HYDRAULICS, PERFORMANCE AND COMFORT OF GROUND COUPLED HEATING-COOLING SYSTEMS

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ABSTRACT

The energy demand for heating is decreasing significantly in modern highly-insulated dwellings. Due to larger glass areas and well insulated buildings overheating becomes a problem.

In a research project several hydraulic schemes with ground-coupled heat pumps and passive cooling with borehole heat exchanger have been evaluated. A parametric study with MATLAB/Simulink simulations using a residential low-energy building with floor heating system has been carried out. Simultaneous simulation of building and mechanical system showed dynamic interaction of floor and ground heat exchanger. Main objective is to estimate energy demand for heating and cooling, thermal comfort and economical feasibility of the overall system.

A big challenge is appropriate control providing an optimal thermal comfort with a minimum of additional energy compared to heating only systems. Especially the meteorological conditions in spring and autumn cause intermittent heating and cooling which increases heating energy demand, since the concrete structure is alternately heated and cooled.

KEYWORDS

simultaneous simulation, heating and cooling, ground coupled heat pump, borehole heat exchanger, hydraulics

INTRODUCTION

The energy demand for heating is decreasing significantly in modern highly insulated dwellings. With this heat pumps are used more frequently for heating and domestic hot water applications. Combined with growing glass areas that tend to overheat highly insulated buildings in summer time and rising temperatures in hot periods the alternative use of heat pumps for heating and cooling comes more and more into focus.

Classical ground coupled heat pump systems are utilized today monovalently for heating and domestic hot water usage. Thus also in summer time the ground heat exchanger (GHX) withdraws heat from the ground and therefore cools it down. Alternatively to that it would be possible with a cooling need in the building to extract the heat from the building with the aid of the floor heating system. On the one hand the lower temperature in the ground could serve as passive heat sink; on the other hand domestic hot water could be produced running the heat pump in simultaneous heating and cooling mode. Recent research on control strategies has been carried out by Olesen (2001).

This passive cooling of the building is very interesting both from energetic viewpoint, as also with regard to the capital expenditure. The cold is produced either with the evaporator of a standard heat pump and utilized only with simultaneous domestic hot water preparation or generated very efficiently (passively) out of the ground heat exchanger. Because the waste heat of the active cooling process is used completely to heat up domestic hot water, no additional consumption of electricity occurs. The geothermal heat exchanger thus has a longer regeneration time since it serves less time as heat source for hot water preparation. Furthermore it can be loaded with heat rejected from cooling application.

Heating and passive cooling with floor heating combined with ground coupled heat pumps represents indeed a technically known concept but is a new application in the residential architecture and could add a contribution to increase efficiency in the expected trend of cooling in buildings. The technical feasibility and the fundamental functionality are undisputed. However there are up to now only little knowledge about the performance of such a concept concerning control strategy, expected effect and the evaluation of the risks. The lack of knowledge concerning hydraulics, control strategy and dimensioning was the topic of research done within the project with focus to energy consumption and resulting comfort.

One employed approach to answer the formulated questions is the simultaneous simulation of building and mechanical systems for studies on optimizing control and extending knowledge on dynamic system behavior. Similar work has been done by Matthes et al. (2006) using Modelica as platform.

SITUATION

Background

The following statements describe the background in the sense of the today usual practice as well as the delimitation of the project concerning considerations on energy demand and control concepts:

- The design of the system is based on the application for heating (also if applied for cooling).
- The control concept of the floor heating system is determined for the use as heating system. (decision: with thermostatic valve OR self regulating without thermostatic valves).
- Self regulating floor heating systems without thermostatic valves yield higher efficiencies due to higher COP in the heat pump caused by smaller temperature differences between the heat carrier and the room.
- Applied for cooling the system with smaller temperature difference between the heat carrier and the room achieves a more extensive usage of cooling capacity out of a borehole heat exchanger.
- The majority of floor heating systems today are implemented with thermostatic valves.
- Bathroom without window frequently do not have any thermostatic valve.
- Market available floor heating and cooling systems usually employ a manual switch to change from heating to cooling mode.

The concept in the case of this study comprises a self regulating floor heating system without thermostatic valves and an automated switchover between heating and cooling application.

Methods

The project was organized in following steps in order to achieve the given aims:

- Evaluation of market available ground coupled heat pumps with cooling option and their hydraulic circuits. Definition of standard circuits for passive cooling only with ground heat exchanger and active cooling with reversed heat pump process.
- Separate simulation of building and mechanical system; first step to generate a yearly heating and cooling sequence for a reference building and the achieved comfort, second step to evaluate the performance of the ground heat exchanger.
- Definition of control concepts for the simulation and evaluation of energy demand and achieved comfort.
- Performance Evaluation on the one hand for passive cooling only with earth heat exchanger and on the other hand for active cooling with heat pump during domestic hot water production.
- Simultaneous simulation of building and mechanical system.
- Summary of the most important design recommendations, characteristic values and cost-benefit analysis.

Reference Building

First step for the energetic and comfort evaluation of cooling options with classical ground coupled heat pumps for space heating was to define a reference building. The chosen building is a built typical low energy one-family house certified with Swiss MINERGIE® label (Anon. A).

Figure 1 Reference building for simulation

The building shown in Figure 1 is characterized by:

- One-family house according to MINERGIE® (Anon. A) requirements in Gelterkinden (canton Basel-Landschaft, CH) at south oriented hillside location with solid construction walls and laterally placed basement outside insulation perimeter
- Energy reference area 153 m^2 (net living space 125 m^2, net volume 305 m^3)
- Specific heating energy need per energy reference area acc. to Swiss standard = 157 MJ/m^2a
- Heating power demand acc. to Swiss standard = 4.1 kW (20°C/-8°C)

HYDRAULICS

The functions „heating“, „passive cooling“ and „domestic hot water“ of ground coupled heat pump systems are discussed in the following in parallel and alternative operation. Warm pipes are represented in red, cold pipes in blue.

In classic heating mode the heat pump withdraws heat via evaporator from the ground heat exchanger and delivers a higher temperature level to the condenser in the heating circuit.

The simplest and most common hydraulic configuration for cooling with heat pump heating systems includes a passive cooling option as shown in Figure 3. The room is being chilled by the floor heating system. The heat is transferred from the floor hydronic circuit via heat exchanger to the ground heat exchanger circuit and emitted to the ground. There are different options to connect the borehole via heat exchanger to the emission system. The heat exchanger could be placed near the heat pump direct in the condenser circuit, thus inhibiting parallel cooling and domestic hot water operation, or in an extra circuit as shown in Figure 3. The cooling power control by means of a mixer can be placed in the ground circuit or the floor circuit.

Most, but not all, passive cooling circuits at the market use a mixing valve for regulation of cooling power to control the flow temperature to the floor heating circuits. Reasons are prevention of condensation on cold piping surface or in the room. In most cases the flow temperature is controlled with a cooling characteristic curve similar to a heating characteristic curve. But if the desired flow temperature could not be reached, the mixing valve opens completely and the system runs with the maximum power the ground heat exchanger is able to deliver.

If the cooling mode is halted during hot water production it is called alternative operation, otherwise in parallel mode the cooling capacity is increased by the heat pump evaporator.

In parallel cooling and domestic hot water mode the connection of borehole and room cooling heat exchanger must assure a sufficient heat source for the heat pump. If the cooling power for the building and thus the heat source for the heat pump are regulated the ground heat exchanger must always be connected to guarantee a continuous heat source. Therefore in cooling mode the floor cooling heat exchanger shall be connected serial to the borehole heat exchanger as depicted in Figure 2.

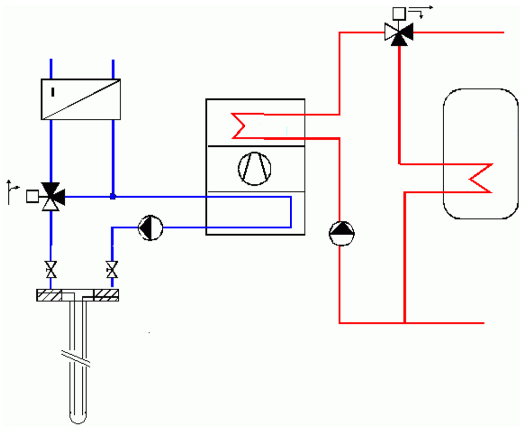

Figure 2 Serial connection of borehole and floor cooling heat exchanger with heat pump

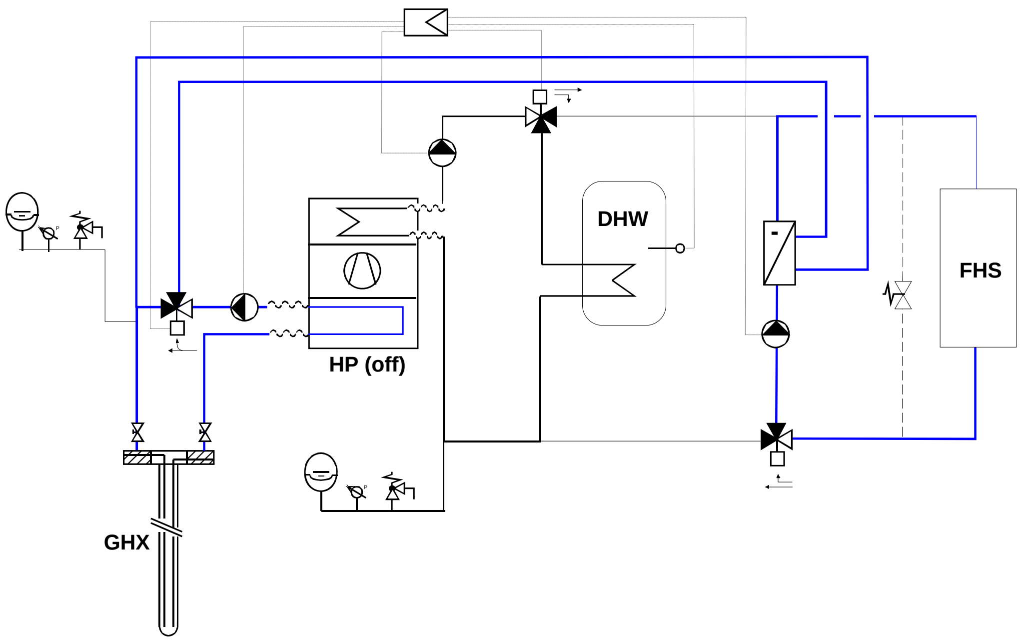

Figure 3 Hydraulic system in passive cooling mode

MODELLING

Simulation Tool

In passive cooling mode the floor heating circuit and the ground heat exchanger are connected via heat exchanger. All elements in the circuit except the circulating pump are passive elements. Thus the reaction of the floor heating system to the room behavior influences the situation in the ground heat exchanger and vice versa. Floor heating and ground heat exchanger have in passive cooling mode a strong interdependence.

The research in the described project thus requires a mathematical tool with which the interactions of the building structure and the mechanical systems can be represented in a sufficient time dynamic range. Separated simulations of building and technical system could show the limits of application and thus basic design criteria, but lack of answers to questions concerning dynamic interactive behavior.

Actually only few simulation tools have the ability to perform simultaneous simulation of building and mechanical system as well as provide the possibility to implement control strategies in an applicable way. One is the CARNOT-toolset (Anon. B) based on Matlab/Simulink which comprises a building model and thermo hydraulic elements.

Simulation Models

The multi zone building model used within the research project consists of one - dimensional multilayer walls, windows and a two node room model. The two node room model separates radiative heat exchange and the state of the room air considering temperature, air humidity and CO_2-content. These elements are commonly used models in advanced building simulation tools.

Since the aim is to evaluate the interaction between building and mechanical system, the coupling element floor heating system is a central element. Koschenz and Lehmann (2000) describe a model for thermo active building elements that can also be employed for floor heating systems within the model boundaries. The three-dimensional heat conduction in reality is represented in the model as one-dimensional heat transfer from the pipe to the layer inside the wall model. Therein the heat transfer resistances between heat carrier and the wall layer, comprising heat transfer resistance along pipe length, heat transfer to pipe wall, heat conduction through pipe wall and heat conduction resistance due to pipe arrangement, are aggregated to one representing resistance as shown in Figure 4. The described model is implemented for the simulation study.

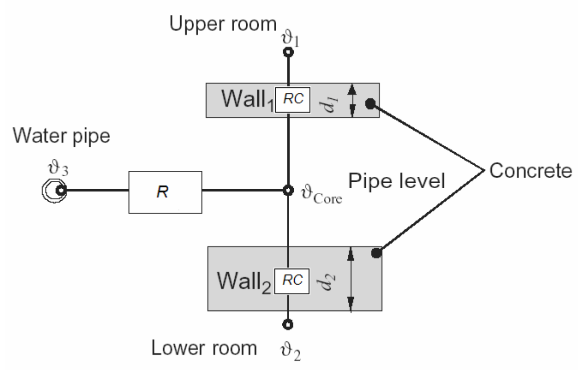

Figure 4 One-dimensional model for floor heating system

The input for the floor heating system in passive cooling mode is equivalent to the outlet of the borehole heat exchanger. Therefore the precise outlet temperature of the borehole heat exchanger has a crucial influence on the cooling capacity of the passive cooling system. Huber and Schuler (1997) describe a model for borehole heat exchanger that has been frequently used and validated in research projects and practical application. The model was implemented at another research institute and has been applied in this project. The model computes the behavior of the geothermal heat exchanger and the ground in the local area as shown in Figure 5. The ground module and the brine module are evaluated separately and coupled with the consideration of the boundary conditions.

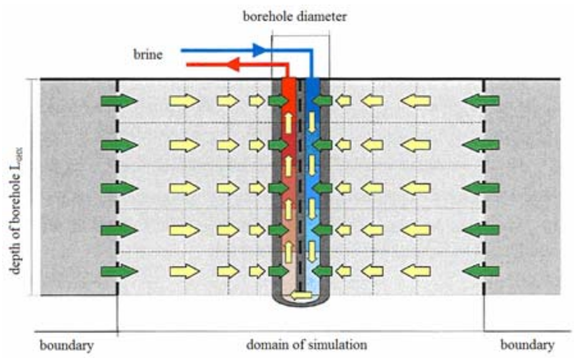

Figure 5 Model scheme for borehole heat exchanger

The hydraulic system in between the ground heat exchanger and the floor heating system has the functionality to connect the two systems and to implement the control functions.

The building model is divided into four thermal zones that represent the parts of the building with similar load characteristics. With it a sufficient precision could be achieved on the one hand for thermal comfort evaluation and on the other hand for the dynamic behavior of the return flow temperature of the floor heating system.

SIMULATION RESULTS

Simulation Study Variants

As reference for the studies the building model called VAR1 was set up in accordance with the results from Swiss standard calculation. The shading at room temperatures above 23 °C was set to 50%.

VAR2 describes an additional passive air cooling where in simulation the air change rate was raised to 1/h when the outside air provides a cooling potential of at least 2 K with room temperatures above 23 °C.

VAR3 is the first simulation variant with floor cooling. Therefore VAR2 was extended with a passive cooling function where at outside air temperatures above 20 °C in 3h average the floor cooling runs controlled via the cooling curve for the floor return flow temperature. Switchover between heating and cooling is automated according to the room and outside air conditions with a dead time between heating and cooling of twelve hours.

As one aim was to prove the cooling capacity of a borehole heat exchanger in VAR4 the shading was reduced from 50% to 25%.

Energetic Results of Building Simulation

Table 1 indicates for VAR1 a thermal heating energy need of 154 MJ/m^2a which meets the result of the standard calculation of 157 MJ/m^2a. The additional passive air cooling in VAR2 yields in a higher heating energy need of 177 MJ/m^2a because of less used heat gains. The additional passive ground cooling VAR3 does not raise the heating energy demand. A dead time of twelve hours between heating and cooling mode in VAR3 is sufficient to avoid intermittent heating and cooling of the floor thermal capacity and with that additional heating energy demand especially in spring and autumn. The passive ground cooling function has minor influence on the performance of the heat pump in heating mode expressed in the SPF_H evaluated for the 3rd year of operation.

Table 1 Energetic result for heating season

	Q_H	E_H	SPF_H
	MJ/m^2a	MJ/m^2a	-/-
VAR1	154	39	3.9
VAR2	177	43	4.1
VAR3	179	43	4.2
VAR4	166	40	4.2

Table 2 depicts the thermal cooling energy need of VAR3 with 45 MJ/m^2a and of VAR4 with 70 MJ/m^2a. The corresponding electrical energy demand is with 3 MJ/m^2a identical for VAR3 and VAR4. Therein a calculated power consumption of constant 140 Watt for the circulating pumps in the ground circuit and the floor heating circuit generate a changing cooling power depending on the situation in the floor and in the ground. The efficiency of the cooling process given as SPF_C show values of 17.2 and 24.5.

Table 2 Energetic results for cooling season

	Q_{PGC}	E_{PGC}	SPF_{PGC}
	MJ/m^2a	MJ/m^2a	-/-
VAR1	0	0	0.0
VAR2	0	0	0.0
VAR3	45	3	17.2
VAR4	70	3	24.5

Comfort Results of Building Simulation

The influence of the passive cooling function on room temperature is shown in Table 3. The average room temperature in cooling season in VAR1 with 29.3 °C decreases to 26.5 °C with a passive air cooling function and to 24.4 and 25.7 °C with passive ground cooling. Overheating, defined as cumulated room temperature hours in summertime over the maximum room temperature according to SIA Standard (SIA 1992), is avoided as shown in VAR3 and VAR4. Even a high cooling energy need because of reduced shading could be covered by the passive ground cooling.

Table 3 Comfort results

	max. room temp.	over-heating	average room temp. winter	average room temp. summer
	°C	Kh	°C	°C
VAR1	34.7	4398	22.4	29.3
VAR2	32.4	626	22.2	26.5
VAR3	28.6	3	22.1	24.4
VAR4	31.5	81	22.3	25.7

Energetic Results of Ground Heat Exchanger Simulation

In the simulations the GHX in passive cooling mode covers the calculated cooling energy need up to 94%. A crucial influence on the fraction of cooling need covered by the GHX has the design of the frequently used heat exchanger between the ground circuit and the floor circuit. Because the cooling power depends directly on the output temperature of the GHX, main challenge is to carry this temperature to the input of the floor system. A rise in the temperature difference in the heat exchanger from 1K to 3K lowers the covered fraction of cooling need from 94% to 66%. The specific cooling capacity per meter borehole heat exchanger ranges between 26 W/m and 40 W/m for a heat exchanger with 1K temperature difference.

SIMULTANEOUS SIMULATION

A simultaneous simulation of building and mechanical system covers the potential to answer questions concerning time dynamic behavior or control strategy of coupled systems. The authors succeeded in building up such a simultaneous simulation for the described system of a floor heating system coupled with a borehole heat exchanger in passive cooling mode.

Figure 6 and Figure 7 show hourly values of the resulting temperatures in the building for the room and the floor surface with the reference of outside air temperature and global solar radiation as primary thermal loads. The room temperature ranges for summer and winter days between 21 °C and 24 °C. The floor surface temperature shows only a small difference to the room temperature though the floor is used as heating and cooling system. The design as low temperature system is reflected in this behavior. Figure 7 additionally illustrates the cooling effect with floor temperatures below the room temperature. Absorption of direct radiation to the floor causes a higher cooling capacity than the temperature difference between floor and room seem to show.

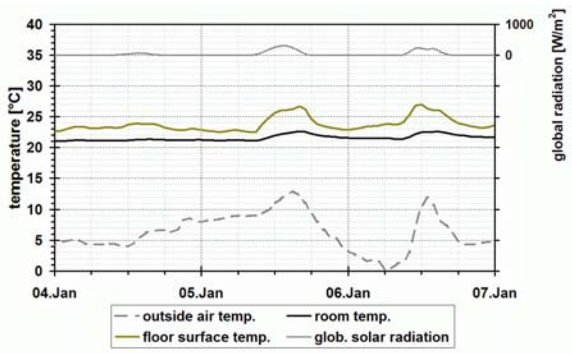

Figure 6 Comfort in winter days

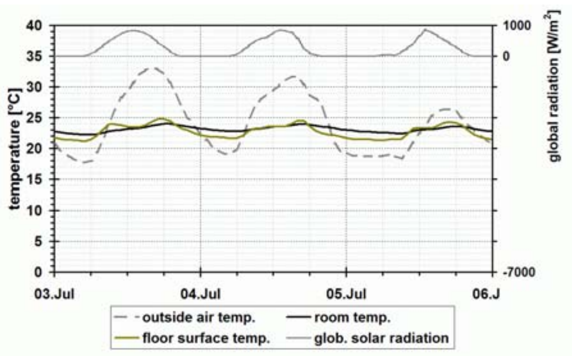

Figure 7 Comfort in summer days

Figure 8 and Figure 9 show hourly values the heating respectively cooling power need and corresponding temperatures in the floor heating system for typical winter and summer days. The maximum heat capacity is given from the chosen heat pump with about 6 kW for winter conditions. The cooling capacity of the GHX in summer time shows the typical behavior for passive cooling mode. In a short time of about 1-2 hours after activating the passive cooling operation a peak cooling capacity of about 6 kW could be noticed (see end of 3.Jul in Figure 9). Later on the cooling capacity ranges significantly smaller around 2.5 kW depending on the room conditions. The depicted COP PGC shows a strong influence on the cooling power. This is obvious due to the fact that the energy use for the circulating pump is constant but the gained cooling capacity has a strong dependence on the temperature conditions in the room and in the ground.

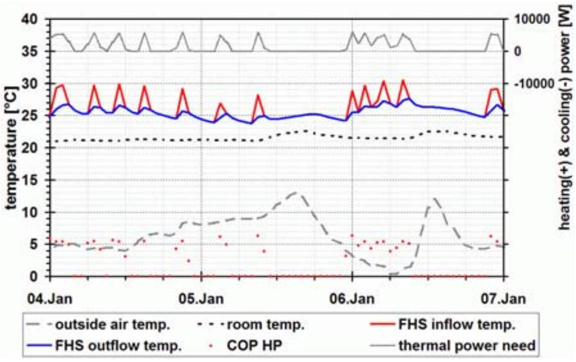

Figure 8 Energy in winter days

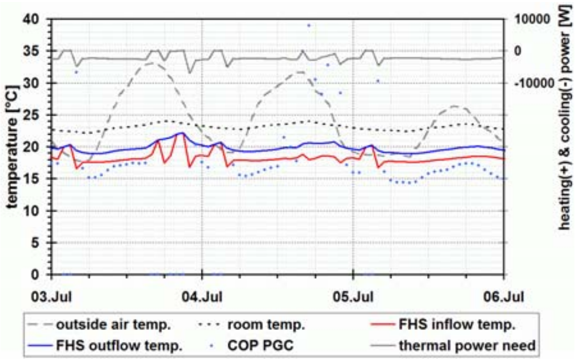

Figure 9 Energy in summer days

Comparison of separate and simultaneous simulation results

A comparison between the separate simulation of building and mechanical system and the simultaneous simulation is shown in Figure 10 and Figure 11 on the one hand for the thermal power extracted from the GHX and on the other hand for the output temperature of the GHX. The dashed lines in the figures show the results of the separate simulation, the continuous lines the results of the simultaneous simulation.

In Figure 10 both curves for thermal power extraction and output temperature of the GHX show a significant deviation. This is in times of system operation caused by a different control strategy where heating power is modulated continuously in the separate simulation and is on-off controlled in the simultaneous simulation. The remaining deviation during switch-off periods is assumed to be caused by modeling with a constant mass flow inside the borehole heat exchanger.

For the passive cooling operation during summer time shown in Figure 11 the deviation between separate and simultaneous simulation results are negligible except the dynamic at switch-on or switch-off events. There the simultaneous simulation shows a higher dynamic interaction between floor and ground which is its main advantage.

CONCLUSION

A passive cooling option is a powerful and efficient extension for classical ground coupled space heating heat pumps used in dwellings. The performance of such systems strongly recommends a design of the twofold used heat emission system and the hydraulic coupling between floor and ground that allows the use of heat and/or cooling sources with small temperature differences to the room temperature.

Simultaneous simulation of building and mechanical system has been accomplished in project work as shown in this paper. The application is up to now limited to special research tasks on the one hand due the high effort that has to be made to get a simulation model with sufficient precision in all required physical domains and on the other hand due to the high computation power needed for such simulations.

DISCUSSION

The described project work is focused on one family houses or small multi-family buildings. Therefore a transfer to other building types has at least to be discussed based on the described assumptions.

System design is based on the function as pure heating system and focused on the additional use of a cooling option with small additional expense. According to the boundary conditions of individual objects an optimization for combined heating and cooling usage may be reasonable.

The presumed cooling load in this study is deliberately high due to solar gains for the reason of performance examination. A comparison to simulation results considering estimated weather data for the year 2050 show similar results even with enhanced external shading.

Not all used models have up to now been thoroughly validated. The results of the simultaneous simulation still show small deviations for certain situations.

NOMENCLATURE

Q_H	thermal heating energy need
SPF_H	system seasonal performance factor for heating
E_H	electrical heating energy use of heat pump
Q_{PGC}	thermal cooling energy need for passive ground cooling
SPF_{PGC}	system seasonal performance factor for passive ground cooling
E_{PGC}	electrical cooling energy use of passive ground cooling system
GHX	Ground Heat eXchanger
FHS	Floor Heating System
DHW	Domestic Hot Water
COP	Coefficient Of Performance
HP	Heat Pump
PGC	Passive Ground Cooling
EWS	Software called EWS for thermal simulation of borehole heat exchanger (Anon. C)

ACKNOWLEDGMENT

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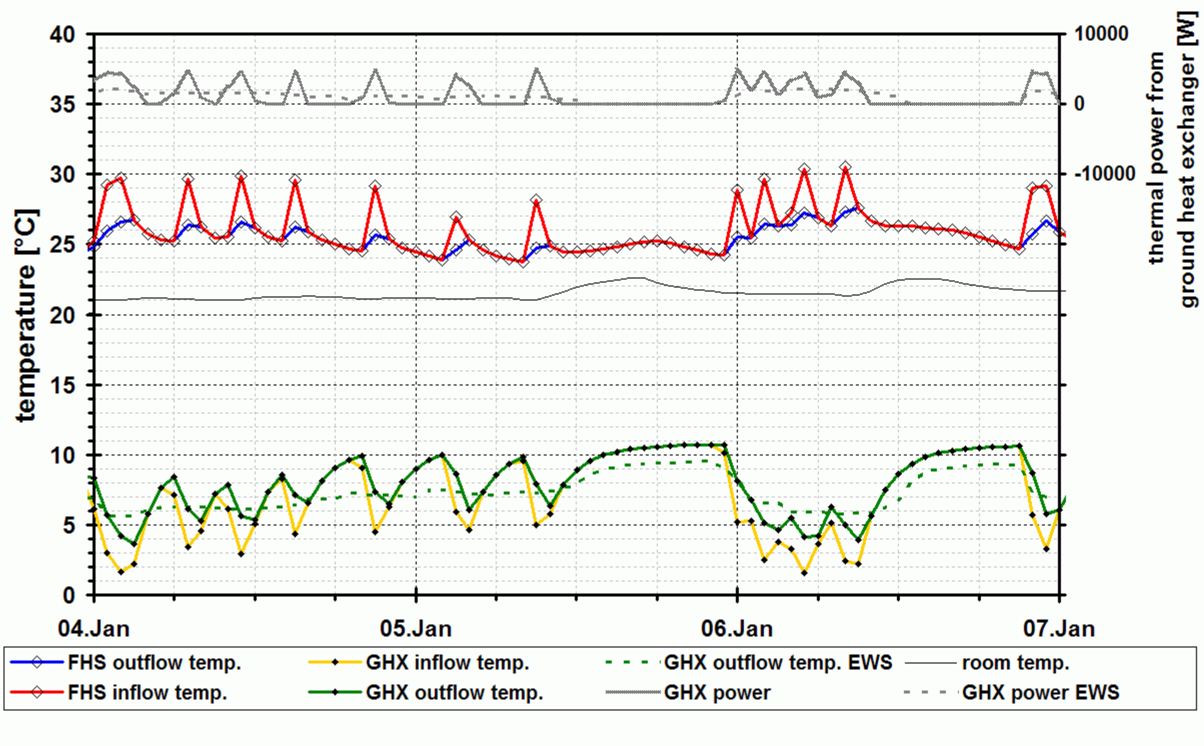

Figure 10 Comparison of separate and simultaneous simulation for floor and ground behavior in winter

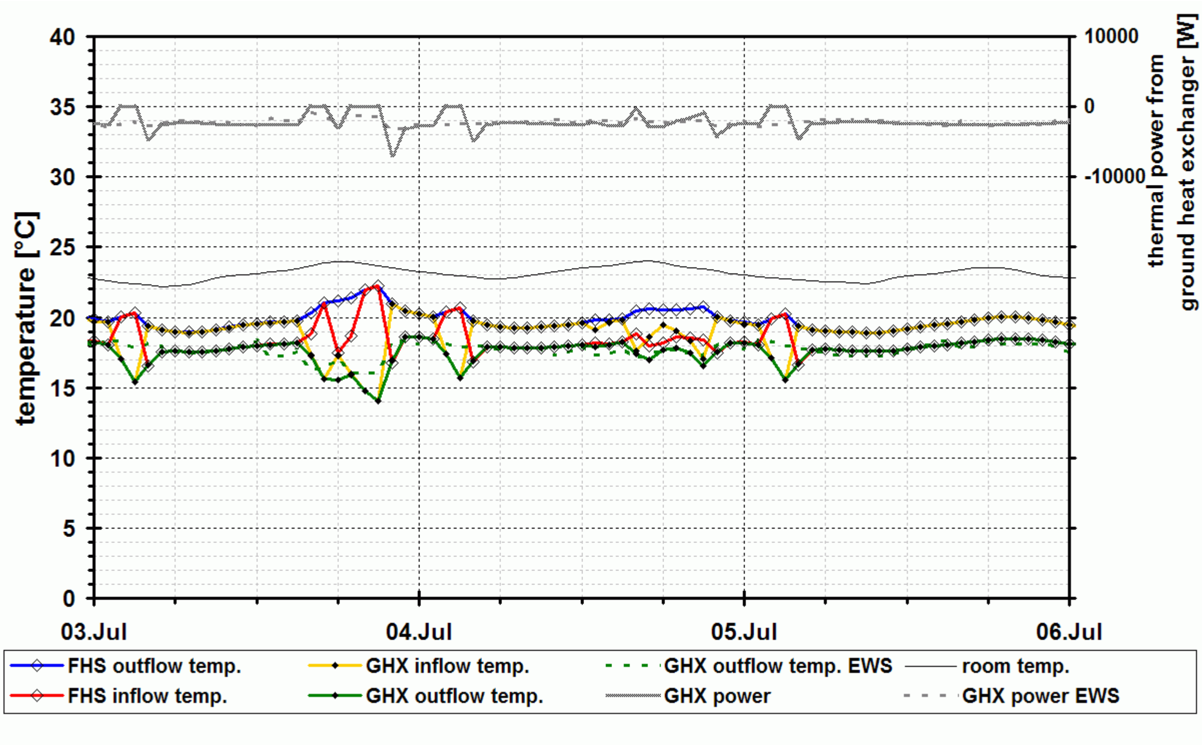

Figure 11 Comparison of separate and simultaneous simulation for floor and ground behavior in summer