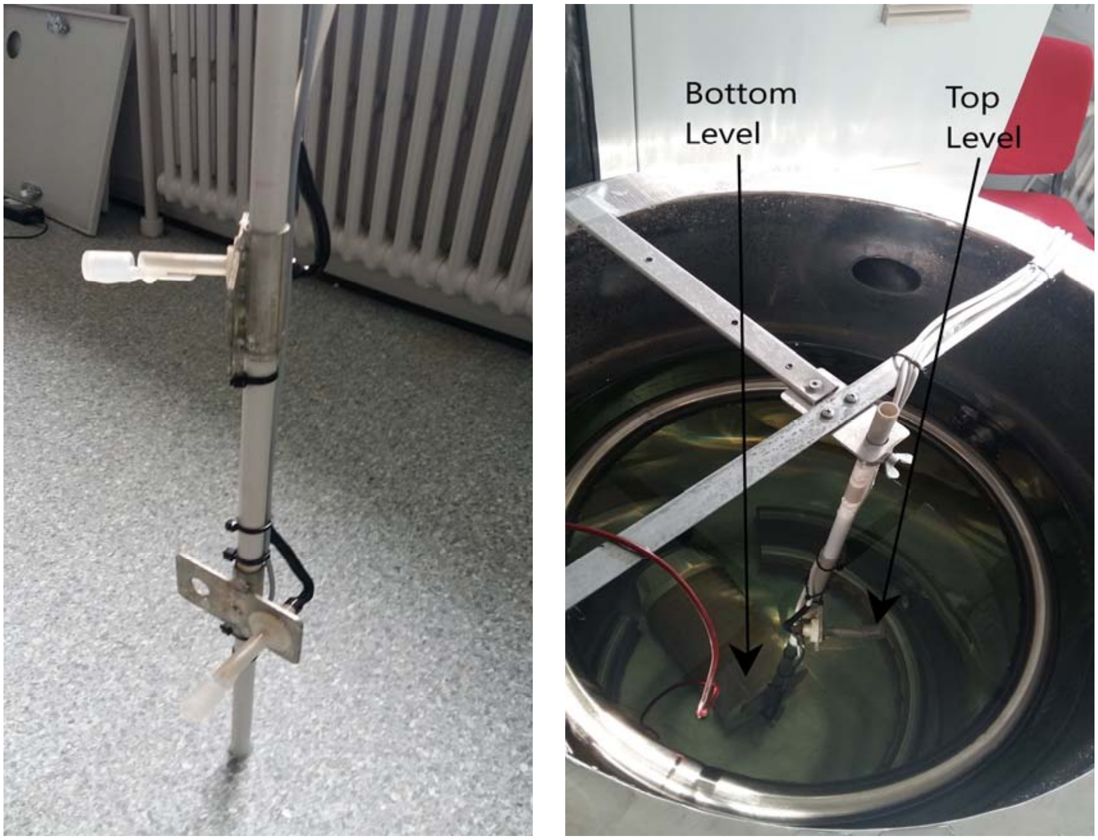


Figure 8. The 3-way Valves

In order to prevent blockage of the filter placed at the bottom of the tank by ice slurry, two level sensors were placed centrally along the height of the tank, as shown in Figure 9b. The sensor at the bottom was placed directly above the filter and the one at the top about 16 cms. below the water surface. The water surface was measured to be 28 cms. from the top of the tank, whose total height was 117 cms. The bottom sensor was placed about 27 cms. above the bottom of the tank. These positions were determined with an intention to optimise the amount of time the heat pump would be allowed to run while generating ice and the amount of ice that needs to be melted in order for the heat pump to restart operation. The level switches used for these experiments were manufactured by WIKA, and are shown in Figure 9a.



(a) Level sensors

(b) Sensors positioned in the storage tank

Figure 9. Ice Level Sensors

Control Strategy

The ISHP was regulated using a computer program built using the software Agilent Pro Visual Engineering Environment (VEE). Agilent Pro VEE is a programming language designed for instrument control. VEE relies on flowchart based modelling as opposed to compiling and executing lines of code. Programs in VEE can be created by connecting icons and by using keywords following basic rules of syntax.

The logic underneath the control strategy can be observed in the flowchart presented in Figure 10. The premise of setting up such a control strategy was to facilitate smooth switching between the heat pump and the direct heating pump i.e. Pump 4 via the 3-way valves, and the solar pump. The parameters used to control these switch-overs are temperatures recorded by sensors placed inside the tank, at the return pipe of the solar loop and the forward or supply pipe of the solar loop. While the temperature inside the tank and the forward temperature from the collector are used to control the solar pump, only the temperature inside the tank is used to switch between the heat pump and the direct heating pump. The heat pump is operational when the temperature inside the tank is below 35˚C. Above this temperature, the system switches to the direct heating loop where the chilled water on the demand side is heated directly using a heat exchanger by the water in the storage tank. To prevent frequent turning on and off of the heat pump, a buffer tolerance loop is

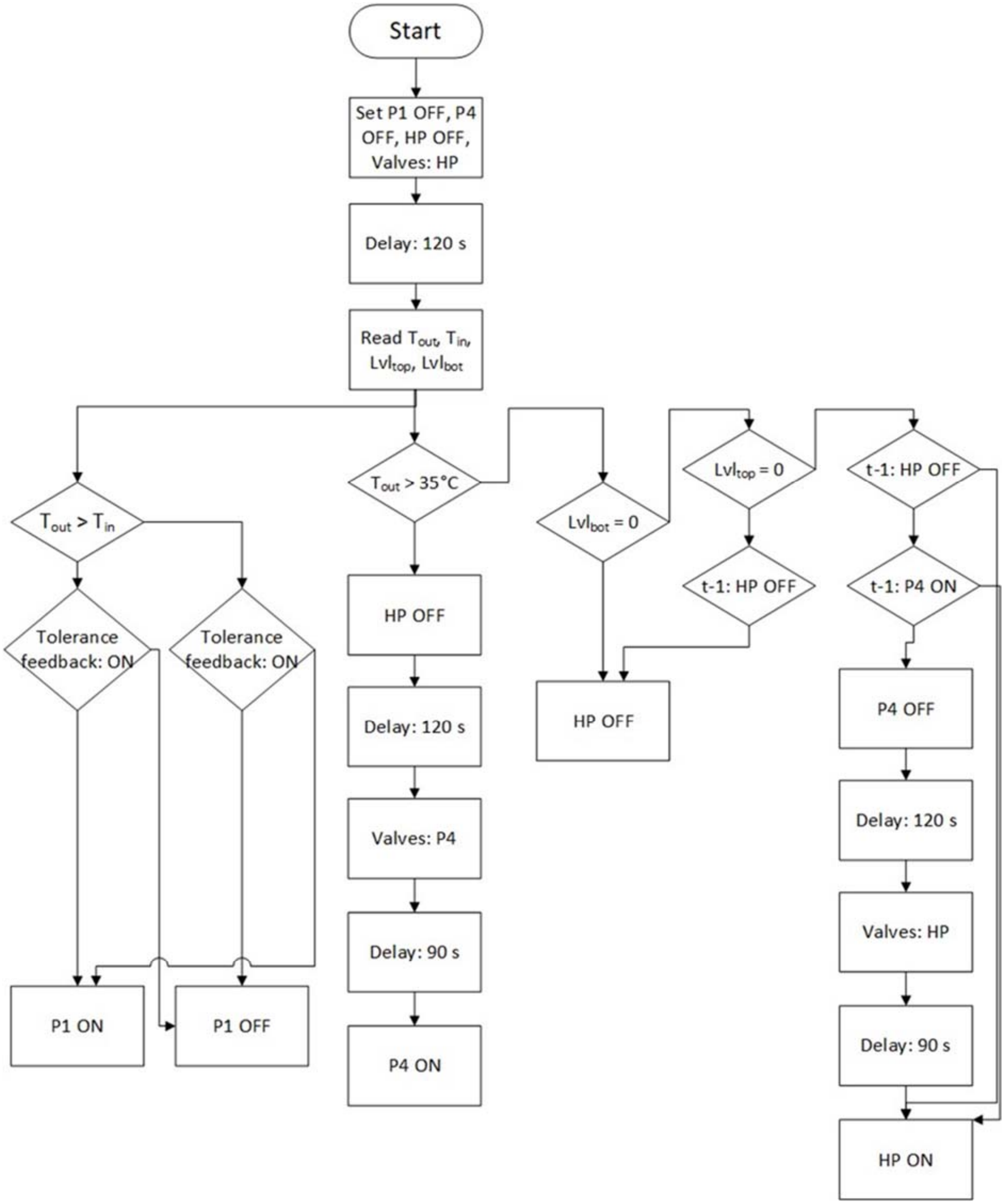


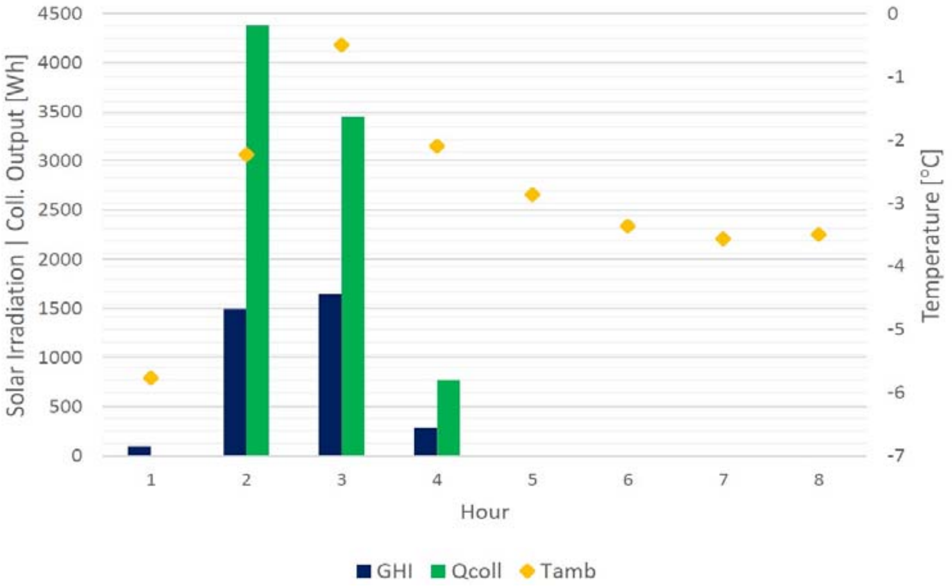
Figure 10. Control logic for the ISHP solar heating system.

used, allowing a tolerance of 1K. This means that the heat pump, if previously on, will not turn off until the temperature crosses 36˚C. Similarly, once turned off, the HP will not turn on until the temperature drops below 34˚C. The value of 1 K has been chosen after having run trial iterations with tolerances of +/- 2 K. Since the temperature change observed during these iterations was gradual and slow, a smaller allowance of 1 K was finally chosen. The control program also allows turning the heat pump off in case of a large build-up of ice in the storage tank. This is enabled by the use of two level sensors placed centrally along the height of the tank. One sensor is placed near the top of the tank and the other near the bottom, just above the filter to prevent ice blockages within it. These sensors are switched on as soon as they are pressed down by the ice formed above it. The heat pump is turned off when both the sensors are switched on, and is turned back on when the ice above both sensors has melted, releasing both switches as a result.

2.2.2 Results

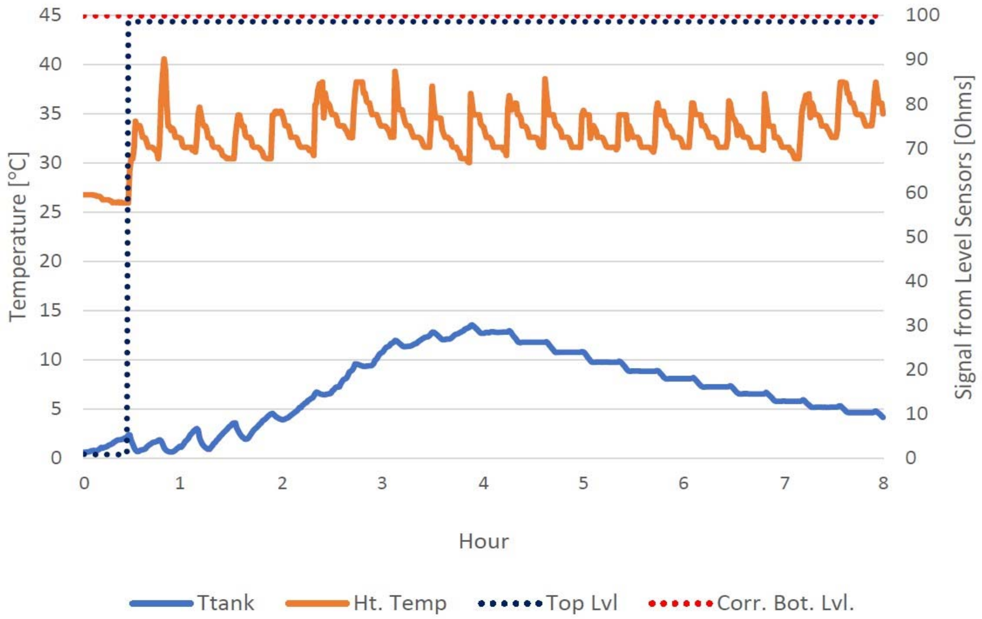
The solar heating simulated ISHP was operated to replicate three different types of days in February in Copenhagen, Denmark. The first set of results describes its operation on a clear day, followed by observations on a cloudy day and then an average day. To speed up the lab test so that the experiment of each conditions can be conducted in 8 working hours, the daily simulation was proportional reduced by 3 times, i.e. the simulation of solar radiation in 24 hours was proportional reduced to 8 hours.

The collector output calculated for a clear day is shown in Figure 11. In relation to the available solar radiation on the day, it can be seen that almost 3 times the heat can be extracted. This can be explained due to the fact that the solar radiation being used from the weather data, is the Global Horizontal Irradiation, which is the total irradiation on a horizontal surface. As described above, this irradiation is corrected for a collector surface sloped to face the sun as much as possible. A maximum heat output from the collector is noted to be 4.37 kWh for the hour simulating 09:00 to 12:00 hrs on a clear day. A maximum collector efficiency of 72 % was observed for the time period with highest solar radiation and lower ambient temperatures. Heat from the collector was made available for only 3 out of the 8 hours of the duration of the experiment.



GHI: Global Horizontal Irradiation, Qcoll: Heat collected from solar panel, Tamb: Temperature of ambient air

Figure 11. Collector output on a clear day



Ttank: temperature in the heat storage tank, Ht. Temp.: temperature of the hot water output from ISHP,
Top Lvl.: signal of the top ice level sensor, Corr. Bot. Lvl.: corrected signal of the low ice level sensor

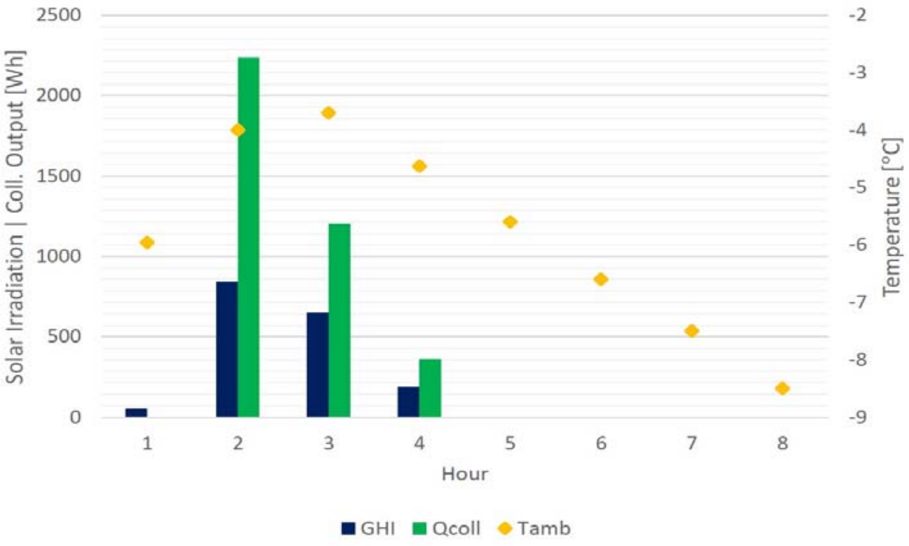
Figure 12. Water temperature and the ice level sensor output in the heat storage tank during simulated clear outdoor climate.

The operation of the ISHP system can be summarized from Figure 12. The graph shows the temperature recorded inside the tank, the heated temperature of the water being supplied to the demand side and the position of the level sensors inside the tank. The level sensors, i.e. the top level and the bottom level sensors, give an output signal of 100 and 1000 respectively, to signal that they are switched off or that there is no longer a presence of ice immediately above the respective sensor. To accommodate both sensors in the same graph, the bottom sensor has been corrected by a factor of 0.1. The output from the sensors is 0 as the switch is pressed down by ice formed inside the tank.

All the experiments were conducted with the same pre-condition of having the tank completely filled with ice in order to simulate an extreme case for the system. Due to this pre-condition, it can be observed that the top valve does not switch OFF until about 20 minutes after the start of operation. This also means that the HP did not switch ON for this period. This happens due to the control strategy disallowing the HP to turn ON until both level sensors have been turned back OFF after complete ice formation in the tank.

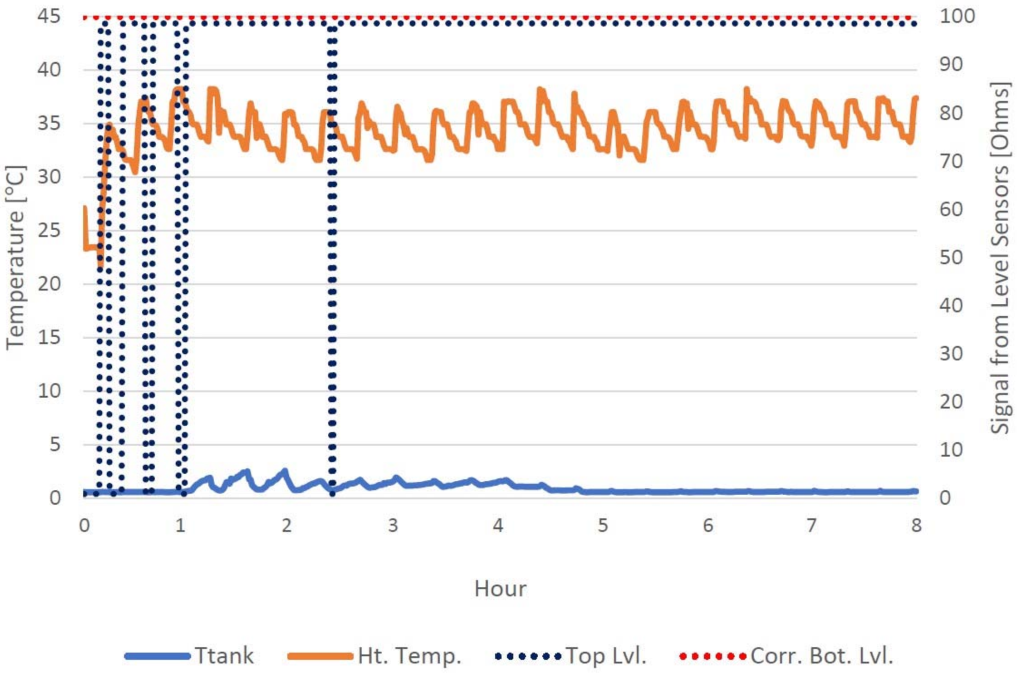
The heating schedule only shows 3 hours of heating during the experiment duration. But due to the limited capacity of the electric heater of 2.85 kW, the calculated heat output from the collector needed to be adjusted in adjacent hours. This is the reason why an increase in the temperature of water can be observed right from the start of the experiment. The heating temperature was aimed to be kept constant at around 35˚C by manually controlling the amount of chilled water entering the flow going into the HP, which explains the slight fluctuation in this temperature. The curve representing this temperature also suggests the intermittent starting and stopping of the HP. Every spike in the heating temperature indicates the HP switching ON and similarly a drop, switching OFF of the HP. The temperature of water inside the tank is observed to rise to about 14˚C at the end of the heating period and consequently drops to about 4˚C by the hour simulating the time period between 0300 and 0600 hrs. The system was able to run without the need to generate any ice during the day due to the heat input from the collector, presenting a higher performance and no reliance on auxiliary heating equipment during a clear day.

On a cloudy day, the irradiation received is much lower than that on a clear day. The ratio of heat collected to the available irradiation is however the same. The maximum amount of heat collected by the collector is calculated to be 2.237 kWh. A maximum collector efficiency of 68 % was achieved during the day, with the lowest being close to 49 % for the period with lower radiations. As the clear day, 3 hours of heat supply is carried out, out of the 8 hours of operation. The pre-condition was kept the same with the tank completely filled up with ice. The operation of the ISHP on such a day is displayed in Figure 14. The effect of the lack of radiation can be clearly observed in the low temperature achieved by the water in the tank throughout the day. The highest temperature recorded by the stored water was about 2.5˚C.



GHI: Global Horizontal Irradiation, Qcoll: Heat collected from solar panel, Tamb: Temperature of ambient air

Figure 13. Collector heat output on the simulated cloudy outdoor climate.



Ttank: temperature in the heat storage tank, Ht. Temp.: temperature of the hot water output from ISHP, Top Lvl.: signal of the top ice level sensor, Corr. Bot. Lvl.: corrected signal of the low ice level sensor

Figure 14. Water temperature and the ice level sensor output in the heat storage tank during simulated clear outdoor climate.

The top level sensor was observed to switch on and off frequently for the first hour due to the lack of heat input. This also highlights the unpredictability of the level sensors. It was observed that on some occasions, the level sensors would switch off because of being pushed up by ice present below it. Thus, the heat pump can be observed to turn back on prematurely, because of the ice not having melted completely around the top sensor.

For more details of the laboratory experiment, please refer to the master thesis of Nishant Shriram Karve [4].

2.3 Task 3. Field validation

2.3.1 Method

The field validation was conducted at DTU's solar lab. The developed ISHP solar heating system was tested in lab during Jan to April of 2020 using a real solar heat collector to collect heat from solar radiation. A test system was constructed in the solar lab for the test. Figure 15 shows the principle of the test system. The test system consists of a 7.6 m^2 vacuum solar collector, the ISHP including the heat storage tank and a heating load simulator.

The solar heat collector was connected to the heat storage tank via a plate heat exchanger. To prevent freezing inside the solar collector, glycol anti-freezing agent was added into the water circulated in the solar collector. Since the water inside the heat storage tank should not contain anti-freezing agent, a plate heat exchanger was installed to transfer the heat from the solar collector to the heat storage tank but separate the water in the solar collector from the water in the heat storage tank.

The experiment of field validation was to simulate a radiant floor heating system using a solar-ISHP for heating supply. A fan-coil unit was used to simulate the heating load that rejected the heat produced from the heat pump to the ambient air in the solar lab. To simulate the thermal lag of the floor heating system, a 20-liter waster buffer tank was installed in series with the fan coil in the hot water loop to prevent too frequent tune on and off the heat pump (see Figure 15).

The control logic of the ISHP is shown in table 2. The operation of ISHP was tuned on and off based on the temperature in the heat storage tank and the heating buffer tank. When the temperature in the heat storage tank reached 40°C or higher, the heat pump will be tuned off; the three-way valves V1 and V2 switched to the heat storage tank and heating was supplied directly from the hot water in the heat storage tank. When the temperature in the heat storage tank was lower than 35°C, the three-way valves V1 and V2 switched to the output of the heat pump and the heat pump was tuned on and off based on the temperature in the heating buffer tank. When the temperature in the heating buffer tank was lower than 35°C, the heat pump was tuned on and running continuously until the temperature in the heating bugger tank reached 40°C. The control program tuned on and off the heat pump to keep the temperature in the heating buffer tank in the range between 35 to

40 °C. The pump P1 that circulates water from the solar collector was tuned off every day between 19:00 and 07:00 when solar radiation was too low.

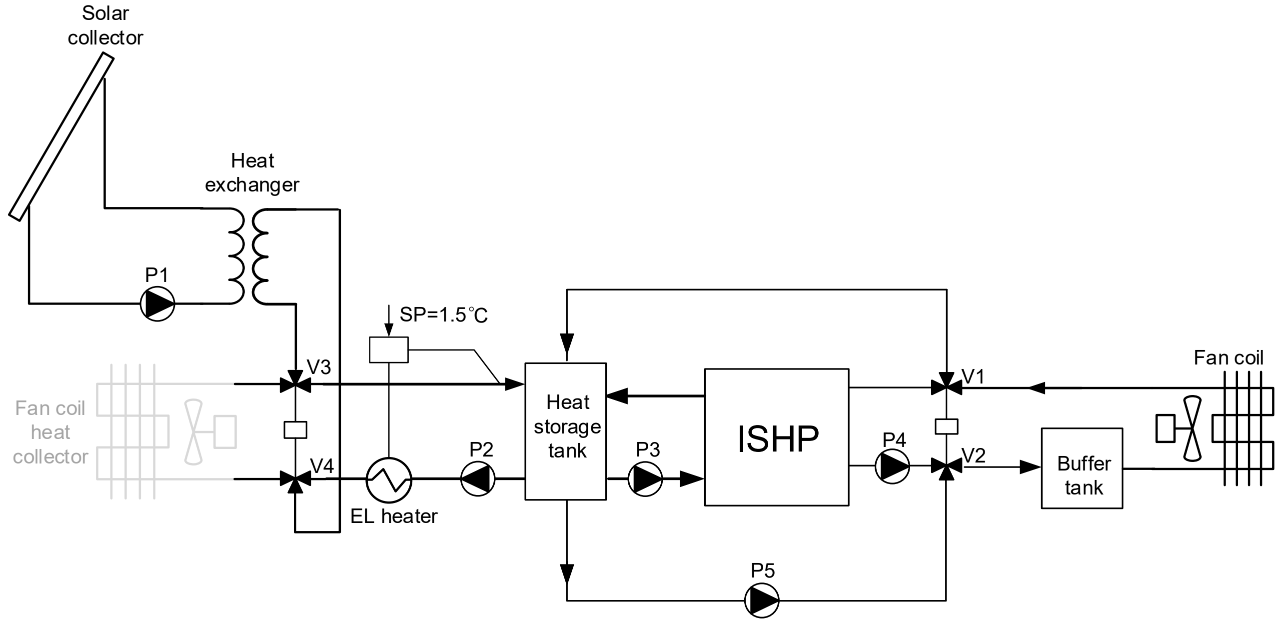


Figure 15. Schematic diagram of the experimental setup.

During the field validation, the fan coil ambient air heat collector was not used due to the time for design and manufacture of such a fan coil was not available. An electric heater was installed to simulate the low temperature fan coil heat collector as showed in Figure 15. A PID temperature controller measured the inlet water temperature of the heat storage tank in the heat-collecting loop and controlled the power input of the electric heater. The inlet temperature to the heat storage tank was usually controlled in the range between 1 to 2 °C when no heat input from the solar collector was available. This was mainly to simulate the heat collection from the low temperature ambient air since the ambient air temperature is usually higher than 2 °C in most of the Danish winter (see measure real air temperature data in Figure 18 and 20). When solar radiation was collected during daytime and the inlet water temperature to the heat storage tank was higher than 2°C, the temperature controller turned off the electric heater automatically. The electric heater also prevented freezing in the heat exchanger during night in case of very cold weather that may occurred during the experimental period.

The water temperature in the heat storage tank was never lower than 0°C. When ISHP started producing ice slurry, the ice floated on top of the water in the tank and the ISHP sucked water from the bottom of the tank. If the heat collected from solar radiation or ambient air was not sufficient to melt the ice in the tank, the ice will accumulate inside the tank until the tank filled with ice. When the ice reached the water filter of the heat pump intake in the bottom of the tank, the ice level sensor was triggered which tuned off the heat pump and heating supply was thus stopped.

Table 2. Control logic of the field experiment

Temp. in heat storage tank	Temp. in heating buffer tank	EL heater	P1	P2	P3	P4	P5	ISHP	V1 & V2	Heating output
≥40 °C		on (ambient air temp. >1°C)	on (07:00-19:00) off (19:00-07:00)	on	off	off	on	off	Heating storage output	Heating supplied from heat storage tank
0-40°C	<35°C			on	on	on	off	on	Heat pump output	Heating supplied by ISHP
	35-40°C			on	on/off	on	off	on/off		
0°C & full of ice				on	off	off	off	off	Heat pump output	Heating supply stopped

(a) (b)

Figure 16. Vacuum solar collector used in the experiment (a) and the ISHP installed in the solar lab (b).

2.3.2 Results

The results of the experiment are shown in Figure 17 and 19. Each figure shows the temperatures of water in the heat storage tank and the temperature of heating supply collected in consecutive 10 days.

Figure 17 shows the data collected in early March when the weather was relatively cold. The outdoor air temperature and solar radiation measured in the same location during the same period are shown in Figure 18. Compared Figure 17 and 18, it can be observed that the water temperature in the heat storage tank mainly followed the strength of solar radiation during the day. At night when no solar radiation was available, the water temperature in the heat storage tank decreased to 0°C and the heat pump extract latent heat of water and produce ice. During this period, the temperature of water in the heat storage tank maintained constant at 0°C until next morning. When the ice was melted by solar heat or the heat from ambient air, the water temperature started to increase by absorbing heat from solar radiation and ambient air. In early March, the solar radiation was not strong enough to heat up the water in the heat storage tank to 40°C. Therefore, heating was supplied by heat pump. The solar heat and the low temperature heat from ambient air was stored in the heat storage tank in the form of both sensible and latent heat to be used by the ISHP.

In Figure 17, it can be observed that the heating supply temperature output from the ISHP maintained at 35-40 °C except for few hours in the morning of March 11th. In this period, the ISHP stopped due to the heat storage tank was full of ice and triggered the ice level sensor in the bottom of the tank that tuned off the heat pump. By examining the weather data, it can be seen that it was due to three consecutive cloudy days without sufficient solar radiation to melt the ice in the heat storage tank. However, the temperature in the heat storage tank only decreased to 25°C and the ISHP restarted in the morning of March 12th when the solar heat melted the ice.

Figure 19 shows the data collected at the end of March and beginning of April when the weather was warmer with strong solar radiation. The results shows that in 7 out of the 10 days, the water temperature in the heat storage tank was heated to over 40°C for more than 6 hours by the solar radiation during daytime. In this period, heating was supplied directly from solar heating and the heat pump stopped operating. In some of the date, the water temperature in the heat storage tank went down to 0°C during the night and the ISHP switched to ice mode to extract heat from phase change of water freezing for a short time. In 3 out of the 10 days, the solar radiation was not strong enough to heat up the water temperature in the heat storage tank to 40°C due to cloudy weather. In these days, heating was supplied solely by heat pump and the heating supply temperature was still maintained at 35-40 °C.

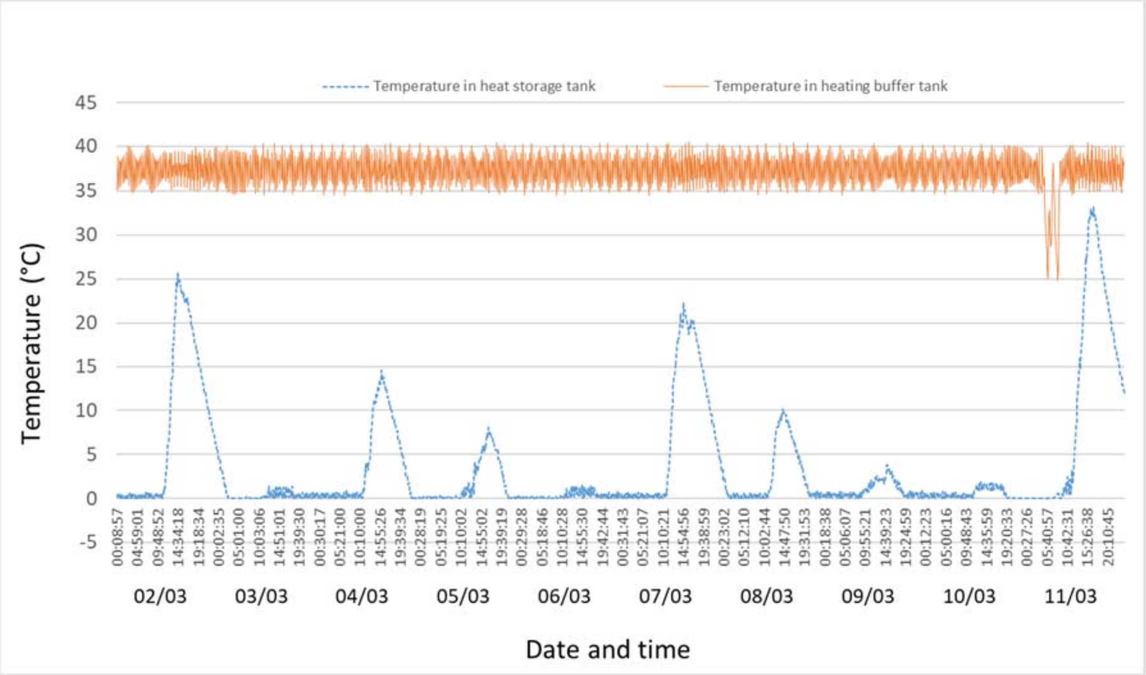


Figure 17. Water temperature in the heat storage tank and the heating buffer tank during March 2 and 11, 2020.

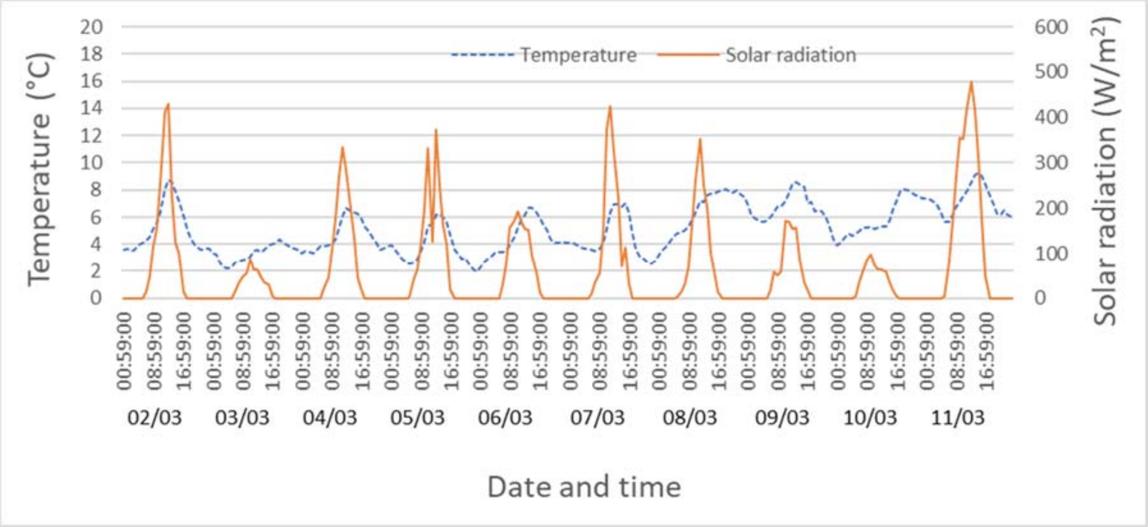


Figure 18. Ambient air temperature and solar radiation in the location of the experiment during March 2 and 11, 2020.

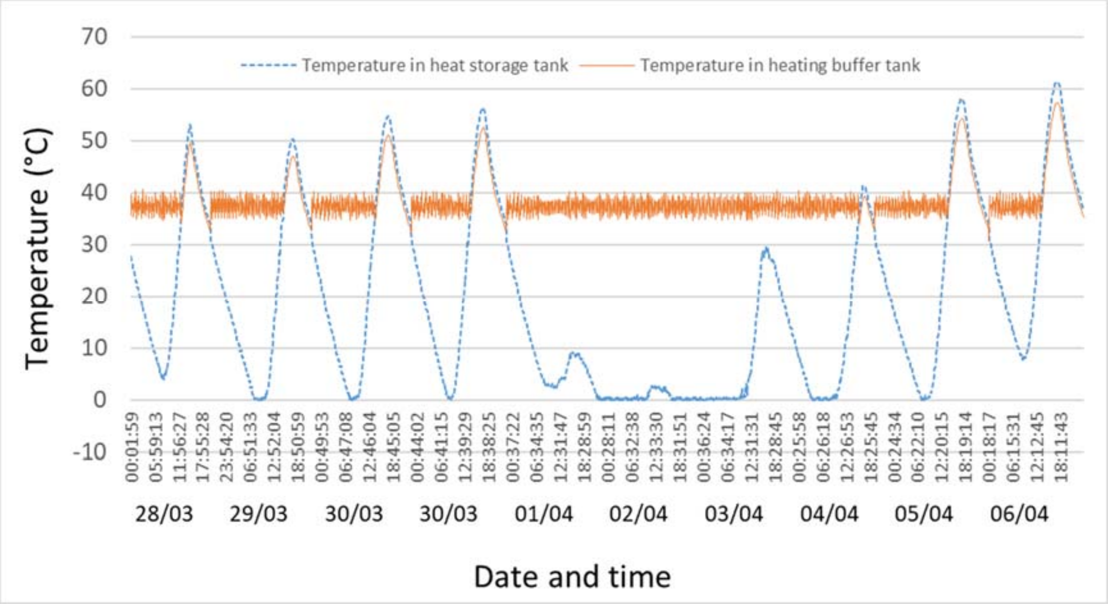


Figure 19. Water temperature in the heat storage tank and the heating buffer tank during March 28 and April 6, 2020.

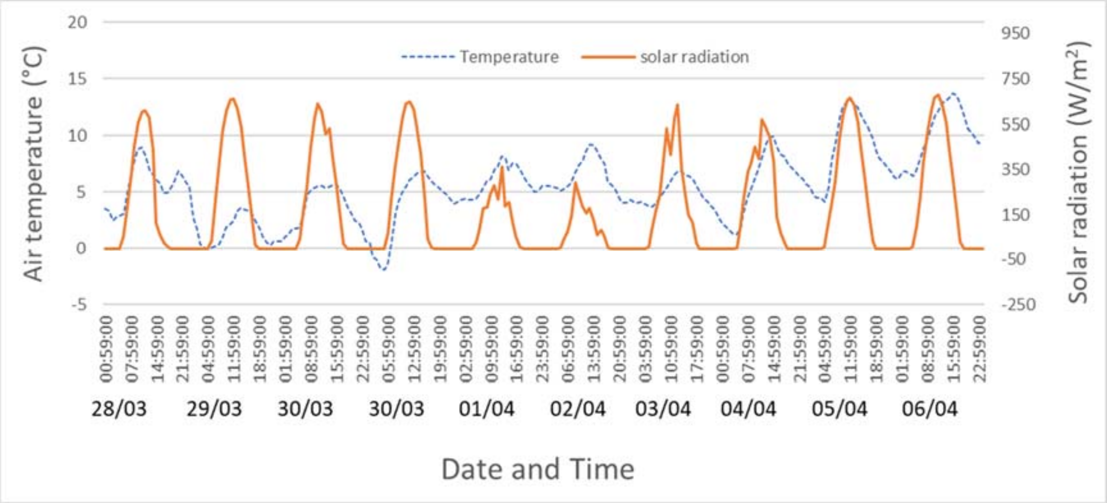


Figure 20. Ambient air temperature and solar radiation in the location of the experiment during March 28 and April 6, 2020.

3. Discussion and conclusions

The ISHP solar heating system was developed and test in this project. The advantages of the design are reducing the size of the water heat storage tank and utilizing low temperature heat source during cloudy climate days. These have been verified in the project.

The research in this project found that ISHP could be combined with low temperature ambient air heat collector to utilize the heat from the low temperature ambient air when solar radiation was not available. This is particularly useful in Danish winter when most of date without sunshine but air temperature is higher than 0°C. Since the heat storage used for the ISHP is mainly the latent heat during the phase change of water, the low temperature heat from ambient air can be collected by melting ice whenever it is higher than 0°C. By observing the Danish winter climate data, it was find that most of the Danish winter days are cloudy but warm, i.e. air temperature higher than 0°C, and many of the cold days are with sunshine. Due to this special feature of the Danish winter climate, the ISHP can always collect heat from either solar radiation or ambient air in most of the days in winter season. Only in case of several consecutive cold and cloudy days, the ISHP may stop operation due to lack of heat collection. However, these days are usually very few in most of years (e.g. several hours in 6 days in 2020) in the Danish winter season. This makes ISHP technology particularly suitable to be used as the Danish heating technology.

The ambient air heat collector was simulated in this study by an electric heater to verify its effectiveness. A more realistic experiment using a real fan-coil air to water heat exchanger may be used to collect the heat from ambient air to further verify this design. The main risk of using a fan-coil air water heat exchanger to collect heat from ambient air could be the freezing of water inside the coil of the air heat collector. A reliable air temperature control must be applied to cut off the airflow to the heat collector before the ambient air temperature goes down to 0°C. Since the ambient air heat collector only operates when the ambient air temperature is higher than 0°C, there will be no ice formed outside the coil of the heat exchanger to block the air passage of the heat exchanger. Therefore, no coil freeze problem for such a heat pump when it operates in air source heating mode. The operation of the heat pump should be very smooth.

To prevent ice block the filter at the water intake of the heat pump inside the heat storage tank, an ice sensor was installed just above the filter. When ice reaches the filter, the heat pump will be switched off. The experiment found that due to the irregular shape of the ice and very fine ice crystal in the ice slurry, when the ice sensor on top of the filter was triggered, there was still a lot of water inside the heat storage tank. The proportion of ice in the tank was about 50% that left 50% of the latent heat from the water not been used. This very much reduced the effective volume of the tank. Therefore, the design of the tank must be optimized to increase the proportion of ice formed before the ice reaches the water intake of the heat pump. One possible design is to separate the ice from the water by a perforated plate installed above the filter of the water intake of the heat pump to allow water flow down but keep the ice above it.

Conclusions

- The ice source heat pump solar heating system developed in this project was very successful. The test in real Danish winter confirmed its designed function of operation. Combined with radiant heating system with 40°C of hot water supply, the minimum COP of the heat pump is 3 and the annual average COP can be much higher.

- In order to operate the heat pump in cloudy days when very low solar radiation is available, a low temperature ambient air heat collector is recommended to collect heat from ambient air. This will insure that the ISHP heating system can operate in most days of the Danish winter season without interruption.

4. Reference

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