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Development of a heat exchanger that can be de-iced for the use in ice stores in solar thermal heat pump systems

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Abstract

Ice stores can be used to improve the system efficiency of heating installations that combine solar collectors and heat pumps in a serial arrangement. Besides the various advantages of using ice stores as a heat source for the heat pump, a possible disadvantage is that growing ice layers on the heat exchanger's surfaces increase the heat transfer resistance which leads to lower heat pump COPs due to lower temperatures in the heat pump evaporator. To improve the heat transfer across the heat exchangers in the ice storage a periodical de-icing of the heat exchangers is proposed and presented in this paper. A prototype for a heat exchanger that is periodically de-iced with (solar) heat was developed. The measurements of an experimental ice storage presented in this paper show a good feasibility of the de-icing and thus a successful regeneration of the heat exchanger's performance. The hydraulic integration of the heat exchangers in a solar thermal heat pump system was designed. A mathematical model of an ice storage with heat exchangers that can be de-iced was developed and validated with data from measurements.

1. Ice stores for heating installations combining solar collectors and heat pumps

Recently an increasing number of heating systems that combine solar collectors and heat pumps have been developed for space heating (SH) and domestic hot water (DHW) preparation in buildings [1, 2]. These systems can be classified into parallel, serial or combined parallel and serial system concepts [3, 4]. Combined parallel and serial concepts not only allow for the use of solar collector heat directly at the temperature level of DHW & SH but also indirectly, i.e. for the evaporator of the heat pump. In these system concepts phase change water/ice stores can be used to store heat from solar collectors before the heat is used by the heat pump.

Ice stores have several advantages compared to high temperature stores. The additional use of phase change enthalpy in ice stores leads to a high volumetric storage capacity so that relatively small-sized ice stores can serve as a seasonal storage. Ice stores have low heat losses during operation at low storage temperature, and can even gain heat if the storage is colder than the surroundings (e.g. for buried ice stores in winter months). Furthermore, the regeneration with solar heat on a low temperature level leads to higher solar gains. Additional boreholes or air heat exchangers are not needed in the system if it is designed in a way that solar heat covers part of the heat demand directly and a large fraction of the heat demand of the heat pump via the ice storage.

2. Dealing with decreasing heat transfer coefficients in ice stores

Only a few solar thermal heat pump systems are currently available on the market that use ice stores from diurnal up to seasonal storage of solar heat [5 to 9]. Most of these ice stores are ice-on-coil types where heat is removed from the storage with long tubes serving as heat exchangers [10]. If the surface temperature of the heat exchanger is below 0 °C, ice can be formed on the tubes' surfaces. If heat is extracted from the ice storage the tubes are covered with a growing ice layer. Depending on the dimensions of the ice storage, the heat exchanger surface and the amount of heat extracted, the ice layer can reach a thickness that leads to a significant decrease of the heat transfer coefficient from the water/ice boundary layer (where latent heat is made available) to the brine inside the heat exchanger. This leads to decreasing temperatures in the brine and hence to a decreasing COP of the heat pump.

The overall heat transfer coefficient, U, through the heat exchanger can be calculated as a function of growing ice layers on the heat exchanger surface according to literature [11]. As the phase change enthalpy is released directly at the boundary between ice and water the temperature at this point is defined by the freezing point of water, i.e. 0°C, and the outer convective heat transfer coefficient is not required for this estimation. For the implementation of flat plate and pipe as heat exchangers the overall heat transfer coefficients can be calculated as shown in eq. 1 and 2:

$$U_{plate} = \frac{1}{\frac{1}{\alpha_i} + \frac{d_{plate}}{\lambda_{plate}} + \frac{d_{ice}}{\lambda_{ice}}} \tag{1}$$

$$U_{pipe} = \frac{\pi}{\frac{1}{\alpha_i d_i} + \frac{1}{2\lambda_{wall}} \ln\frac{d_a}{d_i} + \frac{1}{2\lambda_{ice}} \ln\frac{d_{a,ice}}{d_a}} \tag{2}$$

with:

$U =$ *overall heat transfer coefficients* $[W/(m^2K)]$

$\alpha_i =$ *Inner convective heat transfer coefficient* $[W/(m^2K)]$

$d_{plate} =$ *Thickness of flat plate wall* $[m]$

$d_{ice} =$ *Thickness of ice layer* $[m]$

$d_i =$ *Inner diameter of pipe* $[m]$

$d_a =$ *Outer diameter of pipe* $[m]$

$d_{a,ice} =$ *Outer diameter of ice layer on pipe* $[m]$

$\lambda =$ *Thermal conductivities* $[W/(mK)]$

In the following, the overall heat transfer coefficients of three types of heat exchangers as a function of growing ice layers are compared: One flat plate heat exchanger made of stainless steel and two pipes made of copper or polypropylene (Fig. 1). For each heat exchanger type two typical mass flows with their corresponding inner convective heat transfer coefficients are assumed (further assumptions see Table 1). Before ice is formed the overall heat transfer coefficients of the stainless steel flat plate and of the copper pipe heat exchanger are relatively high and predominantly influenced by the inner convective heat transfer coefficients. The overall heat transfer coefficients decrease rapidly to very low values when ice is forming on the surfaces. Polypropylene pipes on the other hand have low heat transfer coefficients that are nearly independent of the mass flow in the pipe compared to the other heat exchangers.

In measurements that were conducted with a flat plate heat exchanger the overall heat transfer coefficient falls from 220 W/(m^{2}K) to 35 W/(m^{2}K) after an ice layer with a thickness of 6 cm was formed on the heat exchanger's surface. This is in accordance with the behaviour expected from theory.

Table 1. Properties of the different heat exchanger types used for a theoretical comparison of their heat transfer coefficients.

	Flat plate heat exchanger	**Copper-pipe heat exchanger**	**Polypropylene-pipe heat exchanger**
Material of Hx-Surface	Stainless steel	Copper (Cu)	Polypropylene (PP)
Thermal conductivity wall, λ	15 W/(mK)	400 W/(mK)	0.23 W/(mK)
Wall thickness	0.6 mm	1 mm	5 mm
Inner diameter / characteristic thickness	10 mm	50 mm	50 mm
Inner convective heat transfer coefficient, α_i	a) 450 W/(m^{2}K) b) 200 W/(m^{2}K)	a) 1500 W/(m^{2}K) b) 200 W/(m^{2}K)	a) 1500 W/(m^{2}K) b) 200 W/(m^{2}K)
Thermal conductivity ice, λ_{ice}:	2.33 W/(mK) (for all heat exchangers)		

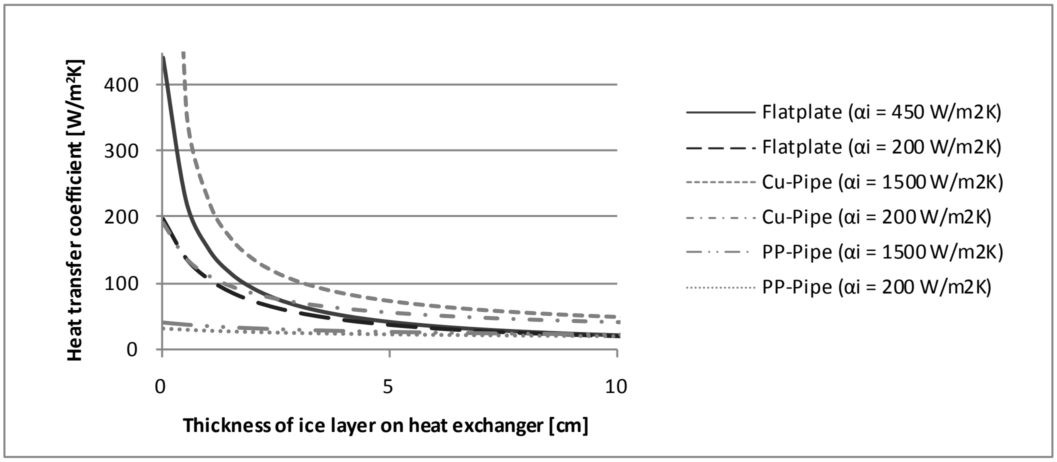

Fig. 1. Calculated overall heat transfer coefficients for three heat exchangers as a function of growing ice layer on their surface. For each heat exchanger two different inner convective heat transfer coefficients are assumed.

To ensure a sufficient heat supply for the heat pump when ice is formed on the heat exchanger surface two strategies can be chosen:

- Mounting of a heat exchanger with large surfaces that deliver enough heat even if they are covered with several centimetres of ice. Usually these heat exchangers also have a large volume which reduces the phase change storage capacity. Another disadvantage can be higher costs for the materials of the large heat exchanger.

- Mounting of a relatively small heat exchanger that can be de-iced by removing the ice layers on the heat exchanger's surfaces if the overall heat transfer coefficient drops below a certain threshold.

In the following the second strategy – the de-icing of the heat exchanger – is investigated with the aim to develop an ice storage of high volumetric storage capacity with low demand for construction materials.

3. Development of a heat exchanger that can be de-iced with heat

3.1 Design and testing of the heat exchanger

Different concepts of heat exchangers that can be de-iced were examined in experiments [12 - 14]. A promising concept with a flat plate heat exchanger that can be de-iced with heat was further developed (Fig. 2). This concept allows a de-icing without any extra parts in the system design that would lead to higher investment and maintenance costs.

The flat plate heat exchanger is placed upright at the bottom of the ice storage and can be extended in a modular way. The ice plates forming on the heat exchanger surfaces cannot grow around either the flat plate's connections to the brine cycle or the edges of the plate. This is realized with extended edges that aren't irrigated with brine and with mounted barriers around the connections. After a short warm up of the iced heat exchanger the ice layers separate from the heat exchanger surface due to their buoyancy and float upwards to accumulate at the surface of the water.

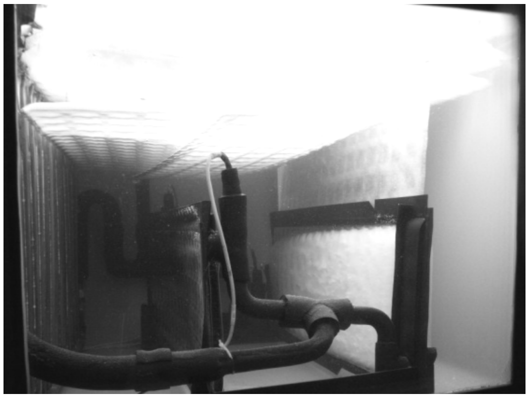

Fig. 2. Side view into the water filled ice storage prototype. Two heat exchangers (centre) during de-icing after several de-icing cycles. The ice plate at the front of the right heat exchanger is still attached to the heat exchanger's surface.

Periodical and automated de-icing with the developed heat exchanger prototype was conducted in an ice storage with a volume of 1 m^3. The effective regeneration of the overall heat transfer coefficient due to the removal of the ice layers can be seen in Fig. 3. The heat transfer coefficient decreases during heat extraction from the ice storage from about 450 $W/(m^2K)$ to 100 $W/(m^2K)$ which correspond to an ice layer of around 1 cm. After an active de-icing (heating up) and at the latest during a passive de-icing (circulation pump off), the ice layers separate and the heat transfer coefficient of the heat exchanger is regenerated for the next heat extraction phase.

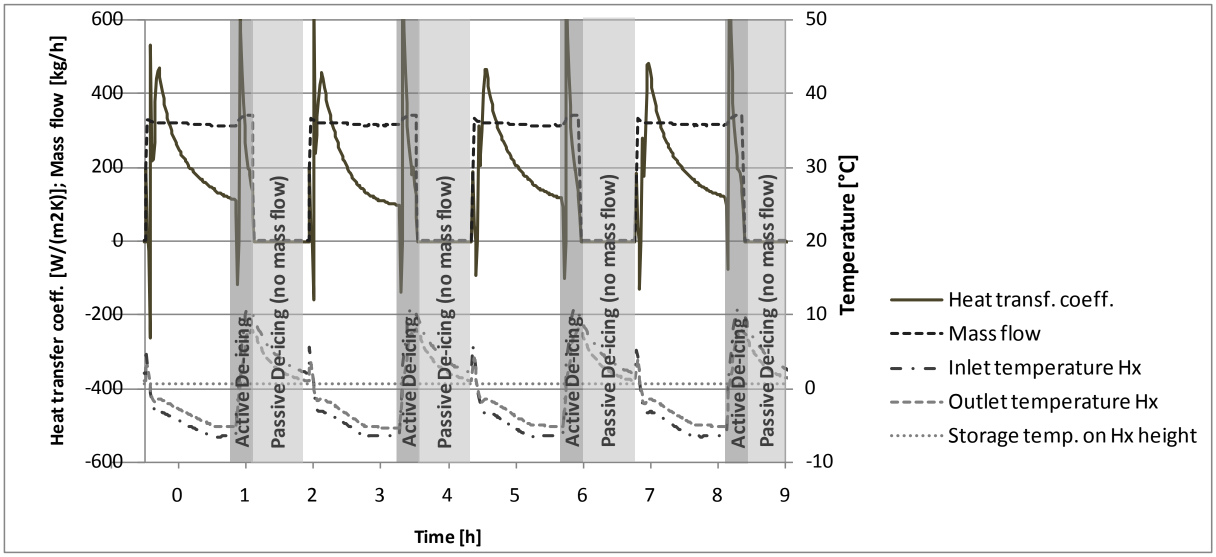

Fig. 3. Periodical regeneration of the overall heat transfer coefficient of the developed heat exchanger (Hx) due to de-icing. During the active de-icing phases the heat exchanger is heated up.

3.2 Hydraulic integration of the heat exchanger

A hydraulic scheme was designed to integrate such a heat exchanger into a brine cycle that combines the solar collectors, the heat pump and a warm storage. The brine cycle can deliver heat from the solar collectors or from the lower part of the warm storage to the ice storage for periodical de-icing of the heat exchanger when the heat pump is off.

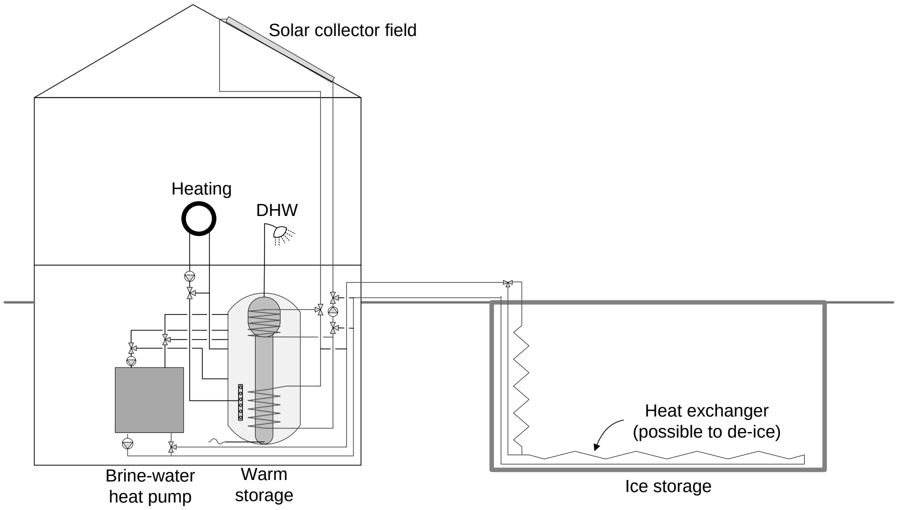

Fig. 4. Simplified hydraulic scheme of a solar thermal heat pump system with integrated ice storage and its heat exchanger that can be de-iced.

3.3 Mathematical model for annual system performance simulation of an ice storage with heat exchangers that can be de-iced

A mathematical model of the ice storage concept with heat exchangers that can be de-iced was developed and implemented into the simulation software TRNSYS [15] and validated.

Validation of the model was done with data from experiments derived from the 1 m^3 ice storage in the laboratory. The simulation shows a good agreement with the measurement both regarding the temperatures at the outlet of the heat exchanger and the energy change in the ice storage (Fig. 5). A consequence of the model is that the simulated outlet temperature is equal to zero in times with no mass flow, leading to a deviation of this value in the passive de-icing phase when the circulation pump is off. This deviation has no consequences on the energy balances as the mass flow is zero.

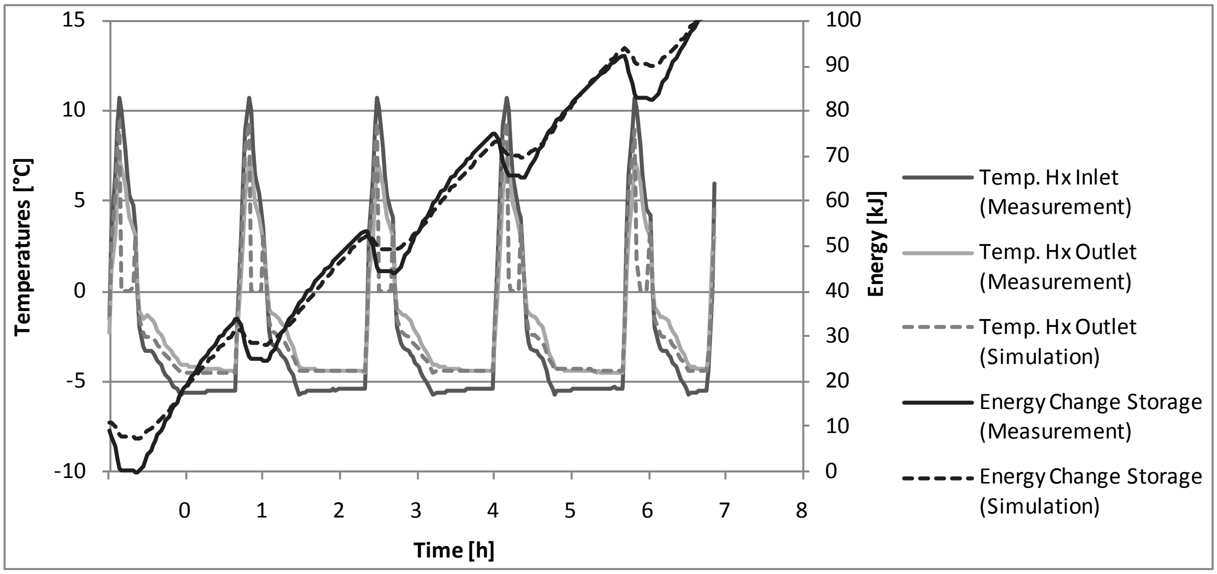

Fig. 5. Validation of the developed ice storage TRNSYS type with heat exchangers (Hx) that can be de-iced.

4. Conclusion

If ice stores are used in combined solar thermal and heat pump systems, increasing layers of ice on the heat exchanger's surfaces in the ice storage lead to decreasing overall heat transfer coefficients and consequently to lower heat pump COPs. To preserve a good overall heat transfer a method has been developed to regenerate the heat transfer coefficient by removing the ice from the heat exchangers with the help of buoyancy forces. A flat plate heat exchanger was developed that can be de-iced periodically. After the short de-icing phase the overall heat transfer coefficient is regenerated which was demonstrated also in experiments. The hydraulic integration of the de-icing in a solar thermal heat pump system was designed. A mathematical model of the ice storage with heat exchangers that can be de-iced was developed and implemented into TRNSYS. The model has been validated with measurements and allows the simulation of combined solar thermal and heat pump systems with the newly designed ice storage.

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