GENERIC SYSTEM SOLUTIONS FOR HEATING AND COOLING OF RESIDENTIAL DWELLING

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Abstract: The energy demand for heating is decreasing significantly in modern highly-insulated dwellings. In a research project several heating and cooling variants with ground-coupled heat pumps, passive cooling with borehole heat exchanger and cooling by night-time ventilation have been evaluated.
A parametric study with MATLAB/Simulink simulations using a residential low-energy building has been carried out with the objective to estimate energy demand for heating and cooling versus thermal comfort and economical feasibility of the overall system.
Beside the most suitable hydraulic scheme the appropriate control providing an optimal thermal comfort with a minimum of additional energy in comparison to heating-only had to be optimised to avoid intermittent heating and cooling in autumn and spring yielding an increase in heating energy demand, since the cooled concrete structure has to be heated-up again, if space heating is required.
As a result of the simulations a proven hydraulic scheme, smart control strategies and guidelines for system design could be derived. The project is a national contribution to IEA HPP Annex 32 on economical heating and cooling systems of low energy houses.

Key Words: ***heat pump, heating and cooling, hydraulics, control***

1 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 is 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.
To proove the system in practice, a field test with a ultra-low energy multi-family residential building started in fall 2007.

2 SITUATION

2.1 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, either 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 lift in the heat pump with smaller differences between the heat medium and the room.
- Applied for cooling the system with smaller temperature difference between the heat medium 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.

2.2 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.

2.3 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 (MINERGIE 2008).

Figure 1: Reference building for simulation (Architect: Bircher+Keller AG)

The building shown in Figure 1 is characterized by:

- One-family house according to MINERGIE® requirements in Gelterkinden (canton Basel-Landschaft, CH) at south oriented hillside situation with solid construction walls and laterally placed basement outside insulation perimeter
- Energy reference area 153 m^2 (net living space area 125 m^2, net volume 305 m^3)
- Hydraulic floor heating system and mechanical air ventilation with heat recovery
- Specific heating energy need per energy reference area acc. to Swiss standard (SIA 380/1 2001) = 157 MJ/m^2a
  Remark: In the meantime (SIA 380/1 2001) has been replaced by (SIA 380/1 2007)
- Heating power demand acc. to Swiss standard (SIA 384/2 1995) = 4.1 kW (20°C/-8°C)
  Remark: Standard (SIA 384/2 1995) has been replaced by (SIA 384.201 2005)

3 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.
A simple and common heat pump based hydraulic configuration for heating, cooling and domestic hot water generation is shown in Figure 2. The room can be chilled by the floor heating system. The heat is transferred from the floor hydraulic circuit via heat exchanger to the ground heat exchanger circuit and emitted to the ground.
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 pre-

vention 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.

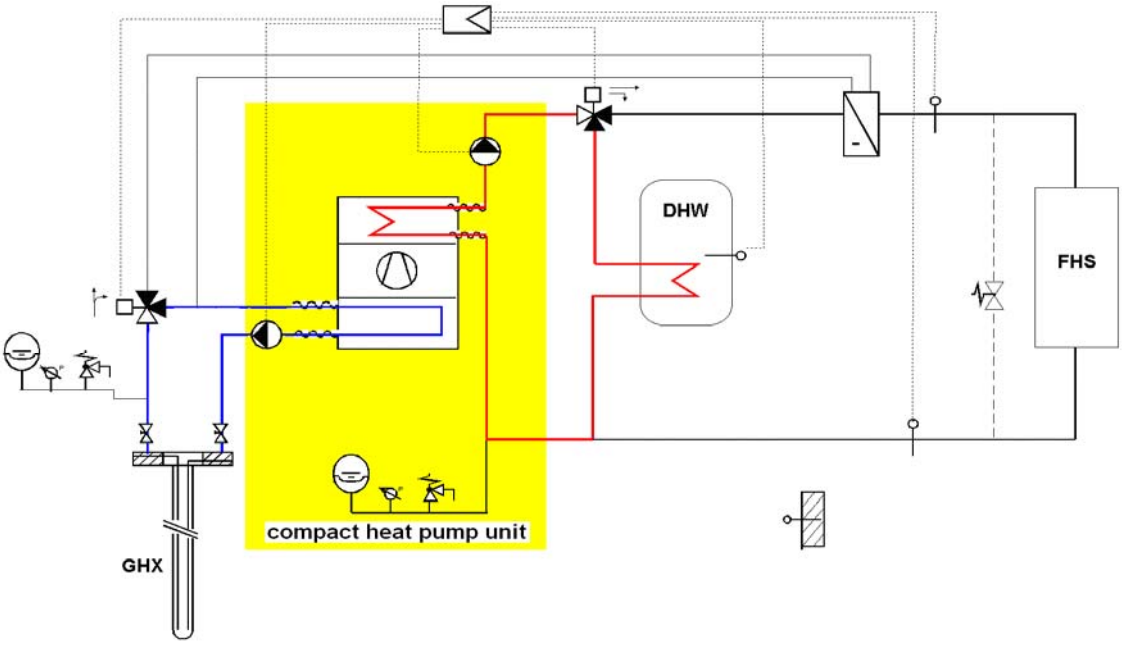

Figure 2: Hydraulic system for heating (FHS), domestic hot water (DHW) or passive cooling with ground heat exchanger (GHX)

4 SIMULATION AND MODELLING

4.1 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 behaviour 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 which represents the interactions of the building structure and the mechanical system 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 behaviour.

Actually only few simulation tools have the ability to perform 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 (CARNOT 2002), based on (Matlab/Simulink 2008), which comprises a building model and thermo hydraulic elements.

4.2 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 irradiative 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 (R) between heat medium 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 3. The described model is implemented for the simulation study.

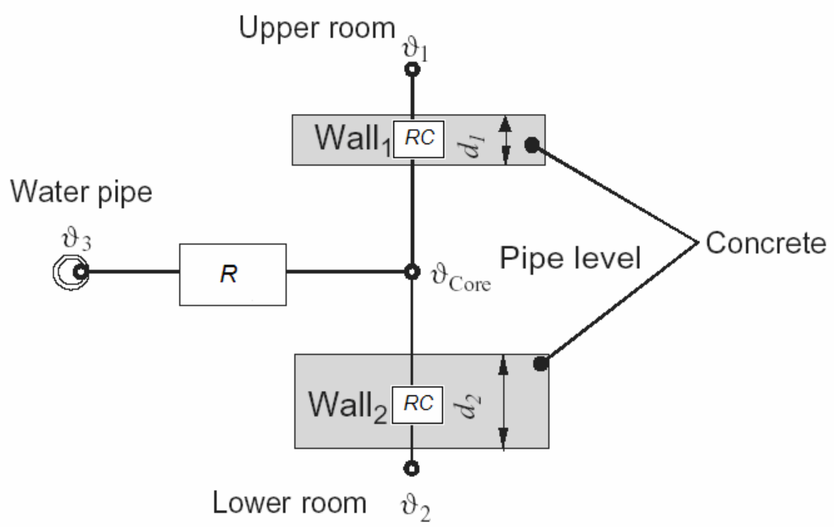

Figure 3: One-dimensional model for floor heating system

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 behaviour of the geothermal heat exchanger and the ground in the local area as shown in Figure 4. The ground module and the brine module are evaluated separately and coupled with the consideration of the boundary conditions.

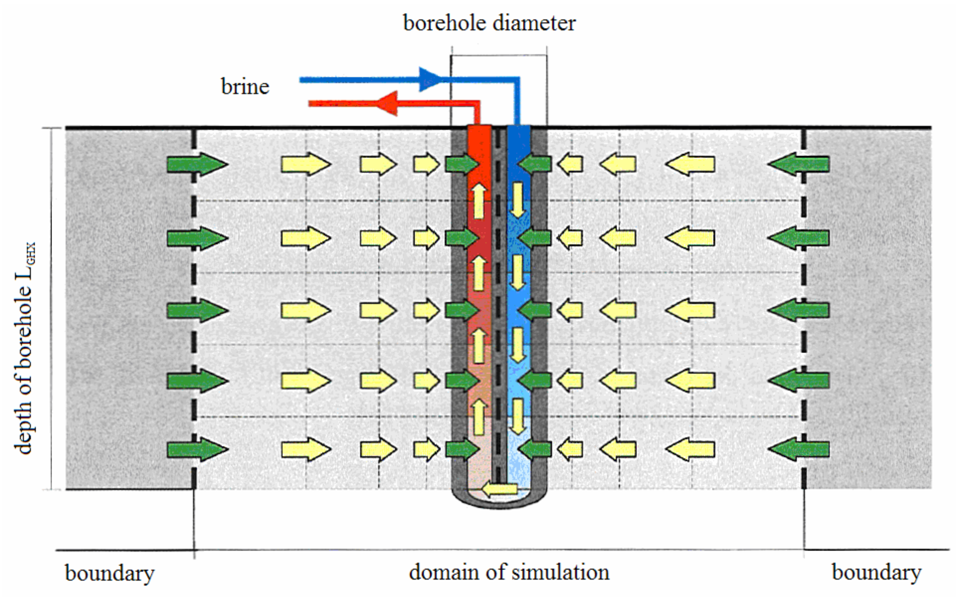

Figure 4: Model scheme for borehole heat exchanger

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 behaviour of the return flow temperature of the floor heating system.

5 SIMULATION RESULTS

5.1 Simulation Study Variants

As reference for the studies the building model called VAR1 was set up in accordance with the results from Swiss standard calculations (SIA 384/2 1995) and (SIA 380/1 2001). 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^{-1} 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.
To prove the cooling capacity of the borehole heat exchanger, the shading was reduced from 50% to 25% in VAR4.

5.2 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 very closely. 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

5.3 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 Swiss standard (SIA V382/2 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

5.4 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.

6 FIELD MEASUREMENTS COSYPLACE

The demonstration of the system performance in a field test is very important for a broad dissemination. In the city of Basel a multi-family residential building has been erected in 2007. It is certified as ultra-low energy dwelling according the Swiss MINERGIE-P® label (MINERGIE 2008). The building is equipped with a ground coupled heat pump with vertical borehole heat exchanger, a hydraulic floor emission system for heating and cooling, a mechanical air ventilation system with ground heat collector and heat recovery (s. Figure 5).

Figure 5: Multi-family ultra-low energy building in the city of Basel (www.cosyplace.ch)

Main features of the building shown in Figure 5 are:

- Multi-family residential building with 5 apartments with solid construction walls at north oriented situation 300 m above sea level.
- 3 stories with additional attic and underground parking lot
- Hydraulic floor heating and passive ground coupled cooling system
- Mechanical air ventilation with heat recovery (air change 0.4 h^{-1})
- Energy reference area 1’064 m^2 (net living space area 741 m^2, air volume 1’890 m^3)
- Specific heating energy acc. Swiss standard SIA 380/1 = 36 MJ/m^2a
- Heating power demand acc. Swiss standard SIA 384.201 = 11.8 kW
- Supply and return temperatures at outside air temperature of -8°C are 30/25 °C

A pilot and demonstration project, funded by the Swiss Federal Office of Energy, has been launched to get more knowledge in this field. The main questions to be answered are:

- Which temperatures and humidities can be maintained to reach comfortable conditions?
- How much heat is generated, how much is used in the individual living spaces?
- How much heat has to be provided for domestic hot water?
- How much heat can be extracted for cooling?
- How is electricity demand allocated to space heating, cooling and domestic hot water?
- How efficient is the system during heating, cooling and domestic hot water operation?
- Are the users satisfied?

In Figure 6 the hydraulic scheme of the installation and the sensors are depicted. Data are logged every 15 minutes.

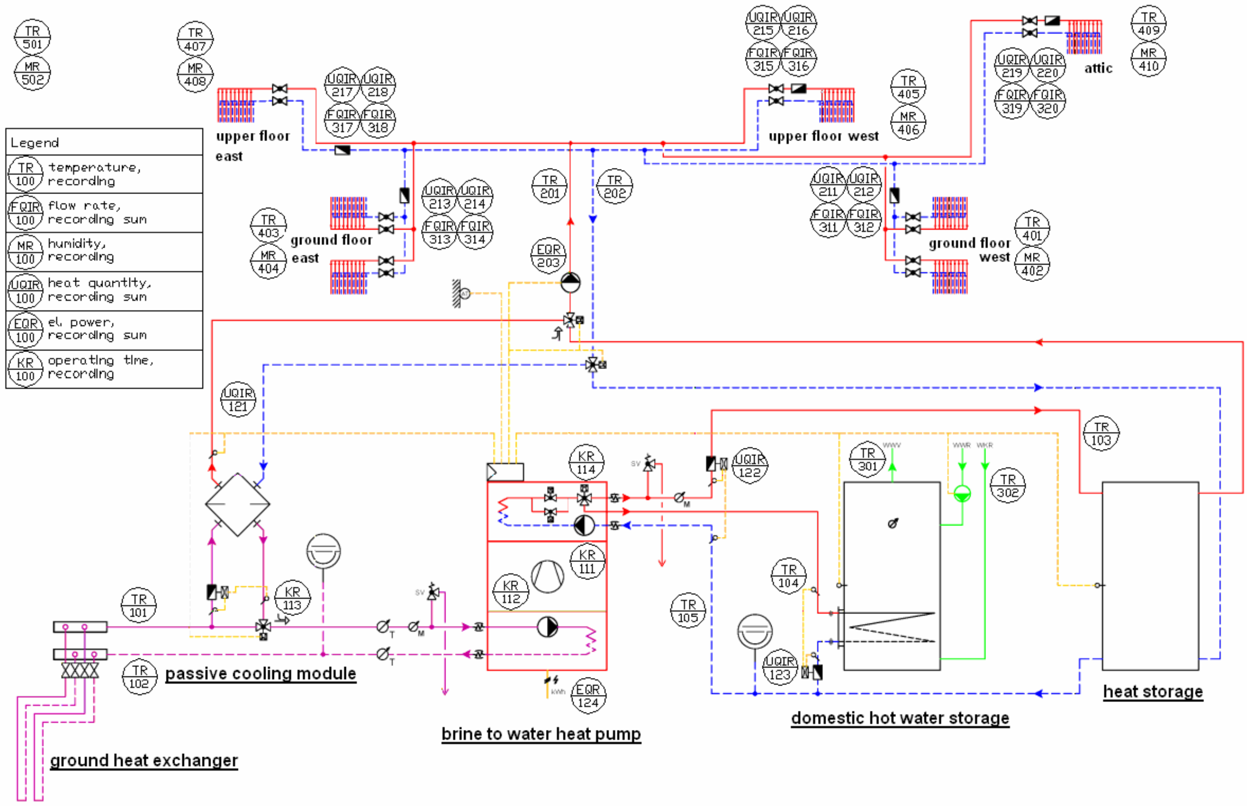

Figure 6: Scheme of the installation for heating, cooling and domestic hot water

Measurements during the period 1. November 2007 until 31. January 2008 show the following preliminary results:

- Heat generated with heat pump (HP) for space heating only is 18'449 kWh or 62 MJ/m^{2}a (see Figure 7, left). This is a comparatively high value, attributed to the initial dry-out of the building and special user behaviour, since not all apartments have been occupied.
- Space heating with the heat pump including control and auxiliaries counts for 73% of electricity, domestic hot water with the heat pump for 16% and circulation pumps for 11% (see Figure 7, right)

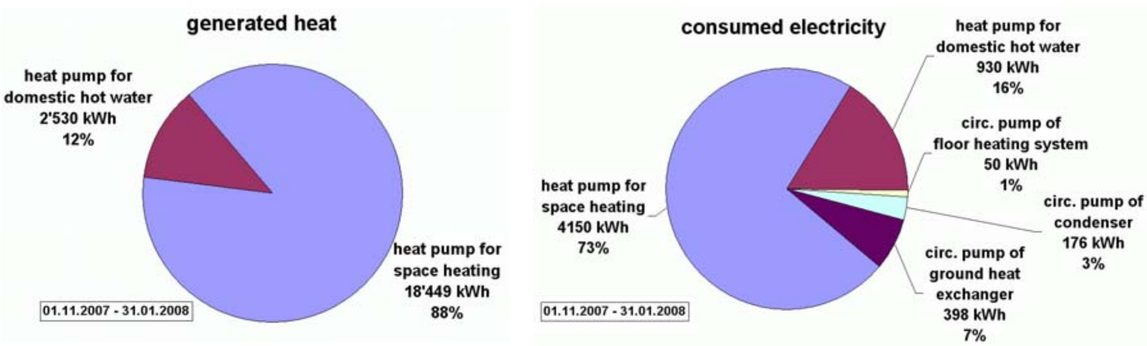

Figure 7: Measured heat and electricity allocation for space heating and domestic hot water

Room temperature in the ground floor apartment varies between 15 °C and 21 °C with a frequency of over 60% in a range from 19 °C to 21 °C. Temperatures in the upper floors are higher, especially in the attic, where almost 90% of time a temperature of 23 °C could be maintained (see Figure 8).

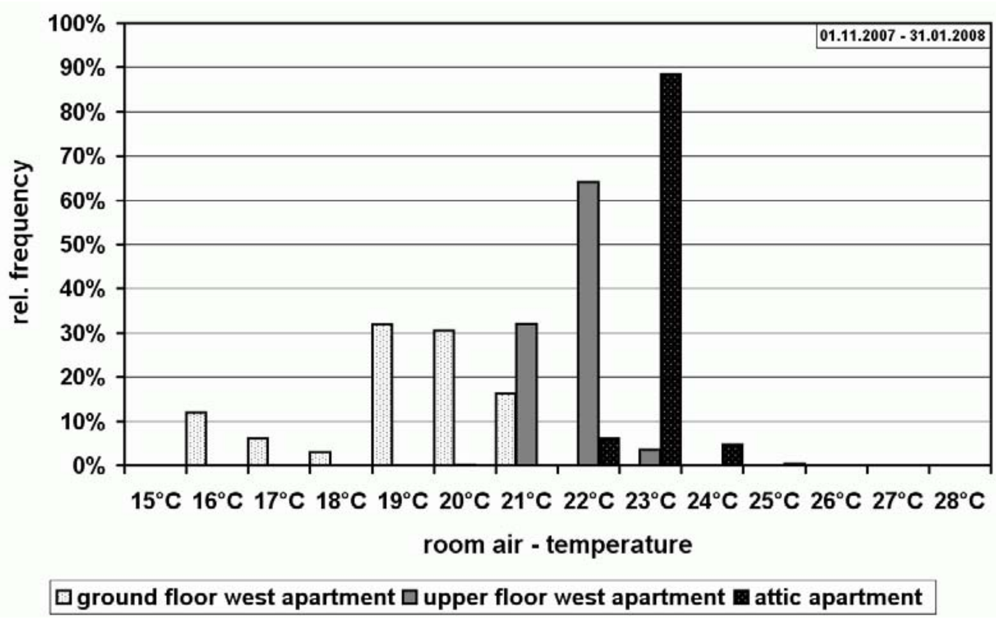

Figure 8: Relative frequency of room air temperatures in different stories

In Figure 9 the weekly performance factors WPF are depicted for heating (h), domestic hot water (ww) and both (hww). The WPF is the ratio between produced heat and consumed energy during a week. Since no direct electric heaters are installed, the WPF is the characteristic value for heat pump efficiency. At outside air temperatures varying from -6 °C to 13 °C a WPF of up to 4.3 can be achieved for space heating and around 2.5 for domestic hot water.

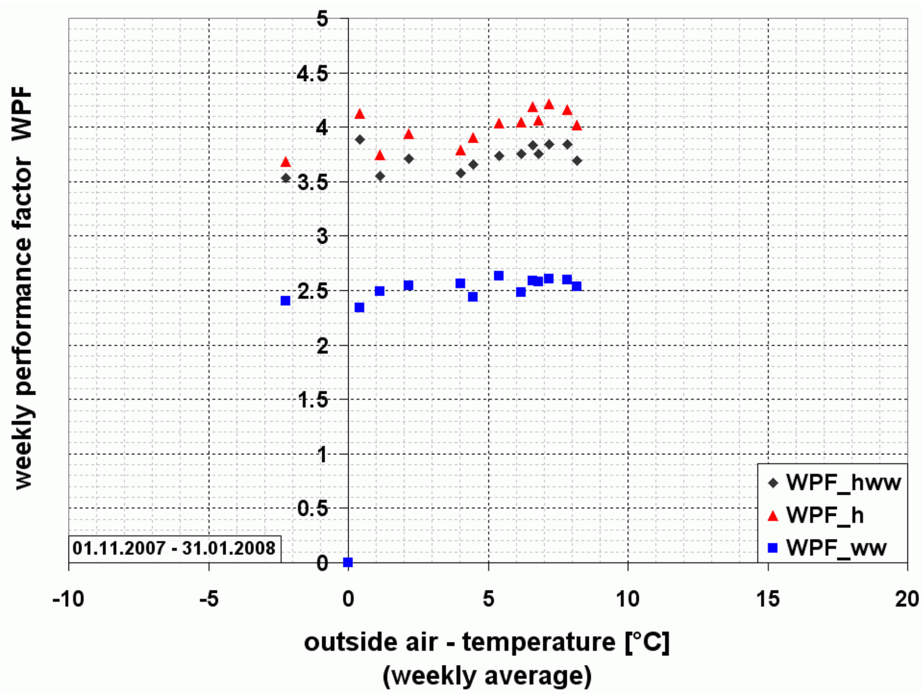

Figure 9: Weekly performance factors of the generation system for different operation modes

7 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.
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.
Preliminary measurements of a multi-family ultra-low energy dwelling show good results for the heating period 2007/2008. The behaviour in cooling mode has to be proven in the upcoming summer period.

8 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.

9 ACKNOWLEDGEMENT

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