IEA HPP ANNEX 32 – RESEARCH FOR HEAT PUMPS IN LOW ENERGY HOUSES

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Abstract

Low energy houses are seen as a key technology for the reduction of CO_2-emissions and have growing market shares in many countries. Residential heat pumps have increasing market shares in new buildings, as well, particularly in low energy buildings. However, there are still development potentials for existing system solutions in terms of component and system performance as well as system integration and functionality. IEA HPP Annex 32 is to accomplish research to explore the promising market of heat pump solutions for low energy houses. This paper gives an introduction to the Annex 32 framework of objecttives, project structures and national contributions. First results of the Swiss national project, which is dedicated to the integration of passive and active cooling functions, yielded a standardised hydronic configuration of ground-coupled heat pumps for space heating, -cooling and domestic hot water, which simplifies the variety of marketable configurations. Design guidelines for the dimensioning of the components and the control have been derived by various simulation studies. Design of the borehole heat exchanger for space heating is sufficient to cover most of the cooling load in passive cooling. Moreover, the reachable comfort and additional costs of the system solution have been evaluated. Even under extreme summer conditions the indoor air temperatures can be kept below 28°C by a combination of shading, passive ground cooling and night-time ventilation.

Introduction

Since the mid of the 90ties, the energy consumptions of buildings were lowered successively by introducing more stringent legal requirements for the space heating consumption in building directives. This led to the development of buildings with significantly reduced space heating needs down to about 15 $kWh/(m^2 \cdot a)$ in German passive houses (http://www.passiv.de). In these houses, the domestic hot water (DHW) requirement can reach up to half of the total heat energy requirement.

Buildings

In order to achieve such low heat requirements basically two directions exist: On the one hand, the thermal insulation of the building is highly increased up to a thickness of 40 cm with conventional thermal insulation materials (at a thermal conductivity of the materials of less than 0.04 $W/(m \cdot K)$). On the other hand, larger south-oriented high-quality glazing is integrated in the façade in order to maximise the passive solar gains. Most buildings are a mixture of the two directions. In order to reduce the ventilation losses, air tightness of the buildings is approved by blower door testing (typical n_{50} value of 0.5) and the necessary hygienic air exchange rate is guaranteed by a mechanical ventilation system with heat recovery at a temperature change coefficient of typically 0.8 and better. For the comfort in summertime, adequate sun protection measures and a reduction of internal thermal gains are required. However, due to growing glazing fractions and higher comfort demands, comfort cooling and air conditioning become more and more an issue not only in commercial but also in residential dwellings.

In some central European countries the markets for low energy houses are already in the growth phase. For instance in Switzerland, already about 30% of all new buildings comply with the requirement of the voluntary building label MINERGIE® (http://www.minergie.ch) which defines a good low energy house, half of these are actually certified according to this label (~8000 installed dwellings). Ultra-low energy houses according to the MINERGIE-P® standard and retrofitting to the MINERGIE®-standard are still a niche market. In Germany, about 15000 ultra low energy houses exist , which comprise 5000 passive houses (Space heating requirement < 15 kWh/(m^2·a)) and 10000 KfW40 houses (http://www.kfw.de) with the requirement of a primary energy consumption for space heating and DHW < 40 kWh/(m^2·a). Moreover, about 40000 low energy houses according to the KfW60 requirements (primary energy consumption for space heating and DHW < 60 kWh/(m^2·a)) have been built since the beginning of the millennium. In Norway a growth from 2000 low and ultra low energy houses in 2006 to 10000 in 2007 took place. In Austria the number of built residential passive houses is about 1800. Other European countries like the Netherlands and Sweden are still in the market introduction phase.

Systems in low energy houses

Due to the requirements of the MINERGIE® standard, about 75% of the installed systems for space heating and DHW are heat pumps, wood or solar thermal (for DHW). In Switzerland heat pumps established as the standard heating system for new buildings with a market share in single family houses of about 70% in 2006.
Germany, Austria and Norway show growing heat pump markets, as well. Sweden has the largest heat pump market in Europe both in new buildings and in retrofitting.

In Germany, so-called compact ventilation systems with exhaust-air heat pump were introduced into the market for passive houses and have a large market share in single family passive dwellings. The technology is currently extended for the application in multi-family houses. The principle layout of the units is given in Figure 1. The core components of these systems are a heat pump and a DHW storage. The heat pump is connected to the exhaust air duct of the ventilation system and extracts further heat after the heat recovery and is used either to reheat the preheated air exiting the heat recovery unit or for hydronic heating. Moreover, DHW is produced by the heat pump, mostly in alternate operation, e.g. the space heating operation is interrupted while the heat pump reheats the integrated DHW tank. Optionally, this system configuration is extended by a ground-to-air heat exchanger, which mainly serves to prevent a frosting of the heat recovery unit. On the other hand, it can be used for pre-cooling in summer, as well. An additional solar collector is mainly used to support DHW production, even though some system configurations would also allow a solar contribution to the space heating.

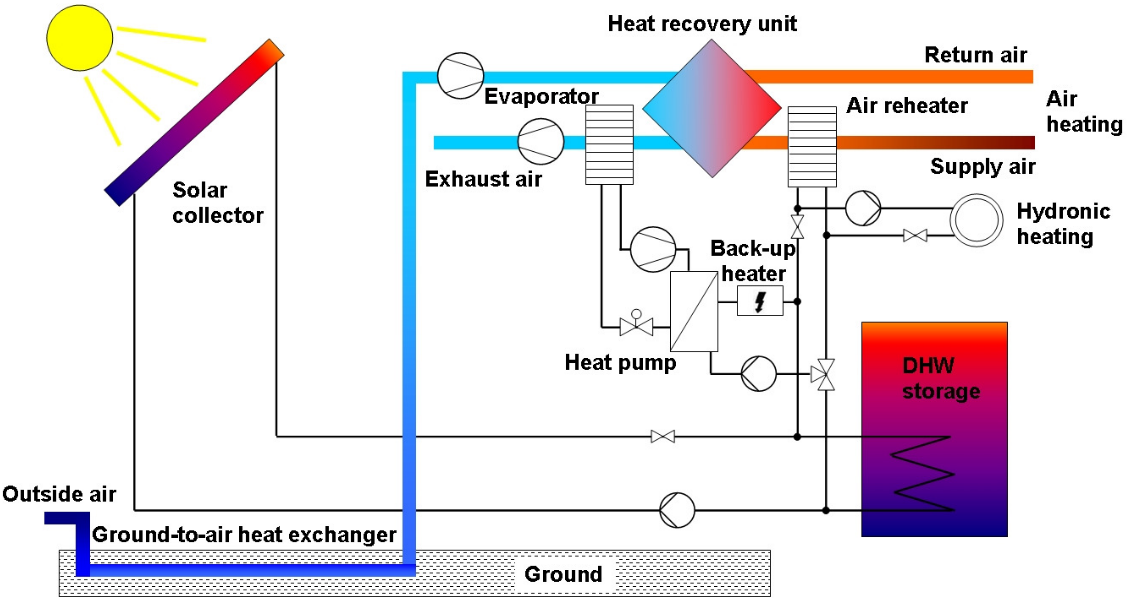

Figure 1 **Layout of ventilation compact units with exhaust air heat pump**

However, despite of the fact that in many countries low energy houses are now a growing market, in most countries the adequate system technologies for the building services space heating, -cooling, DHW and ventilation are missing, since research has mainly concentrated on the buildings. This is related to the adequate capacity range of the system, but also to system performance and costs. On the other hand, the system integration of new functions like space cooling and dehumidification would be favourable for the markets. Hydronic simplifications and standard system layouts as well as control are a further issue.

Moreover, countries which do not have adequate systems on the market wonder about the system performance of already existing systems in central Europe under different boundary conditions e.g. in cold Nordic climate. The main motivation of the participants in IEA HPP Annex 32 is therefore:

- On the national market no particular system solutions for the low energy house market are available, yet, so systems shall be developed or accustomed to the country's specific boundary conditions.
- Systems are already available on the national markets, which, however, have still optimisation potentials or whose functionality shall be extended.
- Due to the relatively short time on the market, there is not much experience with the marketable systems or with new developments. National projects comprise field tests in order to approve feasible operations and identify optimisation potentials.

Research in IEA HPP Annex 32

Annex 32 in the Heat pump Program (HPP) of the International Energy Agency (IEA) entitled "Economical heating and cooling systems for low energy houses" started in 2006 with the participating countries AT, CA, CH (operating agent), DE, JP, NL, NO, SE and the USA in order to support the further development of heat pump systems for the use in low energy buildings and to prove the feasibility of new developments.

Objectives of IEA HPP Annex 32

The objectives of the IEA HPP Annex 32 comprise different levels:

- On the component level, adequate component performance including the auxiliaries and an adequate capacity range of the components for the application of low energy houses shall be derived by new developments or by a redesign.
- The system level comprises the system integration, e.g. a simplification of the hydronic layout, and an integration of new functionalities, e.g. space cooling or de-/humidification. This shall lead to recommended standardised system layouts. Moreover, new system configurations are assessed by simulations or tested as prototypes.
- Field testing will deliver the performance of the system solutions. Field test is related both to marketable systems as well as to new developments. Moreover, adequate instrumentation and systematic energy balancing shall be evaluated, which is suitable for further operation control.

Project structure

National projects are mainly dedicated to the components and system development of integrated heat pump systems of adequate capacity range and evaluation of the real-world operation by lab- and field testing. On the one hand the basis are marketable systems, which are redesigned and extended to further functionalities and on the other hand new developments regarding the refrigerant, the cycle configuration or the heat sources. New concepts, design guidelines and field proven best practice systems are the objective of this research work. IEA HPP Annex 32 is structured in the following 4 Tasks:

Task 1: State-of-the-Art

This task is the basis for further research and consists of a characterisation of the low energy houses (standards, market introduction, retrofitting, research fields) and used space heating and cooling systems. This evaluation includes heat sources, heat distribution and emission systems as well as passive installation (e.g. sun protection, blinds) and load requirements for different application areas.

Task 2: System Assessment

In this task, comparisons of heat pump solutions regarding energy consumption, reachable comfort as well as costs of different heating and cooling systems are assessed, followed by calculations and simulations of systems including their control.

Task 3: Field monitoring

The field monitoring in Task 3 shall yield the system performance and feasibility and an identification of optimisation potentials as well as a documentation of the used monitoring techniques which is useful for operation control during the building operation phase.

Task 4: Design guidelines

On the basis of the results of Task 2 and Task 3 design guidelines shall be derived, standard system configurations shall be developed and a documentation of Best Practice systems shall be made. The design guidelines shall be elaborated as checklists, step-by-step procedures or computer tools, e.g. Excel-Sheets.

Table 1 gives an overview of national contributions accomplished in IEA HPP Annex 32.

Table 1 **Overview of national projects in the frame of IEA HPP Annex 32**

Country	Institution	Focus of work in Task 2/3
AT	IWT/TU Graz	• Development an air-air/water (CO_2-)heat pump for the small capacity range • Prototyping and lab-testing of the best solution of the pre-studies
CA	LTE/Hydro-Québec	• Design, construction, monitoring and optimisation of 2 NOVOCLIMAT low energy houses for cold climate • Monitoring technology for operation control
CH	IEBau/FHNW	• Design guidelines of energy efficient heat pump systems for space heating and cooling • Field test of a heat pump system for space heating and -cooling
DE	FhG ISE, Viessmann GmbH	• Field testing of 140 state-of-the-art residential heat pumps in co-operation with 7 manufacturers and 2 utilities • Field test of 70 retrofit heat pumps for replacement of boilers in dwellings with high supply temperature requirements with the German Utility E.ON
JP	University of Hokkaido, TEPCO and Japanese manufacturers	• Optimisation of systems for moderate climate regarding capacity range and part load operation • Feasibility studies and field test of ground-source heat pumps for the cold climate zone
NL	SenterNovem, different Dutch market players	• Evaluation of calculation/simulation models for low energy houses, system development • Establishment of a certification/subsidy scheme • Field tests in the frame of Dutch low energy house projects
NO	SINTEF Energy research in cooperation with NTNU	• Technology assessment of suited heat pumps for Norwegian low energy houses (cold climate conditions) • Evaluation of performance of ventilation compact units with exhaust air heat pumps for Norwegian climate • Field test of novel water-water heat pump with propane installed in a passive house
SE	SP, KTH and Swedish manufacturers	• Assessment and redesign of Swedish heat pump systems (capacity range, auxiliary consumption) • Further development of Swedish heat pumps for the application in low energy houses (e.g. exhaust air heat pump with hybrid source, combined space cooling/DHW)
US	DOE, ORNL	• Development of a multifunctional heat pump system for space heating, -cooling, DHW, ventilation incl. de-/humidification for Net Zero Energy Houses • Component tests, prototyping and field test of the system

Interim results of the Swiss national project

Background

The Swiss national project is dedicated to the integration of passive and active cooling functions in heat pump systems for low energy houses. As a result, standard system configurations for space heating/-cooling and DHW production with heat pumps shall be derived, eventually coupled to a mechanical ventilation system.

Background of the project is an increased interest of space cooling in residential dwellings. However, there are still insecurities about the hydronic configuration, the operation limits, reachable comfort as well as system performance and adequate control strategies. Favourable for the application are marketable system configurations already containing a heat pump and further components which can be used for a (pre-)cooling in the summertime. These passive cooling opportunities should be deployed first and active cooling with a reverse operation of the heat pump should only be used to cover peak loads, if necessary, in order to minimize the energy consumptions.

Set-up for the simulation study

As a first system, a ground-coupled brine-to-water heat pump with vertical borehole heat exchanger is investigated including the provision of both an active and passive cooling option. In passive cooling mode (also called free cooling, direct cooling) the ground heat exchanger is directly coupled with a heat exchanger to the emission system without heat pump operation. Another option was a simultaneous operation of the heat pump for space cooling and DHW. The simulations have been carried out with the two simulation tools EWS (Huber 2007) (for borehole heat exchanger calculation) and CARNOT-Blockset (Hafner and Wemhoener 2002), a building technology library including also a building model for the Matlab/Simulink (Mathworks 2000) software package.

As building for the simulation study a single family dwelling according to the Swiss MINERGIE®-standard has been taken which is depicted in Figure 2a. The building is an existing dwelling in Gelterkinden, canton Basel-Landscape, which has been investigated in field monitoring for the ventilation, space heating and DHW as described in Afjei (2007). However, in the existing building, no ground-coupled heat pump is installed and no space cooling operation in summertime is presently applied.
The building is situated in a south oriented hillside location and has heavyweight construction walls and a laterally placed basement outside the insulation perimeter. The energy reference area according to the Swiss standard SIA 380/1 (SIA 2001) is 153 m^2 (net living space 125 m^2, net volume 305 m^3) and the heat energy need 157 MJ/(m^2a). The design heat load acc. to the Swiss standard SIA 384/2 (SIA 1995) is 4.1 kW at the combination of 20°C indoor at -8°C outdoor design temperature.

For the heat emission the floor heating system is designed as lowex system, i.e. for low space heating flow temperatures below 30°C and high cooling flow temperatures above 20°C. For the control of lowex systems the self regulation effect can be used to simplify the hydronic configuration. The self regulation effect is depicted in Figure 2b. It can be seen that in the case of low excess temperatures of the space heating emission system, the heat flux in case of a 1 K increase of the room temperature is notably decreased. Thereby, the heat flux is self-regulated by the behaviour of the room temperature. Extra thermostatic valves for the single room control are not necessary. This leads to a simplification of the hydronic configuretion. On the other hand, for the design of the floor emission the low excess temperature has to be considered and spacing of pipes is denser.

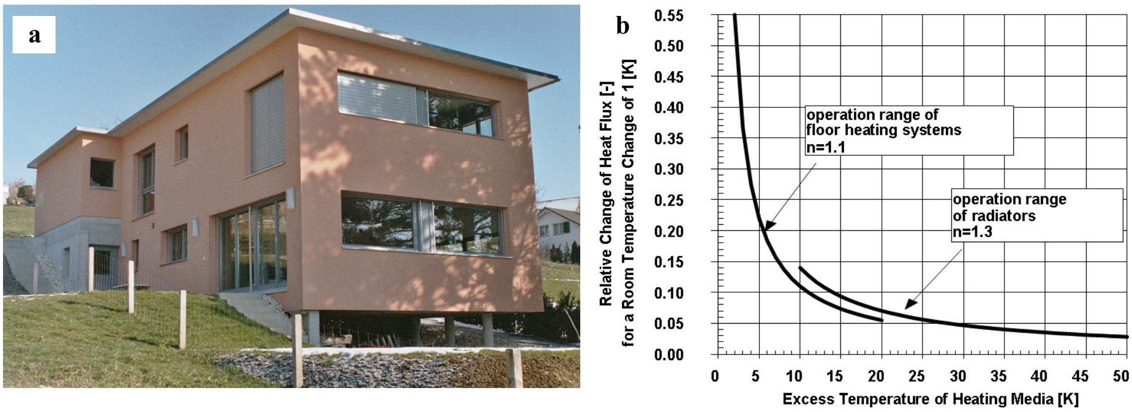

Figure 2 **Considered SFH according to MINERGIE® (a) and self regulation effect (b)**

The modelling of the system components for the floor heating system is given in Figure 3a and for the vertical borehole ground heat exchanger in Figure 3b. Koschenz and Lehmann (2000) describe a model for thermally-activated building elements that can also be applied for floor heating systems due to the model boundaries. In the model, the heat conduction, which is three-dimensional in reality, is represented as one-dimensional heat transfer from the pipe to the layer inside the wall. Therein, the heat transfer resistances between the heat carrier and the wall layer are aggregated to one representing resistance as shown in Figure 3a. This resistance comprises the heat transfer resistance along pipe length, heat transfer to pipe wall, heat conduction through pipe wall and heat conduction resistance due to pipe arrangement. The input of the floor heating system in free cooling mode is equivalent to the outlet of the borehole heat exchanger. Therefore, the estimation of the precise outlet temperature of the borehole heat exchanger has a strong impact on the cooling capacity of the free cooling system. Huber and Schuler (1997) describe a model for borehole heat exchangers that has been frequently used and validated in research projects and practical applications depicted in Figure 3b. The model computes the behaviour of the geothermal heat exchanger and the ground in the near region with a finite difference method acc. Crank-Nicholson and

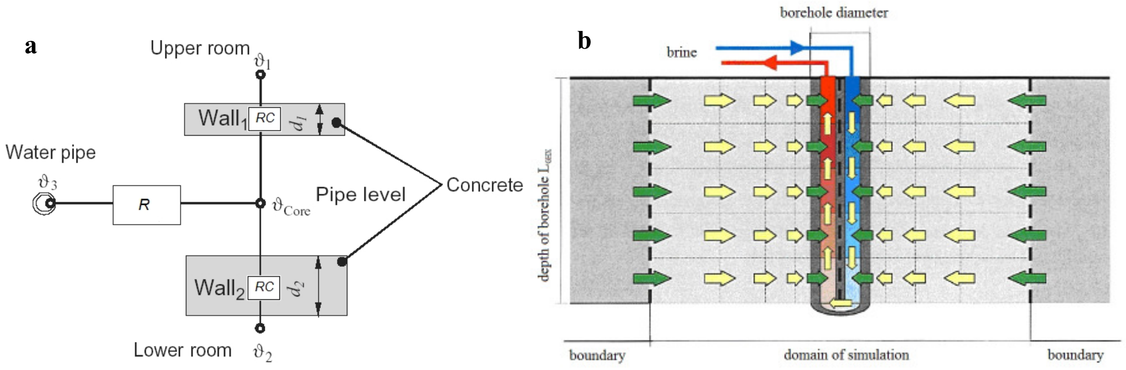

Figure 3 **Modelling of the system components floor emission (a) and ground heat exchanger (b)**

uses in the far region, i.e. r > 2.5m, an approach of a dimensionless transfer function in a half-indefinite area according to Eskilson (1987) and for the vertical borehole heat exchanger an indefinite line source according to Carslaw and Jaeger (1959). The model computes the behaviour of the geothermal heat exchanger and the ground in the local area as shown in Figure 3b. The ground module and the brine module are evaluated separately and coupled with the consideration of the boundary conditions.

In the following some design guidelines as described by Afjei, Dott and Huber (2007) are given.

Standard system layout and system integration of the components

Concerning the hydronic layout, different marketable system configurations has been evaluated which led to a simplified standard layout. Figure 4 shows the layout enabling both passive cooling with the borehole heat exchanger as well as active cooling by simultaneous operation of the heat pump for space cooling and DHW production.

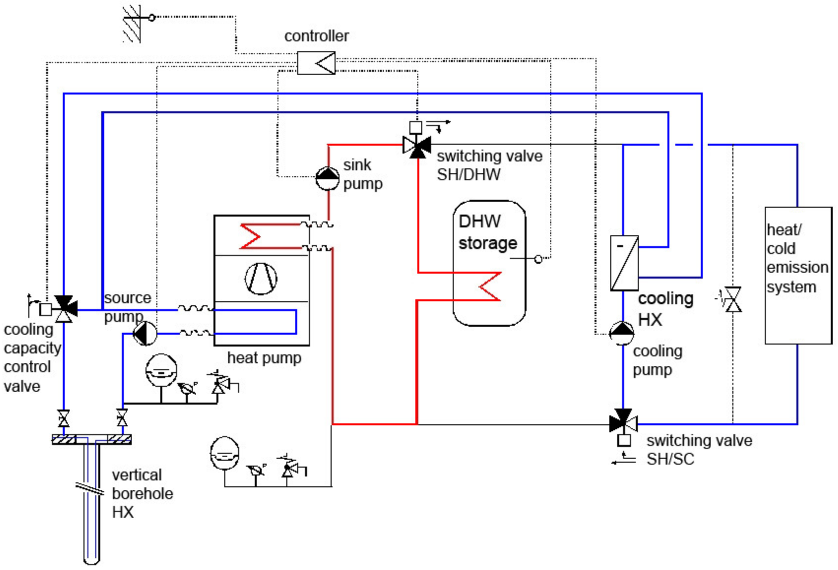

Figure 4 **Standard hydronic configurations including an option of simultaneous space cooling/DHW option**

If the simultaneous operation of space cooling and DHW is not required, the system layout can be further simplified, as shown in Figure 5, where the pump and the valve in the emission system are no longer required. The heat pump is depicted as so-called compact heat pump, where the source and sink pumps are integrated in the heat pump casing. The further evaluation of the system design, which is described in the next chapter, confirmed, that the advantage of a simultaneous DHW production with space cooling is marginal, so the simplification is feasible and useful.

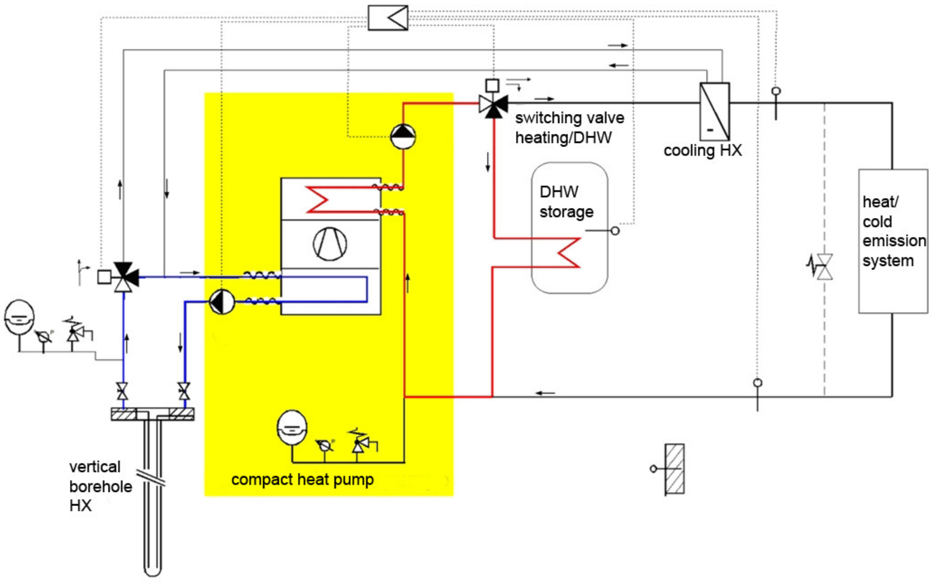

Figure 5 Simplified hydronic configurations without simultaneous space cooling/DHW

The integration of the heat exchanger for the floor emission system is shown in . In any case, a serial integration of the floor heat exchanger before the heat pump evaportator is to be secured in order to avoid a low pressure failure in the heat pump cycle. This failure could occur if the system is equipped with a capacity control and the cooling load is low. Then, in parallel configuration, a shortcut to the heat pump evaporator is the consequence, which is prevented in serial configuration due to the buffering in the ground. The evaluation of the two possible serial configurations depicted in Figure 6a and Figure 6b reveals, that the order heat pump, borehole heat exchanger and floor heat exchanger delivers a higher COP. In situations with capacity control, i.e. in cases with simultaneous DHW operation which delivers a higher cooling capacity than needed in the room, all temperature difference are fixed by this capacity. At same start conditions of the ground the same temperatures for the ground heat exchanger result. However, in the above given order, the inlet temperature to the heat pump evaporator is by the temperature change of the floor heat exchanger higher and thus yields a higher COP for the DHW operation. Moreover, this integration minimises the risk of freezing in the cooling heat exchanger in case of low cooling load due to the buffering in the ground. Therefore, an integration of the floor heat exchanger in the order heat pump, vertical borehole heat exchanger and floor heat exchanger is preferable.

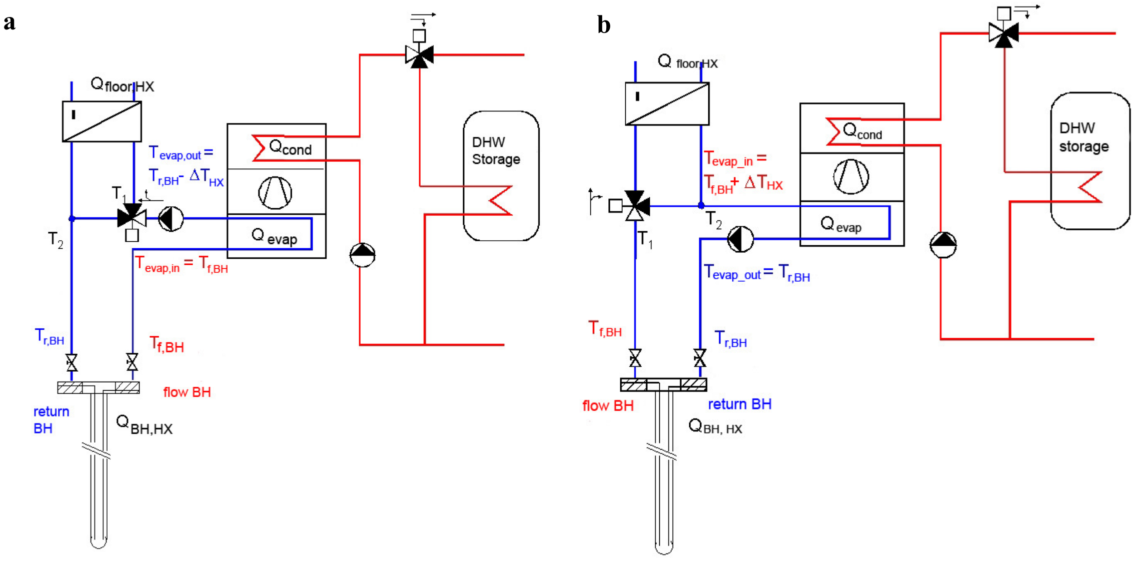

Figure 6 Variants for the integration of the heat exchanger for the floor emission system

Design of the system components

The design guidelines for the components refer to meteorological conditions of the Swiss middle land characterised by the weather data set of Zurich SMA. The simulation showed the following results:

- With a design of the vertical borehole heat exchanger (double U-tube type) according to the space heating operation, 90% of the cooling energy for the summer operation could be covered by direct ground cooling without active cooling. That means that a conventional design of a single vertical borehole heat exchanger for the space heating is sufficient for the cooling operation, too, and active cooling is not necessarily needed.
- Simultaneous DHW and space cooling yield only marginal improvements of 1.7% higher cooling energy, since in alternate operation mode, where the space cooling is interrupted during DHW operation, the cold produced by the evaporator is stored in the ground. After the DHW operation, this stored cold enhances the cooling operation (short term storage effect of the ground). Thus, a simultaneous cooling at DHW production is not worth any extra expense for the hydronic configuration.
- The cooling capacity of the vertical borehole heat exchanger depends on the required flow temperature for the cooling operation. The higher the flow temperature, the larger the capacity of the borehole heat exchanger for the cooling operation. Thus, the crucial point for the coverage of the space cooling energy need is the design of the cooling heat exchanger. At a temperature difference of 1 K in the heat exchanger 94% of the cooling energy can be covered (average borehole cooling capacity 26 W/m). In case of a temperature difference of 3 K, only 66% can be covered at an average borehole cooling capacity of 13 W/m). Therefore, the design of the floor heat exchanger is more important than a particular hydronic configuration.
- Depending on the temperature requirements of the space cooling emission system (affecting the fraction of cooling energy covered by the ground) and the cooling load of the building, the seasonal performance factor of the ground-coupled passive cooling is in the range of 10 to 25. This is due to the fact that the electrical consumption for the circulation pump is not much affected, but the cooling energy significantly changes dependent on the boundary conditions.

Control of the system

Standard systems for space heating and -cooling on the market are equipped with switchable thermostatic valves. That means, an action by the user is required to switch the control valves from heating to cooling operation, since in space heating operation, the thermostatic valves close, when the room temperature increases. However, in space cooling operation, a reverse operation is required, i.e. the thermostatic valves have to open in case of an increasing room temperature.

In the investigated system no manual activation of the user is required due to the self-regulation effect, i.e. the space heating and cooling is always activated. Concerning the control of this automated operation the following issues have to be considered:

- In the intermediate season both space heating and space cooling need can occur, leading to an intermittent heating and cooling operation. In order to prevent a counter-heating effect due to the high inertia of floor emission system, a dead time of 12 hours after the heating operation should be provided. Otherwise, it might occur that the space heating and -cooling may only act on the thermal mass of the floor emission system, and the room temperature will not be much affected, causing higher energy consumption in both modes.
- Dew point control is normally not required for Swiss boundary conditions. This is due to the fact that the minimum comfortable surface temperature of the floor is a stronger boundary condition than the dew point temperature (see description of comfort in the next chapter). A moderate cooling curve can minimize the condensation risk.
- A capacity control of the space cooling operation is useful, e.g. by a cooling curve. Thereby, the capacity of the borehole heat exchanger can be best adapted to the cooling needs in the room and therefore, the cooling need can be covered by passive cooling to a large extend.

Evaluation of thermal comfort

The considered comfort boundary has been set to an indoor temperature of below 28°C in summertime according to the Swiss standard SIA 382/2 (SIA 1992). Comfort boundaries for the floor surface temperature were set to 20°C minimum and 29°C maximum.

The reduction of the indoor air temperature that can be achieved by a passive cooling operation is in the range of 2 K to 4 K. That means that in combination with adequate shading and night time ventilation, even in extreme summers (simulation with extreme extrapolated weather data set of 2050) the indoor temperature can be kept in a comfortable range. An energy efficient cooling with the heat pump can thus guarantee a comfortable room temperature.

However, rooms with a higher moisture content (e.g. kitchen) and/or higher requirements for the surface temperature (in particular the bathroom where barefoot walking is quite often), shall not be cooled with the floor emission system due to comfort considerations and the risk of condensation.

Additional costs

For the passive cooling option additional components are needed compared to a pure space heating/DHW operation. These additional components are

- heat exchanger between borehole circuit and floor emission system (cooling heat exchanger)
- control valve with sensor for cooling curve
- controller for heating and cooling
- switchable thermostatic valves (depending on the design of the emission system)

The total investment costs of these additional components are in the range of 2000 €. Furthermore, in cooling mode operational costs are in the range of 12 € occur, mainly for the circulation pump electricity.

Conclusions

In IEA HPP Annex 32, further development of heat pump systems for the use in low energy houses is accomplished. Main results are new concepts for integrated heat pumps, design guidelines and standard systems for this application field as well as field monitoring of installed systems to characterise real world operation and Best Practice systems.

In the Swiss national project, design guidelines for a ground-coupled heat pump system, working on a floor emission system for both space heating and –cooling, have been derived. The heat pump is also used for the DHW production. The investigation led to a standardised simplified hydronic layout for the system, both for passive and active cooling with simultaneous DHW production. However, in most cases a passive cooling is sufficient with the adequate combination of different passive measures like shading, night time ventilation and passive cooling with the borehole heat exchanger. Moreover, simultaneous DHW and space cooling operation yield only a marginal improvement compared to the alternate operation, since short-term storage of the evaporator cold in the ground during DHW operation can be used later for passive cooling. With application of an adequate cooling curve, a dew point control is not required for Swiss boundary conditions.

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