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High-Ice project

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Contents

1. Project objectives

In High-Ice project ice storages and heat exchangers for waste water heat recovery as components of heating systems that combine solar collectors and heat pumps are investigated. Computer simulations and measurements are conducted to analyze in which way both ice storages and heat recovery should be integrated in a heating system in a way that leads to lowest primary energy demand and lowest environmental impact of the whole heating system. In addition, the solutions should be economical feasible, too. For ice storages the concept of de-icing its heat exchangers will be developed further. A prototype of a cost-effective ice storage will be constructed.

2. Work carried out

2.1. Mathematical model of an ice storage

For the simulations in High-Ice project a mathematical model of an ice storage with heat exchangers that can be de-iced is needed. Basic parts of such a mathematical model could be taken from another project of SPF ("Pilotanlage WP-Sol COP6+"). However, newly needed features have forced to develop a new model based on the experience obtained from WP-Sol COP6+ project.

The ice storage model assumes a heat transfer processes in the storage along the hight of the tank. It is based on the solution of a one dimensional transient conduction equation with different heat sources and losses.

The new features of the model can be summarized as:

- Four different heat exchangers can be connected both in series and in parallel and are capable to be iced and de-iced. Immersed coil and flat plate heat exchanger types can be calculated.
- Each heat exchanger can choose between two models for the calculation of the global heat transfer coefficient UA.
- The ice fusion is a consequence of the energy balance in each control volume. All energy contained in the water until to a predefined temperature level (e.g. $t \sim 0.5^oC$) is used to melt the ice.
- The ice formation starting point is calculated as a function of the surface temperature of the heat exchanger.
- The model is able to predict a continuous icing mode with some restrictions.
- Water temperatures are calculated in all control volumes also if ice is present in the storage tank.

- Cylindrical and rectangular shapes of the ice storage can be simulated.

The ice formation prediction is based on the quasi steady state approximation, *i.e.* neglecting the capacity of the solid layer, explained in [1]. When the ice layer is growing on the flat surface of the heat exchanger the heat of conduction from the fluid to the external surface of the plate is equal to the heat of fusion.

2.2. Validation of the ice storage model

2.2.1 Validation for cylindrical storages and immersed coil heat exchangers

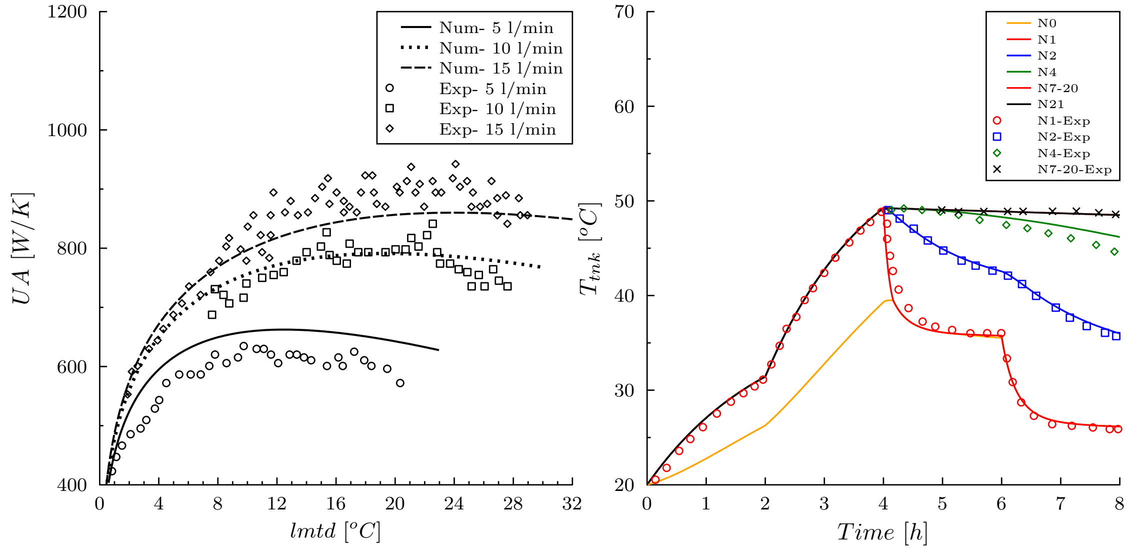
To validate spiral coil heat exchangers experiments published in the literature for a heating operation mode are employed. We have carried out validations using a cylindrical configuration and spiral coil immersed heat exchangers using the model of the heat exchangers UA calculations based on the generic expression suggested in [4]. Experiments from [2] were used to validate the heat exchanger behavior for a fully mixed storage tank. The experiments consist in charging the storage tank up to 70^oC. The outlet temperature of the immersed coil is tracked and results are presented along the logarithmic mean temperature for different mass flow rates in the heat exchangers. Results with our model have shown to be satisfactory (Fig.1a).

From the above experiments the inversion algorithm model was not validated because the tank was fully mixed. For this reason we have used the experiments presented in [3] were the spiral coil is placed in the bottom layer of the tank and the reversion algorithm is used to mix up the layers when the bottom layer is warmer than the rest. With these experiments we also have validated the storage model itself, since temperatures at 10 different heights of the storage were compared to the experiments with a good accuracy (Fig.1b).

2.2.2 Validation for rectangular storages and flat plate heat exchangers with our experiments

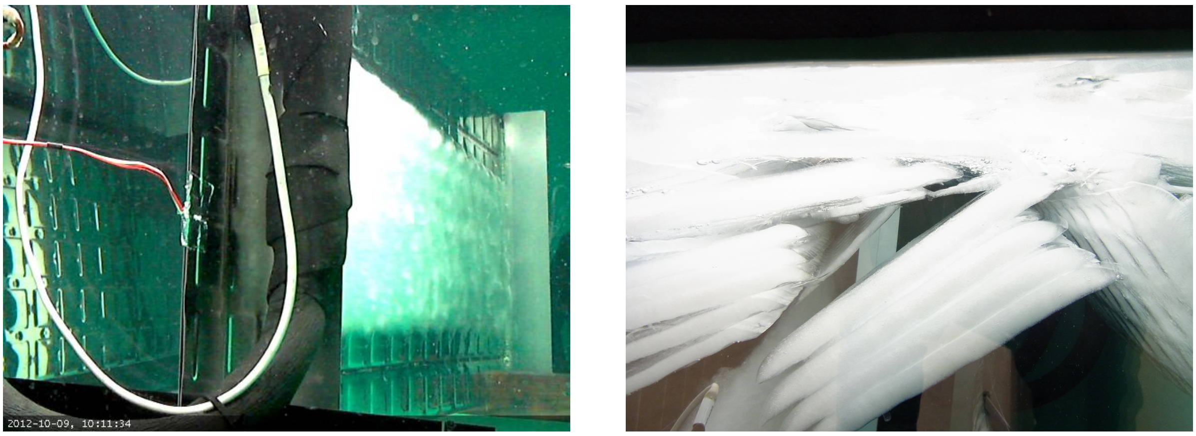
To validate the mathematical model for flat plate heat exchangers the ice storage with a volume of $1\ m^3$ were conducted in the SPF laboratory for all relevant operating modes (details of used flat plate hx see [6]). The storage tank is meant to be used not only for icing mode, but also as a normal sensible storage tank.

The experimental setup consists on two heat exchangers on the wall of the store connected in series plus one heat exchanger at the bottom of the storage tank that is allowed to produce ice (Fig. 2a and b). All of them are flat plate fully irrigated heat exchangers.



(a) (b)

Figure 1: a) UA of the heat exchanger compared to experiments from [2] and b) storage tank temperatures compared to experiments from [3]. ($lmtd$ = logarithmic mean temperature difference)



(a) (b)

Figure 2: Side views into the ice storage in the SPF lab a) wall heat exchangers (left) and heat exchanger that can be de-iced (right) and b) accumulated ice layers at the storage's water surface after several icing and de-icing cycles (thickness of layers $\sim 2\ cm$).

For the validations we have conducted many operating modes. The most relevant are:

- Natural cooling (NC): Cooling down of the storage without mass flow through the heat exchangers.
- Natural melting (NM): Melting of previously formed ice in the storage without mass flow through the heat exchangers.
- Forced cooling (FC): Cooling down of the storage with mass flow through the heat exchangers and without ice formation.
- Forced heating (FH): Heating up of the storage to temperatures of 50^oC using all heat exchangers connected in series.
- Ice and De-Ice (IDI): Alternated icing and de-icing of the flat plate heat exchanger. The sequence is e.g. one hour of icing mode and 15 min of heating and thus de-icing. In this 15 min the ice attached to the heat exchanger is melted, detached from the heat exchanger surface and floats up to the water surface of the storage.
- Continuous icing (CI): Growing of the ice layer without any de-icing. The thickness of the ice layer can be measured and compared to numerical results.

The mass of ice was only measured once in each experiment with ice forming as each measuring was interfering the floating ice layers considerably through breaking ice layers and though increasing the heat exchange between the ice and the storage's liquid water.

Hereafter some of the most relevant experiments are presented. In Fig.3a the storage tank temperature and the mass of ice is compared against experimental data for the NM case. At the beginning of the experiment we had around $70\ kg$ of ice that were melted during 65 hours until we did another measure of the ice. At this time the numerical mass of ice shows a good agreement with the experiments. Four temperatures in the storage at the heights of $z_1 = 3.5$, $z_2 = 24.5$, $z_3 = 45.5$ and $z_4 = 65.5\ cm$ were measured and compared with calculations. It can be observed that also the evolution of the storage tank temperatures is in good agreement respect to the experiments.

The case of IDI is presented in Fig.3b. In this case the mass of ice is also found to be in good agreement with the experiments. However, the storage tank temperatures are not as accurate as in the case of NM. This is something we can expect since in this case layers of ice are floating up from the heat exchangers to the tank surface disturbing the water in the storage tank. Clearly this is not a one dimensional case and we can not expect to have a high degree of precision with our model. Nevertheless, the storage tank temperatures calculated are in the order of acceptance for the purpose of the model (notice that the maximum error is around 3^oC).

The immersed heat exchanger outlet temperatures are presented in Fig.4a for the case of FH and in Fig.4b for the IDI experiment. For the case of FH the outlet temperatures of the three heat exchangers are compared to experiments with a satisfactory results. The outlet and surface temperatures of the ice heat exchanger are shown in Fig.4b for the IDI mode for four

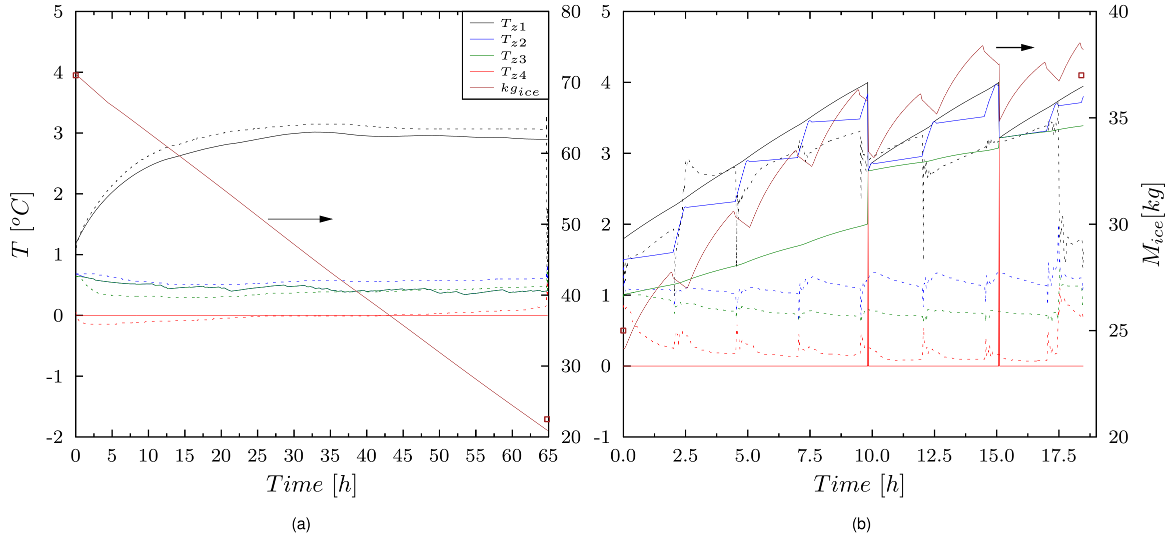


Figure 3: Storage tank temperature (left axes) and mass of ice in the store (right axes) for a) natural melting (NM) and b) ice and de-ice (IDI). Solid lines are used for numerical calculations and dashed lines and symbols for experimental data.

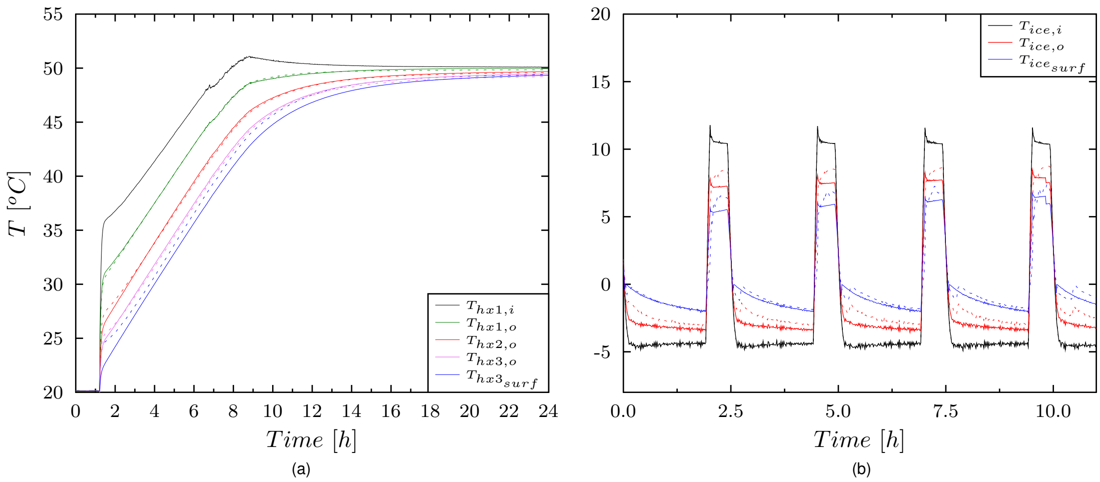


Figure 4: Immersed heat exchanger temperatures for a) forced heating (FH) and b) ice and de-ice (IDI). Solid lines are used for numerical calculations and dashed lines for experimental data.

cycles of ice and de-ice. The surface temperature is used as the threshold to start the icing mode in the model. From these results, it can be observed that the model predict the ice and de-ice mode with satisfactory results.

2.3. Setting up a simulation environment in TRNSYS 17

A simulation environment for different buildings and their heating system was set up in TRNSYS 17. Main parts of a TRNSYS simulation structure from a EU project in which SPF is taking part ("MacSheep project") could be used as a basis for this High-Ice simulation environment. This may allow a comparison with the results of McSheep project in a later phase of this project. Further, the control strategy and the system of hydraulic connections for implementing an ice storage with heat exchangers that can be de-iced could be taken from a SME project that is going on at SPF (details see [5]). Nevertheless large changes had to be done in the TRNSYS simulation deck. The implementation of the ice storage model and its diverse hydraulic connections has been time-consuming. The validated ice storage model was combined in the simulation deck with a 2-dimensional model of the ground surrounding the buried ice storage. Devices for heat recovery are not implemented in the simulation deck yet.

3. National / international cooperation

An exchange of ideas and a knowledge transfer with the Institute of Thermal Engineering (IWT) of Graz University of Technology in the topic of heat recovery has been started. IWT finished a research project in the field of heat recovery, solar thermal energy and heat pumps in November 2012. The project report is not published yet.

SPF is currently constructing a pilot plant in a building consisting of a collector field of $50\ m^2$, a $18\ kW$ brine-heat pump and an ice storage with a water volume of $75\ m^3$. Flat plate heat exchangers made of stainless steel that can be de-iced with heat are used in the ice storage. The operation of the pilot plant will start in January 2013. Findings will be used for High Ice project. The pilot plant and its development are financed by a Swiss utility company.

4. Evaluation 2012 and Outlook 2013

The mathematical model of SPF of the ice storage was improved leading to better predictions also for smaller ice storages as the ice formation starting point now is determined by the heat exchanger's surface temperature. The modifications in the model now allow the simulation of a larger variety of ice storage designs. The validation of the ice storage model was done for a large variety of operating modes. The comparison of measured data and the simulation results showed a satisfying accordance.

To complete the TRNSYS simulation deck for first system simulations in a next step heat recovery models and wast water profiles have to be implemented into the deck. Before that the analysis of the results of the research project of IWT on the topic of heat recovery is recommended.

Further steps in High-Ice project will be to start first system simulations to get first insights into promising combinations of ice storages and heat recovery, to start the evaluation of new heat exchanger materials and designs for de-icing and to set up the life cycle assessment software (Simapro) to estimate the environmental and energetic impact of the simulated heating systems.

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