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Simulation of a solar-ice system for heating applications. System validation with one-year of monitoring data

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ABSTRACT

In the present paper a dynamic system simulation for a combined solar thermal and heat pump system including an ice storage is presented. The simulated system was validated with one-year measurements from a pilot plant situated in Rapperswil-Jona, Switzerland. The system is installed in an old kindergarten with a yearly heating demand of around 35 MWh and a high temperature hydronic heat distribution system (radiators). The pilot plant is composed of 50 m^2 of covered and 14 m^2 of uncovered collectors, both with selective coating; a heat pump of 17 kW, a sensible storage of 3.5 m^3 and an ice storage of 75 m^3. The monitored yearly system performance factor was 4.6.

The system simulation was compared to measurements at monthly and yearly bases for global variables of interest such as system performance factor, energy flows between the collectors, ice storage, heat pump and combi-storage. The yearly difference in system performance (SPF_{SHP+}) was found to be within the uncertainty range. After the system was validated, a sensitivity analysis was conducted. The most sensitive parameter was found to be the variation of ground properties between two extremes, i.e. from wet clay to dry sand where differences up to 4% were found in the yearly SPF_{SHP+}.

Results from annual simulations with Meteonorm weather data were compared with results from simulations using measured weather data for the climate of Zurich. The average of the results of 13 years with real data showed an increase of SPF_{SHP+} of 24% compared to the results obtained with Meteonorm data.

1. Introduction

The energy demand used for heating and cooling in Europe is around 46% of the total energy demand. As stated in [1], the building sector is responsible for 56% of the total heating and cooling demand in Europe. Therefore, the increase of system efficiency by increasing the share of renewable use in the building sector is expected to have a high impact at European level and necessary to reach the targets of the European Commission by 2050 [2].

One way to increase the share of renewable energy consists in combining different technologies and integrate them in a proper way. An example is the combination of solar thermal and heat pump systems. In Europe, most of the companies in the heating sector started to offer these type of systems in recent years with a strong concentration of those based on Germany and Austria [3].

A recent example of research done in this topic is the study conducted in the framework of the Solar Heating and Cooling programme (SHC Task 44) and the Heat Pump programme (HPP Annex 38) of the International Energy Agency (IEA) summarized in [4]. The publications related to this IEA task provide a good overview of the performance and relevance of these systems.

Combined systems using solar thermal collectors and a heat pump can be operated in series, parallel or in a combination of both [5]. Series systems are those that use solar thermal as a source for the heat pump. When solar is the only source for the heat pump, it is likely that the system will face periods of time when not enough energy can be extracted from the collectors to run the heat pump. In this circumstances, the temperature in the evaporator of the heat pump drops below the minimum accepted temperature and a back-up needs to be installed to provide the heating demand. If electricity is used as a back-up system, the system performance factor is highly negatively affected by the use of it and therefore it should be avoided. One alternative to avoid or reduce the operating hours of the back-up system is to use a water or glycol storage in the source side of the heat pump. When water is used as storage medium, usually the storage size is not large enough to be operated always above 0 °C and therefore ice is formed on the heat exchangers.

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The interest in solar-ice systems is growing in central Europe, where climatic conditions are appropriate. A likely explanation of the market push is mainly related to regulations that restrict the drilling of boreholes. For this reason solar-ice systems have been established as an alternative to ground source heat pump (GSHP) systems with some advantages such as: (i) usually not submitted to regulations of water and soil (ii) no need to regenerate the ground for densely exploited regions (iii) ice storage is accessible, allowing to solve leakages or replace heat exchangers (iv) ice storage can be installed in the cellar when no ground space is available (v) it is a flexible system able to adapt to building size restrictions, i.e. the same system performance can be reached with different combinations of collector area and ice storage volume and (vi) higher performances compared to GSHP can be achieved if direct solar heat is used extensively. However, solar-ice systems have some disadvantages such as the added complexity and usually slightly higher cost compared to GSHP if the same performance is desired. Regarding the use of water as storage medium, although other materials can be used with melting temperatures above 0 °C, the price of water, its availability, non-toxicity and high latent heat of fusion, makes its use for this application the most favorable alternative.

First attempts to include ice storages in solar thermal heat pump systems were already made in the 1970s [6]. However, only in the course of the present decade a number of companies started offering this type of heating system on the market. Some field test results show performances in the range of ground source heat pumps [7] and even higher [8].

Several heat exchanger concepts for extracting the latent heat from ice storages are possible. Each concept has to ensure that the ice layer on the heat exchanger does not grow too much as this would result in too low source temperatures for the heat pump. From all the existing ice storage concepts only ice-on-coil are established in the solar heating market. In this work, the concept based on immersed flat plate heat exchanger that are de-iced thermally is used. This concept applied to solar heating systems was developed at our institute, Institut für Solartechnik SPF, and details of it can be found in the final report of the project High-Ice [9].

Some research activities have been published where different combinations of solar thermal and heat pump systems with ice storages have been analyzed. Nevertheless, most of the published research is either based on field activities [7,10,11] or on simulation studies [12–15]. Regardless of its importance, a rigorous validation of the whole system with field measurements has not been provided yet in the literature. Design criteria for solar-ice systems are difficult to be defined without dynamic yearly system simulations and many questions regarding an adequate system design have not been addressed so far. However, simulations using different system sizes, hydraulics and controls could lead to misleading conclusions when the full system setup is not well validated with measurements. In this work, a validation of a solar ice system is presented using monitored data from a pilot plant designed, supervised, and monitored by our institute. The solar-ice system framework validated in this work has been used to analyze the solar-ice system concept in previous publications [15,9] changing sizes of collector area and ice storage volume, using different collector types and for different building demands using the climates of Strasbourg and Zurich respectively. Moreover, the cost of the different system combination along with the Life Cycle Assessment of the whole system was presented in [9].

2. Methodology

Energy simulations were conducted with the simulation environment TRNSYS-17 [16] where the connections of different components were defined. The basic components to model a solar-ice system are: solar thermal collectors, heat pump, (buried) ice storage, sensible thermal combi-storage, building and system control. Specifically, the key aspects in the simulations presented here are the models of the ice storage, the ground that surrounds it, and system control algorithm. These models were developed within the project High-Ice [9] and presented and validated in separate papers [17,18]. All the other models used in this work were developed and validated previously. A summary of the most important component models is given in Section 3. When all the component models were available, the TRNSYS environment was used to link all components by defining the hydraulics of the system as shown in Fig. 1. The real data of each component was used to define its parameters for the simulation. The ambient and solar radiation profiles from the monitored systems were used as inputs for the models and actualized for each time step.

As said before, the system simulation is based on components that have already been validated. Nevertheless, from the authors experience, it is not enough to have well validated components, the whole system set up has to be verified and validated, too. Moreover, results are strongly influenced by the control algorithms which have to consider the local particularities. In order to ensure the credibility of the obtained results, several systematic checks were carried out for all simulations. Heat balances were ensured in all individual components, hydraulic loops and also from a system's perspective. Only one iteration problem of the TRNSYS solver in the whole yearly simulation was observed. High number of iteration problems may indicate that an error exists, typically in a control strategy. Once the errors were solved, validations of the whole system were carried out.

3. Mathematical formulation of main component models

A solar-ice system is composed by a collector field, ice storage, heat pump, combi-storage, building and the control that regulates the system. Besides the modeling of all these components for the present application, also the ground behavior needs to be considered. A summary of the main models is given hereafter:

3.1. Coupled ice storage and ground model

The ice storage is based on a de-icing concept to reduce the heat exchanger area in the storage while avoiding low temperatures in the heat pump evaporator. The thermal de-icing concept is based on the melting of an ice layer on the surface of specially designed flat plate heat exchangers made of stainless steel. The heat exchangers are located in the bottom part of the storage in such a way that de-iced plates can float up to the surface of the storage where ice is accumulated [19]. The energy used for de-icing is mainly obtained from the solar collectors, although other sources can be used if necessary.

The mathematical formulation and validation of the ice storage model was presented in [17], and its coupling with the ground was formulated and validated in [18] using the monitored results of the pilot plant used in the present work. Therefore, the interested reader is referred to the mentioned publications for further details on this topic. A summary is provided hereafter for a completeness of the paper.

The mathematical formulation is based on the solution of the energy conservation law applied to the water of the storage:

$$\rho c_p V \frac{\partial T}{\partial t} - h_f \frac{\partial M_{ice}}{\partial t} = \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) V + \dot{Q}_{ext} + \dot{Q}_{hx} \qquad (1)$$

where c_p is the specific heat capacity, h_f the enthalpy of fusion, M_{ice} the mass of ice, $\dot{Q}_{ext}$ and $\dot{Q}_{hx}$ are the heat fluxes between the storage