INFLUENCE OF CONTROL PARAMETERS ON THE SYSTEM PERFORMANCE OF GROUND COUPLED HEAT PUMP SYSTEMS: A SIMULATION STUDY

J. Hoogmartens, L.Helsen

Division of Applied Mechanics and Energy Conversion, University of Leuven (K.U.Leuven), Celestijnenlaan 300A/B-3001, Leuven, Belgium

ABSTRACT

Geothermal heat pump systems have a large potential for energy savings and associated greenhouse gas emissions. However, inappropriate control may counteract these saving potentials. This study evaluates the influence of different control parameters on the system performance of a ground coupled heat pump system in a residential building. To this end a dynamic simulation model is built in TRNSYS, coupled to Matlab in order to implement the controller. The simulation results show that using a room thermostat coupled with heating curves, night increase or smart control of the circulation pump for floor heating leads to large potential energy savings. Using a legionella program or a constant supply temperature for floor heating performs less energy efficiently than the reference model.

INTRODUCTION

Heat pumps reduce the primary energy use (and thus associated greenhouse gas (GHG) emissions (Jenkins et al., 2008)) while guaranteeing thermal comfort when they are combined with an appropriately sized heat emission system (Sanner et al., 2003). In addition, they have very low levels of maintenance requirements.

Ground-coupled heat pumps (GCHP) have extra advantages. First, the source (ground) temperature in a well sized system is relatively high (around 10°C) and does not vary much, resulting in a relatively high and stable system performance (Healy et al., 1997). Since smaller differences between condenser and evaporator temperatures in a heat pump result in a higher coefficient of performance (COP), using the ground as a heat source leads to a high seasonal COP. In Belgium, a typical GCHP has a COP between 3.5 and 5.6 (Hoogmartens et al., 2011). All conventional heating systems have smaller COPs, e.g. electrical resistance heating has a COP of 1, oil-fired boilers have a COP of 0.65-0.7 and condensing gas boilers have a COP of 0.8-0.85 (Healy et al., 1997). Consequently, a GCHP may provide yearly energy savings up to 65-70% in comparison to conventional heating systems (FHP, 1986). Second, the use of ground heat in winter allows to apply passive cooling in summer. Therefore, GCHP systems are extremely beneficial in applications that require both heating and cooling, by using seasonal thermal energy storage in the underground. Guaranteeing the long term thermal balance of the ground is a constraint that deserves the required attention.

A bad control can counteract all these advantages so that the expected savings are not reached. This study evaluates the influence of control parameters on the global system performance of a GCHP system in a residential building, while requiring a minimum level of thermal comfort.

To achieve the goal of this paper a dynamic model of a detached residential building has been developed in TRNSYS. The control part has been implemented in MATLAB. Both software tools are coupled with a type 155 component of TRNSYS.

SIMULATIONS

Base case

The reference model consists of a well-insulated detached single-family house with a floor heating system, a ground coupled heat pump (GCHP) and a controller, connected to the heat pump unit and all circulation pumps.

A reference Belgian detached house has been used in the model (Verplaetsen et al., 2000), which has a total occupied floor area of 271 m² of which 130 m² is heated by a floor heating system that feeds both the ground floor and the first floor. The building consists of a living room, a kitchen, and an entrance hall at the ground floor and four bedrooms, a night hall and a bathroom at the first floor. Furthermore, a basement and an attic are part of the building. The specified surface areas of each room and the glazed surface with corresponding orientation are listed in Table 1. The building is well-insulated according to the Belgian EPB-directive. Compared to the required maximum insulation score (K45), the building has 5 K-points less, K40 (EPB, 2011). This corresponds to an overall U-value of the building of 0.44 W/(m²K). In each room scheduled internal heat gains of persons, lighting and electrical appliances are incorporated. Infiltration is included in the model too by specifying for each room an amount of air changes per hour. The floor heating system is connected to a ground coupled heat pump. This on/off controlled heat pump is modelled with the type 668 component of TRNSYS which uses

Table 1: Building data

Type of room	***Surface area (m²)***	***Floor heating (Y/N)***	***Glazing surface (m²) Orientation***
Living room	56.5	Y	1.5 N 3 W 6 S 1 E
Kitchen	11.2	Y	1 N 1.5 E
Entrance hall	6.6	N	1 W
Bedroom 1	11.2	Y	0.75 E
Bedroom 2	13.5	Y	1 W
Bedroom 3	16.1	Y	0.75 E
Bedroom 4	13.3	Y	1 W
Night hall	10.2	N	/
Bathroom	8.5	Y	1.5 W
Basement	74.3	N	/
Attic	50.3	N	/

heat pump performance curves. The model ascertains thermal capacity and COP as a function of inlet brine temperature from the ground model and outlet supply temperature to the floor heating system of the building or to the domestic hot water tank. A set of data curves were obtained from the Viessmann technical guide of the Vitocal 300G for ground source heat pumps (Viessmann, 2008). Data of the used BW/BWC 110 unit are shown in Fig. 1. The GCHP system has a nominal thermal power of 10.2 kW in specified test conditions (source temperature of 0°C and load temperature of 35°C). The vertical ground heat exchangers are modelled by the type 557a of TRNSYS. The sizing of the virtual ground source and the other implemented ground parameters are supplied by a professional driller who calculated these variables with the EED-software. As a result a ground model of four vertical double U-tubes of a depth of 65 m has been set up.

Furthermore, a 390 l domestic hot water tank is implemented (type 534) in the TRNSYS model. The implemented parameters are derived from the Viessmann Vitocell 100-V which is sized for domestic hot water production in combination with heat pump systems (Viessmann, 2007). A 4-person based scheduled tap pattern is applied to the storage tank.

For the control of space heating, two heating curves (HC) with a dead band of ±2°C are defined, determining the return temperature of the under floor heating system as a function of the running average of the ambient temperature (taken over 3 hours): one

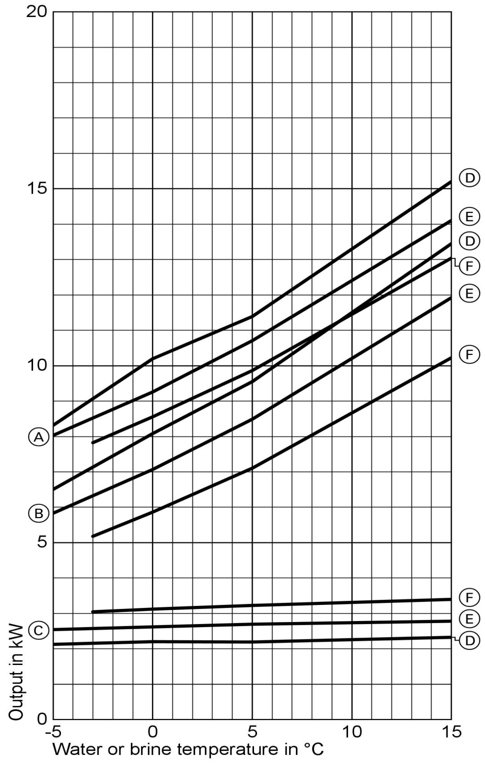

Figure 1: Heat pump performance curves Vitocal 300G BW/BWC 110. A: heat power (kW), B: cooling power (kW), C: compressor power (kW), D: Tsupply=35°C, E: Tsupply=45°C, F: Tsupply=55°C

for heating during the day (called high/day HC) and one for heating at night (called low/night HC) because comfort is less crucial during night. This control strategy is current practice in domestic heat pump systems coupled with under floor heating. Besides space heating, also domestic hot water (DHW) is supplied by the heat pump. Domestic hot water is preferentially produced during the night (at 53°C, sensor at the bottom of the storage tank), and during the day only when it is highly needed (indicated by a drop of the top temperature of the storage tank below 43°C). During two holiday periods (each having a duration of 1 week), one in summer and one in autumn, no heat for space heating nor domestic hot water production is generated.

The heat pump has a minimum standby time of 20 minutes when it has been switched off, to limit the amount of pending cycles. The circulation pump for space heating is turned on during the whole heating season except when domestic hot water production is needed and during the holidays. Simulations have been run for two years and evaluated over the second year (to eliminate the influence of initial conditions) using a time step of three minutes (small enough for control purposes). The climatic data for Uccle, Belgium are applied to the building.

Parameter changes

Ten variations on the implemented reference control strategy were simulated. All new implemented control strategies were chosen such that the minimum requirement of thermal comfort is reached. An automated, optimal tuning of control parameters has not been executed.

The ten control strategies simulated are listed below.

1. Higher heating curves (HC Higher)
2. Lower heating curves (HC Lower)
3. Room thermostat combined with heating curve
4. Room thermostat combined with heating curve and room temperature compensation
5. Constant water supply temperature
6. Night increase
7. Higher domestic hot water temperature
8. Larger dead band
9. Inclusion of legionella program
10. Smart control of circulation pump

By implementing the first two variations, the influence of increasing or decreasing the requested indoor air temperature on the yearly energy use can be studied. Both changes can not be evaluated with respect to thermal comfort because these are typical changes depending on user's behaviour. Shifting the heating curves (Viessmann, 2006) results in an increase or decrease of the yearly average indoor temperature with 1°C.

Next two control strategies use a room thermostat to define whether the heat pump should be switched on or off. The reference living room temperature is set to 22°C with a dead band of ±1°C during the day; at night the set point temperature is decreased to 20°C with a dead band of ±1°C. When the room thermostat gives a heating signal to the heat pump it switches on based on the implemented heating curve of the reference case until the room temperature reaches the upper limit of the living room set point temperature or the return floor heating temperatures reaches the upper limit of the implemented dead band of the heating curve. The circulation pump for floor heating switches on/off together with the heat pump unit. In the fourth parameter change, an extra room thermostat compensation is implemented. If the deviation from the set point room temperature is much larger than the tolerated dead band limit (because e.g. domestic hot water production or after a holiday), the heating curve is increased by a certain proportion depending on the deviation to fasten the reheating of the house.

To check the statement (often encountered on the street) that a constant temperature to the floor heating system is economically more interesting than night set back, the fifth parameter change is simulated. Instead of using the lower heating curve during night, the higher one is used for the whole period.

As sixth parameter change, a switch between the reference high (day) heating curve and low (night) heating curve is applied, which means that the High HC is used during night and the Low HC is used during the day. In this way the thermal mass of the building is optimally used and the heat pump can perform longer during night at lower energy prices (on/off peak electricity tariffs are used). Moreover, internal gains and solar gains during the day are used in a more useful way. At night the whole structure is heated to a higher temperature. Together with internal and external gains during the day, , a minimum temperature can be maintained sometimes (mainly in spring and autumn) even without using the heat pump during the day.

The next change is applied to the set point of the domestic hot water tank. Instead of heating the storage tank at night to 53°C, the heat pump will heat the storage tank to 56°C. During the day, the upper tank set point temperature is increased from 43°C to 48°C.

A dead band of ±2°C was implemented in the reference case. This dead band is broadened to ±3°C as next parameter change.

In the second last parameter change a legionella programme is installed for domestic hot water production. On a weekly frequency the heat pump will heat the storage tank to the set point temperature of 53°C, afterwards an electric back-up heater will heat the storage tank to 60°C. From the legal point of view it is not an obligatory control strategy (and therefore not implemented in the reference case), but most heat pump installers implement it to minimise the risk of legionellosis infection.

Finally, an advanced control of the circulation pump of the floor heating system is simulated. Instead of turning on the circulation pump during the whole heating season (as it is done in most of the real cases), the circulation pump will be normally switched off except during one quarter each hour. During this quarter the real (measured) return water temperature is compared to the implemented set point of the return water temperature of the floor heating (derived from the HC). Only if the return water temperature drops below the lower limit of the dead band, heating is necessary and therefore the heat pump (and circulation pump) will work until the return temperature of the floor heating reaches the upper limit of the dead band after which the heat pump and circulation pump switch off again.

Evaluation criteria

The simulation results are evaluated with respect to two main criteria: thermal discomfort and energy use. The evaluation is performed on a yearly basis.

Discomfort is expressed as the average number of Kelvinhours (Kh) overheating or subcooling on a specified time basis (see Fig. 2, 3) for all heated rooms, except the bathroom (since no problems were observed during the simulations). Comfort in bedrooms is evaluated at night while comfort in living room and kitchen is evaluated during the day. For a whole year, the Kh overheating and subcooling of all heated rooms (without bathroom) are summed. This total number is divided by the amount of heated rooms to get the average annual amount of discomfort per room. The applied thermal comfort limits are derived from the 10% PPD boundary of (Peeters et al., 2008) which is based on ISSO 7730,

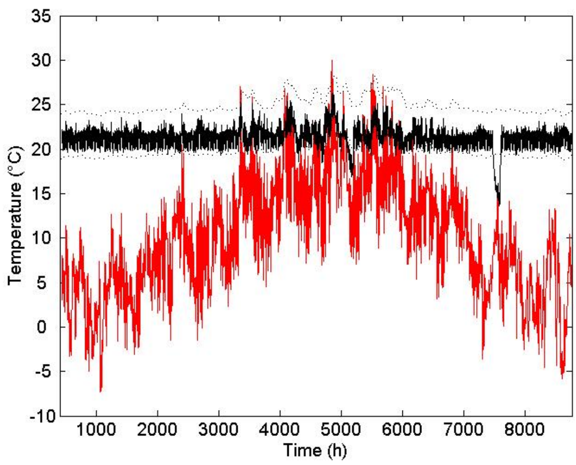

Figure 2: Thermal comfort limits living room, kitchen; Red: Outdoor temperature Uccle; dotted lines: thermal comfort limits; black line: indoor temperature living room of reference case

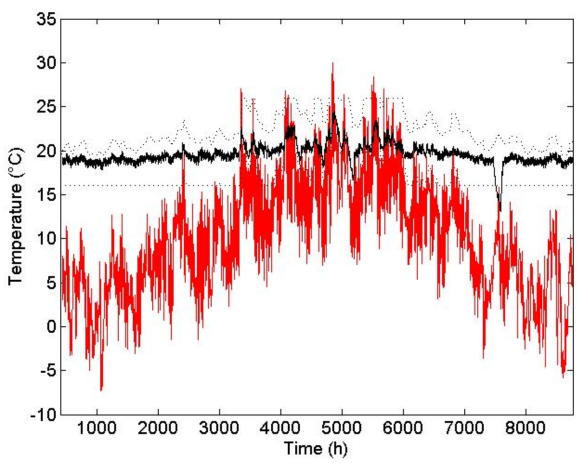

Figure 3: Thermal comfort limits bedroom. Red: Outdoor temperature Uccle; dotted lines: thermal comfort limits; black line: indoor temperature bedroom 1 of reference case

ASHRAE 55-2004 and other comfort literature. Energy use is defined as the total electrical energy consumption (kWh) for both space heating and domestic hot water production on a yearly basis. All electrical components in the heat pump system (source pump, heat pump unit, circulation pumps, controller, back-up heater) are included.

Furthermore, the yearly CO_2-emissions and yearly operating costs are determined. The CO_2-emissions are calculated based on the hourly amount of CO_2-emission of the Belgian electricity production park (Voorspools, 2004). The operating cost is calculated based on the hourly amount of electrical energy use during peak and base load hours with their respective tariffs. Finally, the seasonal performance factor (SPF) of the heat pump system is determined following the European standard (prEN 15316-4-2, 2009). The system boundaries used to define the SPF are shown in Fig 4.

RESULTS AND DISCUSSION

The simulation results are summarized in Fig. 5 as a trade-off between the energy use and the thermal discomfort. The horizontal axis presents the yearly electricity use for space heating and domestic hot water production of the simulated house with the chosen control strategy for the GCHP system (indicated by a number index next to the symbol). The vertical axis shows the average yearly amount of discomfort in all heated rooms. The red plus sign accompanied by the index 'Ref' indicates the reference case, for which the total yearly energy use is 5,820 kWh. The majority of electrical energy is consumed by the compressor (4,710 kWh). Moreover, the circulation pump for floor heating (588 kWh) followed by the source pump (407 kWh) consume an important part of the total electricity consumption. Continuous operation causes the high electricity consumption of the circulation pump, in contrast to the source pump, which is characterized by an electric power twice as high but significantly less operating hours. The controller (88 kWh), the circulation pump for DHW production (34 kWh), and the electrical back up heater (0 kWh) use negligible parts of the yearly energy use. The SPF of the reference case is 4.3. The domestic hot water production set points are controlled in such a way that no electrical back-up heating was necessary for the implemented tap profile. This energy use will remain the same for all simulations except the legionella program simulation (which is discussed in a later section of this paper). The total discomfort is defined by the average overheating and subcooling in all heated rooms. Overheating and subcooling were defined following the 10% PPD boundaries of ISSO 7330. By studying the results into more detail (see Fig. 2 and 3 for the reference case), discomfort is mainly caused by subcooling. The average overheating in all rooms is limited to 2 Kh per year and is fully attributed to internal gains in the kitchen.

No overheating has been detected in the other rooms. The average yearly amount of Kh subcooling is 92. The largest part of this subcooling takes place in the living room and the kitchen and is completely situated in summer. During summer the indoor temperature always stays around 20-21°C but the thermal comfort limit for subcooling raises to 23°C. The total amount of hours during which the indoor air temperature exceeds the comfort limits is on a yearly basis only 0.07% for overheating and 1.96% for subcooling. The operating cost for this GCHP system is calculated on a yearly basis, using peak (19 c€/kWh) and base (13 c€/kWh) load tariffs. For the reference case the total operating cost is € 753. This can be compared to a static calculation of a condensing gas boiler with a seasonal efficiency of 85% and a natural gas price of 5 c€/kWh, for which the total operating cost is € 1,353. Large savings on operating costs are possible by using GCHP systems. Also the savings regarding CO_2–emissions are substantial. The dynamic simulation of the reference heat pump system in TRNSYS gives a total yearly CO_2-emisison of 3,499 kg. This result can be compared to a static calculation of a gas condensing boiler with a nominal CO_2-emission of 201 g/kWh (EPB, 2010) leading to a total emission of 5,440 kg. Besides large operating cost savings, also large CO_2 emission savings are possible by using GCHP systems.

All other control strategies are compared to this reference case. A first adaptation is a positive and negative shift of the heating curves. As this control strategy is related to user preferences and directly influences the indoor air temperature, the evaluation of thermal comfort does not make sense. By changing this parameter of the control strategy only the potential energy savings or extra energy need is studied. Increasing or decreasing the heating curves results in a positive or negative shift of 1°C of the yearly average indoor temperature in all heated rooms. Point 2 (HC Lower) in Fig. 5 shows that large energy savings (730 kWh/year) are possible by decreasing the heating curves. On the other hand, by increasing the heating curves (point 1 (HC Higher) in Fig. 5), 780 kWh/year extra electrical energy is needed. This extra energy use translates itself to a lower SPF of the heat pump system (-4%). Thus adapting yourself (e.g. by using warmer clothing) to a somewhat lower indoor temperature has a significant beneficial effect on the yearly electrical energy use.

Both room thermostat controls (points 3 and 4 in Fig. 5) result in important energy savings while maintaining the same level of thermal comfort in all rooms of the building. The reason is that the room thermostat turns off the heat pump earlier than the heating curve does. Since the circulation pump is switched off together with the heat pump unit, large energy savings were reached. The amount of overheating is lower compared the reference case. However, subcooling increases slightly due to the fixed set points during night and day, summer and winter. Similar to the reference scenario, subcooling is mainly observed during summer.

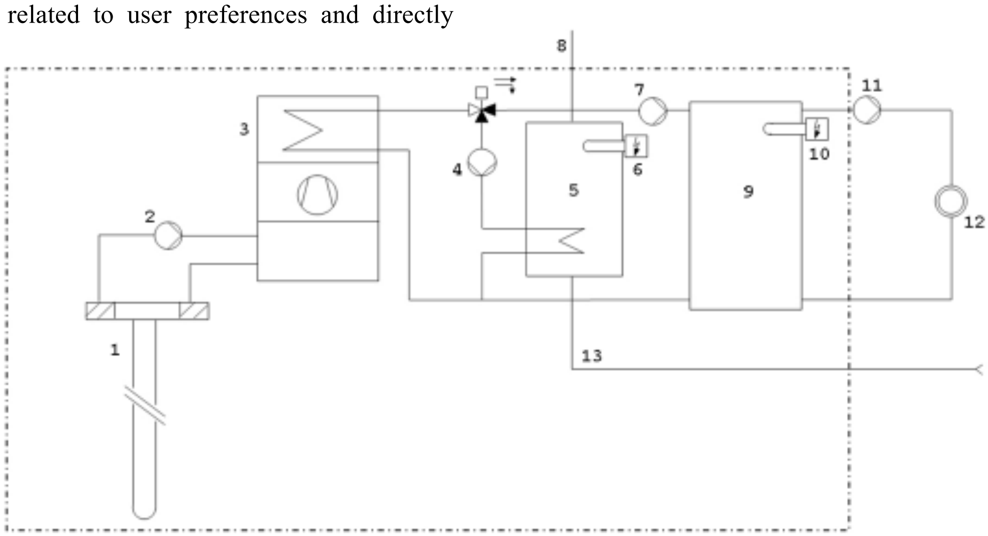

Figure 4: SPF boundary (denoted by dash-dotted line) European standard prEN 15316-4-2. 1. Heat source; 2. Source pump; 3. Heat pump; 4. DHW pump; 5. DHW storage; 6. DHW back-up heater; 7. primary pump; 8. DHW hot water outlet; 9. SH storage; 10. SH back-up heater; 11. SH circulation pump; 12 Heat emission system; 13. DHW cold water inlet

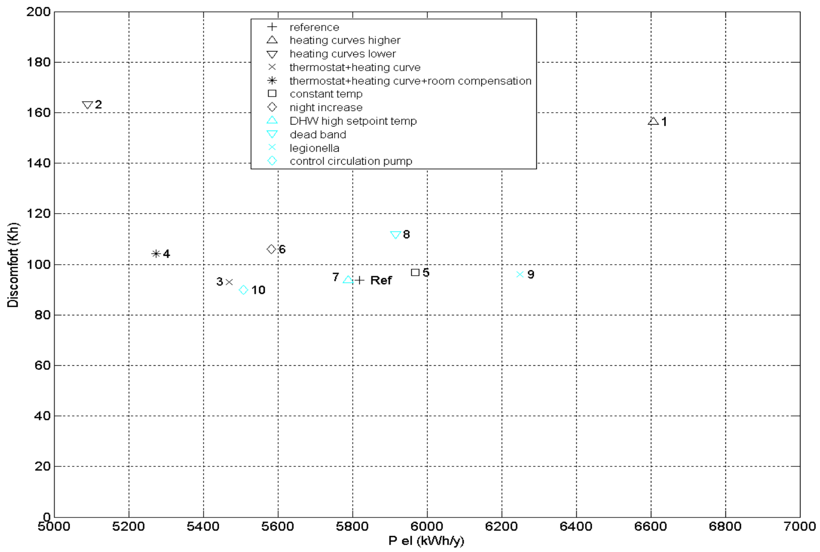

Figure 5: Trade-off between energy use (kWh/year) and average thermal discomfort (Kh) of reference case and 10 control adaptations

The extra implemented room temperature compensation leads to an extra electrical energy saving, however at the expense of a larger thermal discomfort. The compensation control provides a faster heating when the real indoor air temperature deviates significantly from the set point temperature. The parameters, however, are not yet fully optimised.

The constant water supply temperature control (presented by point 5 in Fig. 5), combined with the use of the reference higher (day) heating curve for the whole period, results in higher energy demand for an almost equal (slightly lower) indoor thermal comfort. The number of overheating hours is higher compared to the reference case, raising from 0.07% to 0.34% due to overheating in the bedrooms during the winter nights. The larger thermal energy demand may also cause a decrease of the ground temperature and as a consequence of the GCHP performance (when the borefield sizing is not adjusted), which may even further increase the energy demand compared to the reference case.

The next implemented control strategy is the application of night increase, where the high (day) heating curve and lower (night) heating curve of the reference case are switched (point 6 in Fig. 5). This change results in a lower energy demand at the expense of a slightly higher discomfort. The lower energy demand can be explained by raising the indoor temperature at night and using external and internal heat gains useful during the day, therefore the heat pump is switched off for a longer time compared to the reference case. In some periods of the year, the heat pump only works at night, while external and internal heat gains keep the indoor temperature on a minimum level during daytime. Moreover, due to the night increase the heat pump works with higher water supply temperatures (which represents less performing operating conditions) at night, when the electricity tariff is lower, thus saving money. The higher discomfort is caused by increased overheating at night in de bedrooms, similar to the previous simulation results (constant temperature) on the one hand, and by the increased number of hours subcooling in the living room and kitchen in summer on the other hand.

A higher set point for domestic hot water production (point 7 in Fig. 5) results in a similar result as the reference case. Extra electrical energy input, to deliver slightly higher set point temperatures, is compensated by energy savings for the circulation pump. To heat the storage tank to 56°C, the heat pump has to heat up the water in the condenser to higher temperatures (order of 60°C, which is a safety limit for the heat pump). When the heat pump delivers water of 60°C the heat pump and circulation pumps are switched off for 20 minutes. Moreover, while the heat pump is operating for DHW production it can not generate space heating. However, this causes no problems with respect to thermal discomfort.

A larger dead band around both high (day) and low (night) heating curves (point 8 in Fig. 5) results in a larger energy use and larger thermal discomfort. Because of the larger band, the heat pump will have to operate for longer periods. The larger band around the heating curve causes a larger amount of hours overheating and subcooling. This control strategy has, evidently, a large impact on the amount of on/off switching, which decreases substantially.

The legionella program (point 9 in Fig. 5) is often used in the Flanders region (to avoid the risk of legionellosis infection) although it is not obligated for domestic heating installations. On a weekly basis the domestic hot water tank is heated to 60°C. In a first phase the heat pump is used as long as possible. To bridge the last few degrees, an electric resistance at the bottom of the tank is used. The extra electrical energy needed for this control strategy is 486 kWh. This extra energy use is the main reason of the lower SPF (-7%): 4.0 instead of 4.3. For space heating, no changes are implemented and therefore no change on thermal discomfort is observed.

The smart control of the circulation pump (point 10 in Fig. 5) tries to limit the energy use of the circulation pump by turning it off when the heat pump unit is not working during the heating season, except one quarter each hour to compare the real return temperature to the set point temperature. By applying this control, a significant saving of electrical energy is obtained without increasing thermal discomfort in the heated rooms. A small improvement in thermal comfort is even observed. This improvement is spread over subcooling and overheating and is observed in the living room and kitchen, which are both rooms characterized by the highest internal heat gains.

Fig. 6 presents for each control strategy the relative increase or decrease in total electrical energy use, operating cost and CO_2-emission on a yearly basis compared to the reference case. The obtained differences for energy use (black bars), operating costs (gray bars) and CO_2-emissions (white bars) are in the same order of magnitude for all investigated control parameters. The (small) deviation between CO_2-emissions on the one hand and energy use or operating costs on the other hand is caused by the differences between night and day CO_2-emissions of Belgium's electrical power plants. The Belgian electricity park is dominated by nuclear power plants, which deliver the base load during night and day. Peak loads are covered by smaller, more modulating power plants (IEA, 2009) with higher GHG emissions. Fig. 6 also shows a significant difference of 13% compared to the reference case by increasing or decreasing the heating curve. By changing the indoor temperature slightly (± 1°C), large savings are possible for all evaluation criteria considered in this study. Both strategies have, however, important implications on indoor thermal comfort. By applying these control strategies, changes in clothing will be necessary to maintain the same thermal comfort experience.

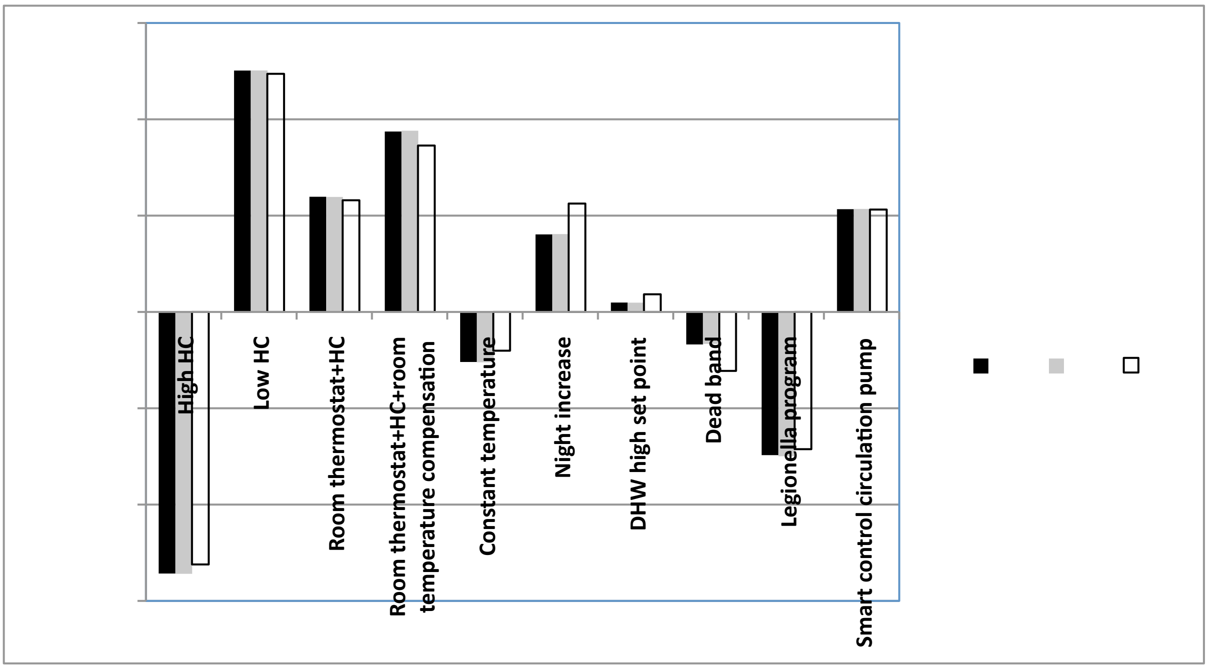

Figure 6: Relative comparison to reference case. Black bar: energy use; Gray bar: working cost; White bar: CO_2-emission

The implementation of a room thermostat also delivers high savings. By adding an additional room compensation control, even larger savings, up to 9%, are possible. The next control strategy with positive consequences on all evaluation criteria is the implementation of a smart circulation pump control. This control strategy will not change the SPF (Fig. 4) of the heat pump system, because the energy consumption of the circulation pump is not included in the SPF definition. Night increase is the last tested control strategy which delivers a significant positive influence on energy savings, operating costs and CO_2-emissions. Especially, the savings on GHG emissions are striking.

Raising the set point of the domestic hot water tank or implementing a larger dead band around the heating curves have rather small influences with respect to the different evaluation criteria

Commonly used control strategies, like a legionella program or feeding the floor heating system with a constant temperature, are pernicious for the yearly energy demand of the heating system as well as the CO_2-emissions and operating costs.

The variations of these control parameters have been investigated independently. Therefore, conclusions can not be drawn regarding their mutual influence.

CONCLUSION

A reference TRNSYS-model based on product specifications and previous field tests has been constructed to study the influence of control parameters on the system performance of a domestic ground coupled heat pump system. Besides system performance also indoor thermal comfort and potential savings in operating costs and CO_2-emissions have been assessed. The simulated heat pump system generates heat for both space heating and domestic hot water production. Year-round dynamic simulations are made using TRNSYS (for modelling the dwelling, weather, heat pump system, storage tank) and MATLAB (for modelling the control strategy) based on 3-minute time steps. Different control strategies and parameter variations are compared to the reference model, while implying a minimum required thermal indoor comfort.

The simulation results show that using a room thermostat, if desired extended with a room temperature compensation controller, has a positive influence on the total energy use for the heating system as well as for the yearly operating costs and de CO_2-emissions. Two other control strategies with high potential savings are the use of a smart control for the circulation pump for space heating or the application of night increase instead of night set-back. Those control strategies can save up to 5-9% of the electrical energy consumption, CO_2 emissions and operating costs on a yearly basis. Besides eliminating the risk for infection, the legionella program has only drawbacks: it consumes a lot more energy and money and is responsible for extra GHG-emissions.

The influence of raising or lowering the indoor temperature with 1°C in all heated rooms on energy use is substantial (up to 13%). However, indoor thermal comfort is no longer guaranteed and adaptation of clothing is needed to maintain a comfortable experience.

REFERENCES

D.P. Jenkins, R. Tucker, R. Rawlings, Modelling the carbon-saving performance of domestic ground-source heat pumps. Energy and Buildings 41 (2009) 587–595

EPB software, www.energiesparen.be, consulted on February 24, 2011

F. H. P. (1986). FHP Earth Temp. Heat Pump Systems, FHP Manufacturing, Ft. Lauderdale, Florida, U.S.A.

Hoogmartens J., Franck G., Van Den Schoor F., Helsen L, Monitoring the system performance factor of domestic heat pump systems in Flanders (Belgium), ISHVAC 2011: 7th International Symposium on Heating, Ventilating and Air-Conditioning, Shangai, 2011

IEA, 2009. Energy policies of IEA countries, Belgium 2009 overview.

P.F. Healy, I. Ugursal, 1997, Performance and economic feasibility of ground source heat pumps in cold climate, international journal of energy research, vol. 21, 857-870 (1997)

prEN 15316-4-2, Heating Systems in Buildings – Methods for the Calculation of System Energy Requirements and System Efficiencies- Part 4.2 Heat Pump Systems, CEN, Brussel 2009

Sanner B., Karytas C., Mendrinos D., Rybach L. Current status of ground source heat pumps and underground thermal energy storage in Europe. Geothermics 32 (2003) 579-588

TRNSYS, A transient simulation program, version 16.1. Solar Energy Laboratory, University Of Wisconsin, USA, 1992

Verplaetsen F., Berghmans J, Vergelijking van verwarmingssystemen voor woningen;CO_2-emissie ten gevolge van woningverwarming met behulp van een warmtepompsysteem, 2000

Viessmann Vitocal 300G Planningsaanwijzing 4/2008, www.viessmann.be, consulted on March 15, 2010.

Viessmann Vitocell 100-V Technisch blad 4/2007, www.viessmann.be, consulted on April 5, 2010

Viessmann Vitodens 200, serviceaanwijzing, 10/2006, http://www.viessmann.be, June 23, 2010

Voorspools, K., 2004. The modelling of large electricity generation systems with applications in emission-reduction scenarios and electricity trade. Katholieke Universiteit Leuven, Leuven