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235 - Unglazed Solar Collectors in Heat Pump Systems: Measurement, Simulation and Dimensioning

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Abstract

Two heat pump-systems with borehole and unglazed solar thermal collector are measured and simulated in TRNSYS as part of a research project. Compared to systems without collector the collector yield increases the average temperature level of the heat pump system on the evaporator side. A collector model is developed and evaluated considering the long-wave radiation exchange and the condensation heat gains. The annual collector yield is measured as 545 kWh/m²a, of which 4% are determined as heat gains through condensation. Further simulations in TRNSYS show the interdependency of collector area, borehole length and heat pump system performance. The additional heat source component collector reduces the required borehole length and simultaneously improves the heat pump system performance in comparison to a solely borehole supported heat pump. In addition the system sensitivity for the heat source parameters is reduced significantly, thus resulting in a more certain system planning and operation.

Keywords: heat pump system, unglazed solar thermal collector, condensation heat gains

1. Introduction

Unglazed solar collectors (SC) provide a high collector yield at a low temperature level. They may therefore be applied to the best advantage as heat source in heat pump systems (HPS) [1]. During winter, in the period of maximum heating demand, unglazed SC can gain heat on a very low temperature level only. Thus a second heat source is needed, which offers ambient temperature independent heat to the HPS. As such heat sources vertical borehole heat exchangers (BHE) are applied.

The role of an unglazed SC is to increase the source temperature level of a HPS, showing an enormous potential for reducing the electrical consumption of the heat pump. If the average temperature level of the heat source is increased by 5 K the annual HPS performance factor (HPF) improves from 3.4 to 4.0. The HPF is defined as the heat supplied by the heat pump divided by its electricity consumption for one year of operation.

In such a two source HPS application the solar heat is either supplied directly to the heat pump condenser or to the BHE. The heat is transferred to the BHE for thermal regeneration of the cooled soil surrounding the BHE. A direct use of the solar heat for space heating or domestic hot water preheating is not regarded in this paper. These solar assisted ground coupled systems offer a high dynamic, a complex interdependency and particularly unknown behaviour, which can not be described properly with common steady state methods used for BHE dimensioning. Hence detailed numerical simulations are required. The realization and evaluation of two HPS pilot plants were in the focus of a research project, where a TRNSYS-simulation configuration could be validated and used for further extrapolating studies.

2. System Concept Description

The following HPS system concept has been selected for the investigations. It may be described by the characteristics given below:

- Unglazed Collectors: Inexpensive, uncritical operation mode (no stagnation, no steam generation), uncomplicated opportunities for building integration
- In order to realize an uncomplex system: Solar heat only directed to the evaporator side of the heat pump and: No option for direct use of solar heat for domestic hot water or space heating foreseen.
- Limitation of the investigations: Heating systems for small buildings (< 30 MWh/a heating demand)
- Thermal soil regeneration as the main target: A permanent increase of the yearly mean HPS source temperature if compared to a non-solar BHE system is the aim, but a significant seasonal storage effect is not planned. Thus, even with SC the ground is mainly serving as a heat source.

All these characteristics and restrictions form a reasonable unit. As for small buildings the seasonal storage effect may not be achieved due to the high thermal losses, the solar heat is mainly used for the regeneration of the soil. This leads to lower source temperatures in winter. Under these conditions unglazed SC find an ideal application temperature level, due to the fact that they are operated nearby or even below ambient air temperature.

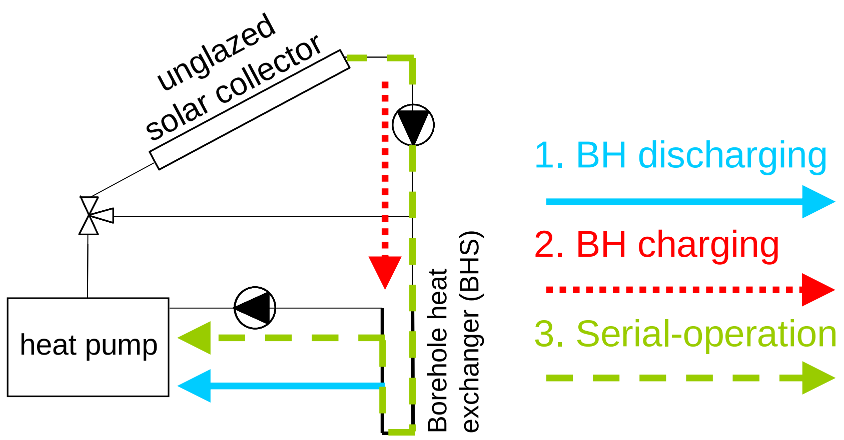

Fig. 1. System concept and operation modes. A common heat pump system with BHE is extended by an unglazed SC. Only the heat source side of the heat pump is shown.

The system (Fig. 1) is operated in three modes: Charging, discharging and serial operation. While operating in the discharging mode the BHE delivers with its own ground heat to the heat pump, whereas in the serial-operation mode the BHE is supported by the SC as additional heat source. In the operation mode “charging”, the collector is heating up and thus regenerating the soil around the BHE, while the HP is turned off. This concept realizes a simple hydraulic connection of the components and therefore allows different volume flow rates in the collector and BHE circuit.

3. Measurement Results Pilot Plant in Limburg

During the project two pilot plants have been investigated by the ISFH. The pilot plant Limburg is measured since September 2006, the pilot plant Klein-Koeris (near Berlin) since November 2007. Due to the short measuring period of the HPS Klein-Koeris, only the results of the plant Limburg are presented in this paper.

The HPS Limburg supplies a 300 m² single-family house with heat and consists of 14 BHE each with a depth of 17 m, a 16 kW heat pump and 44 m² roof integrated, unglazed solar collectors produced by the company Rheinzink (QUICK STEP SolarThermie).

The measured monthly mean values in Fig. 2 show a strong seasonal variation. Therefore it is necessary to analyse the total energy fluxes and the performance factor at least on a one year lasting time scale.

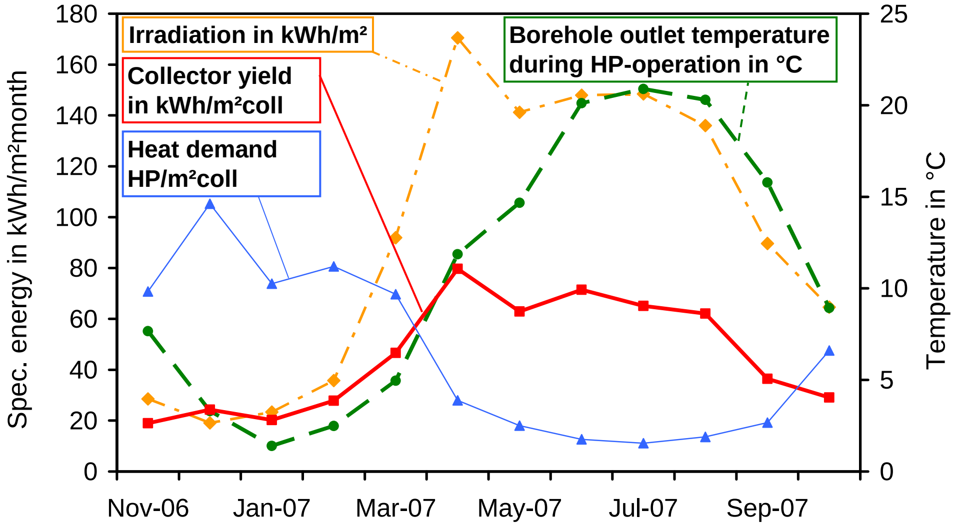

Fig. 2.: Measured monthly mean values of collector yield, heating demand at the heat pump evaporator, irradiation and borehole outlet temperature in the course of one year at the Limburg plant (Nov. 2006 - Nov. 2007)

The HP delivers 33.3 MWh/a of heat energy, which covers the demand of the floor heating system (70%) and the domestic hot water system (30%). The annual HPS performance factor (HPF) amounts to 4.0, if the power demands of collector and borehole pump are neglected. With these additional consumers the HPF is 3.5.

The measurements show a 20% higher electric power consumption of the HP compared to the manufacturer information. With the promised efficiency of the HP, the HPS would come up to an annual performance factor of 5.0. The measured collector yield of 545 kWh/m^{2}a covers the annual heat demand on the evaporator side of the HP.

Further results can be derived from the measurements:

- The unglazed collector charges the borehole during summer. The borehole reaches a maximum monthly mean outlet temperature of 20°C during HP operation.
- A high specific collector yield of 545 kWh/m^{2}a is reached. Due to collector operation during night with convective and condensing gains the collector yield in December is higher than the irradiation.

- The averaged measured outlet temperature of the BHS is 6°C. Typical design temperature of a HPS without solar thermal system amounts to approx. 0°C.
- On summer days with high irradiation a temperature of 20°C to 25°C is reached at the source side of the HP (Fig. 3). In the following night the source side temperature can drop down to 10°C. This high temperature difference in the course of a day emphasizes the need of dynamic simulations to describe the accurate behaviour of HPS.

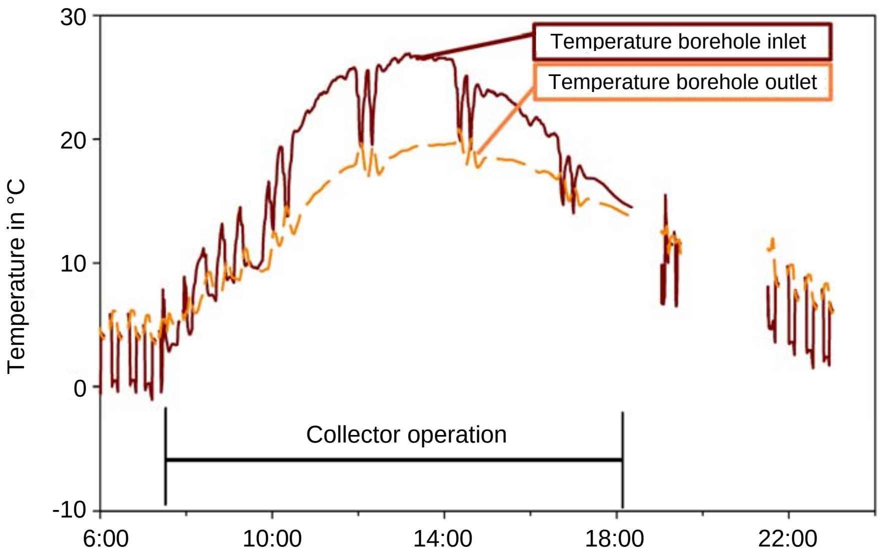

Fig. 3. Temperature at borehole in- and outlet in the course of day (8-Apr-2007, plant Limburg). The figure shows the temperatures while collector pump and HP are running.

The collector model regarding EN 12975-2 is much more complex for unglazed than for glazed SC. In addition to the irradiance and the ambient temperature the wind velocity and the infrared radiation exchange is needed too. For collector fluid temperatures nearby or even below ambient temperature condensation on surface of unglazed collectors has to be regarded. The literature mentions condensation heat gains amounting to 5% up to 30% of the collector yield. A condensation model was developed [2] and validated by measured data and finally implemented in a TRNSYS collector type for unglazed SC.

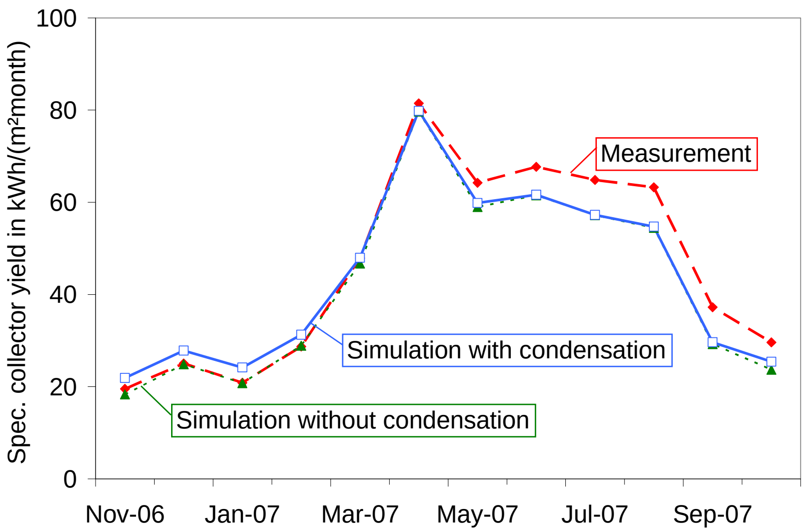

Fig. 4. Measured collector yield compared to simulations with or without condensation.

Simulations of the Limburg plant show a total share of the condensation gains in the annual collector yield of 4%, maximum daily shares of up to 30% have been observed. During the winter period condensation heat gains reaches highest fractions of the collector yield (average value 14%). Considering condensation the difference in simulated and measured collector yield drops from 8.4% down to 5.3% (Fig. 4). It is assumed, that the residual difference is primarily caused by fundamental problems in measuring the representative wind velocity and ambient temperature over the large area of the unglazed collector array.

4. Simulation Results and Conclusion

The single components and the whole HPS were modelled in TRNSYS and validated using the measured data. A long period of validation is very important, because the operational behaviour of the HPS shows a significant difference between summer and winter.

Subsequent to validation a reference system is built up in TRNSYS and the correlation between annual HPS performance factor (HPF) and the main influencing factors such as collector area, borehole length etc. is investigated. The boundary conditions of the reference system are shown in Tab. 1.

Tab. 1. Boundary conditions of the reference system simulated in TRNSYS

Parameter	**Value**
Space heat demand	60 kWh/m^{2}a
Radiator heating	40°C
Domestic hot water, 4 persons	170 l/d at 45°C
Heat pump	7.5 kW thermal
Total heat demand	11 MWh/a
Collector tilt angle	45°, azimuth 0° (south)
Weather region	TRY 7 (Kassel)
Heat conductance of the soil	2 W/mK

Fig. 5. shows as simulation results the course of HPF as a function of the borehole length an the collector area. If the power consumption of the collector pump is considered, the HPF is reduced by ΔHPF = 0.2 (energy class A) and ΔHPF = 0.4 (energy class D)[1] respectively.

There is not only one target variable for system dimensioning according to Fig. 5. The choice of collector area and borehole length leads to two possible targets: energy saving and investment cost. The standard borehole dimensioning of the reference system based on VDI 4640 leads to a borehole length of 70 m and a simulated HPF of approx. 4.0. Starting from this design point the HPF increases from 4.0 up to 4.4 by adding 20 m^2 collector area to the HPS. The same improvement may be achieved by using a borehole depth of 130 m instead of 70 m. The same HPF in the reference system may be achieved, if a short borehole of 35 m will be regenerated by a 10 m^2 collector array.

Beside saving of investment cost (BH length) and current cost (electric energy consumption) the usage of collector in HPS enhances the planning certainty of the whole system. The curves of the systems with collector are much more flat than the curves without collector (Fig. 5). Thus extreme supercooling of the BHE caused by improper dimensioning of the system can be prevented by integrating a collector. E.g., a difference in thermal conductivity of the soil of 1 W/mK instead of

[1] Each with ideal pump dimensioning and operating at design point.

2 W/mK decreases the HPF of the reference system from 4.0 down to 3.7. The system with 20 m^2 collector area is almost unaffected by this modified thermal conductivity. Similar positive effects of the collector may be stated, if the real heat demand of the building is higher than assumed for the design process.

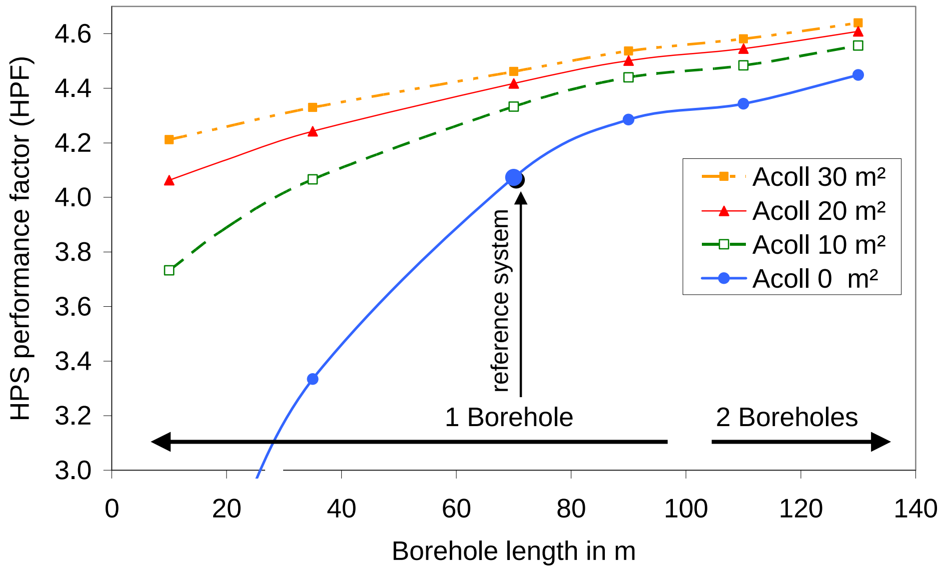

Fig. 5. Correlation of HPS performance factor (HPF), collector area and borehole length. Electric power consumption of the pumps is neglected.

Beside collector area and borehole length additional parameters influence the HPF. Based on a solar assisted HPS (15 m^2 collector area, 70 m borehole length) the influence of other parameters on the HPF is investigated (Tab. 2). Changing the heat conductance of the soil or the weather region effects the system by up to ΔHPF = 0.2. On the side of the heat consumption (supply temperature of the space heating and domestic hot water system) the influence on the HPS is much stronger.

Tab. 2. HPF sensitivity of reference system with collector to changes in system parameters (design point: collector area 15 m^2, borehole length 70 m, HPF = 4.4)

Influencing parameter	**Value in ref. system**	**Changes**	**ΔHPF**
HP-characteristic	COP 0/35 = 4.6	WP 1 COP 0/35 = 4.4 WP 2 COP 0/35 = 4.7	-0.3 +0.1
Heat conductance of the soil	2 W/mK	3.6 W/mK 0.4 W/mK	+0.1 -0.3
Space heating system	Radiator 40°C	Radiator 50°C Floor heating 35°C	-0.4 +0.2
Domestic hot water system	$T_{storage}$ = (45+3)°C	$T_{storage}$ = (60+3)°C without DHW	-0.6 +0.4
Space heat demand	60 kWh/m^{2}a	30 kWh/m^{2}a 100 kWh/m^{2}a	+0.1 -0.3
Weather region	TRY 07	TRY 15, TRY 06	-0.2

It may be summarized, that a HPS without SC is much more sensitive towards modifications on the source side. The solar collector in a HPS minimizes the risk which may be caused by unforeseen high heat extraction or a lower ground heat conductance.

Acknowledgment

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