COMPUTATIONAL ASSESSMENT OF COOLING WITH LOW-TEMPERATURE HEATING SYSTEMS

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ABSTRACT

This paper describes the results of a computational study on the feasibility of cooling houses in the Netherlands with a system consisting of a heat exchanger in the soil, a heat pump, and a low-temperature heating system. The study is based on simulation of the building using the transient thermal simulation tool VA114, simulation of the thermal storage system using the dedicated Earth Energy Designer (EED) program, and simulation of the indoor air flow using the CFD-tool WISH3D.

The results indicate that cooling with such a system is indeed feasible in the Netherlands, if care is taken of the limitation in specific cooling power to prevent condensation. Using constant temperature control, the temperature difference between water and air is limited to 5 K, resulting in a specific cooling power of 12 W/m^2. Other passive measures, like solar shading and night ventilation therefore are also required.

With this peak load limitation the capacity of the thermal storage system for cooling is sufficient when it is designed for heating only.

KEYWORDS

domestic cooling, low-temperature heating system, thermal storage

1. INTRODUCTION

In Europe the cooling of houses is rapidly gaining momentum. This is caused by demands of occupants for increased control over indoor air temperatures, climate change and maybe augmented by the side effects of building designs being made energy efficient from a heating point of view (high-insulating and airtight building envelopes, solar windows, etc). So far the main solution to these cooling demands has been an increased use of air conditioning units. However, the use of such active cooling systems increases energy demands and therefore is undesirable from a sustainability point of view.

One possible alternative to the installation of air conditioning units is the use of the following system for cooling purposes: a heat exchanger in the soil, a heat pump, and a low-temperature heating system (floor or wall heating). This combination is already widely used as heating system, and as such has a high user acceptance. Using this system for cooling would mean that only a limited number of additional components has to be installed. However, this dual use of heat exchanger, heat pump and a low-temperature heating system currently remains at an exploratory stage. Actual application is limited to a small number of experimental projects. A scheme of the system is given in figure 1.

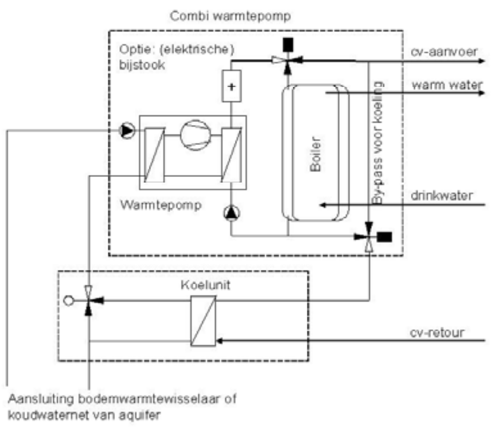

Figure 1 HVAC schematic lay-out

2. OBJECTIVES

A number of fundamental questions about the use of these systems for cooling purposes remain: is the capacity of a thermal storage system that has been dimensioned for heating purposes sufficient for cooling purposes as well? And is it possible to 'misuse' low-temperature heating systems for cooling purposes, or does this result in problems in the field of cooling power limitation, condensation problems and thermal comfort due to stratification, radiation asymmetry etc?

The aim of the work described in this paper is the computational assessment of the feasibility of cooling houses in the Netherlands with a heat exchanger in the soil, a heat pump, and a low-temperature heating system. Furthermore, the paper will comment on the findings regarding the simulation of this combination of systems using a set of complementary simulation programs.

3. APPROACH

The computational assessment has been carried out in four different stages, focusing on different aspects.

Stage 1 dealt with the thermal behavior of the house itself, studying the heating and cooling loads under different climate and control regimes. Regarding climate the impact of an average and an untypical warm year have been studied; regarding control regime the impact of traditional measures like sun shading devices and night ventilation have been taken into account. For this stage the transient building simulation program VA114 (VABI, 1993) has been used. VA114 is developed to calculate temperature series plus heating and cooling loads in buildings; it allows for a multi-room model that takes into account the heat transfer between adjacent spaces. VA114 can simulate different HVAC systems. If necessary it allows for the incorporation of shading by surrounding buildings. The tool is one of the main simulation programs used for consultancy work in the Netherlands, and it is validated using the BESTEST procedure.

Stage 2 dealt with condensation risk inside the house, basing itself on the indoor air temperatures as found in stage 1, complemented with humidity data from the corresponding climate files. Possible solutions were defined and implemented. A set of new building simulations with VA114 was carried out to study the balance of limited cooling load and overheating hours.

Stage 3 addressed the capacity (and dimensions) of the thermal storage system in the soil. The heating and cooling loads from stage 1 were used to define the target values. For this work use has been made of a specific tool for the simulation of ground source heat pump systems and borehole thermal storage, Earth Energy Designer (EED). EED has been developed to define the layout and size of systems, and to do more detailed parameter studies. For calculation of the heat transfer by non-stationary conduction EED assumes the soil to be vertically homogeneous.

Stage 4 returned the focus to the house, studying thermal comfort, stratification and radiation asymmetry. Here use has been made of the TNO in-house CFD simulation program WISH3D. WISH3D can be used to the calculate air speed, pressure, temperature and particle distributions in enclosed spaces as well as around buildings. WISH3D also has the option of plotting comfort parameters (Predicted Percentage of Dissatisfied, Draught Risk).

In order to provide context to the computational assessment the findings of the work were compared with feedback from an experimental project in real practice. This allows to make a number of additional remarks on the feasibility of the envisaged cooling system in real world projects.

4. MODELLING

For the simulations with VA114, EED and WISH3D the following sections describe the main assumptions and modeling steps.

4.1. Reference house

For building lay-out and properties the simulation work is based on houses as realized in an experimental project in real practice in the Netherlands that utilizes this system: Hofstad in the city of Houten. See figure 2. Findings from first year of occupation of this same project have been used to provide feedback from practice on the computational results as found in this study, as discussed in the previous paragraph.

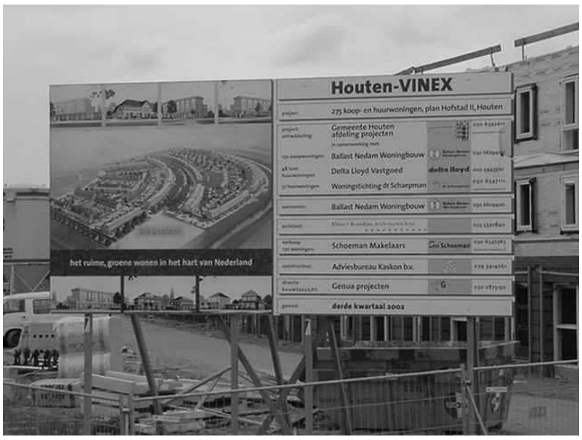

Figure 2 Project Hofstad during realization

Floor plans and construction for one of the houses in a row have been obtained. For VA114 these were simplified into a three zone model with one zone for each floor of the house (1 = living room/kitchen zone, 2 = bedroom zone on first floor, 3 = attic zone on second floor). See figure 3.

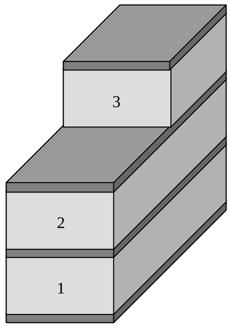

Figure 3 Schematic building design in VA114

The materialization of the house is as follows (outer layers first):

- outer walls: bricks (0.100m), cavity (0.030m), insulation material (0.100m), bricks (0.100m);
- floors: concrete (0.180m), finishing layer (0.030m), floor covering (0.008m);
- common walls: concrete (0.120m), cavity (0.030m), concrete (0.120m);
- windows/window frames: HR Glazing, ZTA-value 0.450, LTA-value 0.600, U-value 1.700
- doors: board (0.050m);
- roof: gravel (0.025m), insulation material (0.130m), concrete (0.300m).

Regarding occupancy the following assumptions have been made:

- day settings 7:00 - 23:00; night settings 23:00 - 7:00 hours. For the daytime settings a heating set point of 20°C and (where relevant) a cooling set point of 24°C has been used.
- Ventilation is constant at 0.75 h^{-1};
- Internal heat loads:
  7:00-17:00: Zone 1 400 W, Zone 2 50 W, Zone 3 25 W
  17:00-23:00: Zone 1 1000 W, Zone 2 50 W, Zone 3 25 W
  23:00-7:00: Zone 1 100 W, Zone 2 300 W, Zone 3 150 W.

For the calculation of humidity aspects the external humidity was raised by 0.002 kg/m^3 to represent the impact of inhabitants, plants, cooking etc.

4.2. Climate years

The outdoor climate has been simulated using climate files for the meteorological station of De Bilt. For normal climate conditions use has been made of the Test Reference Year deBilt.TRY. This is a synthetical year that is constructed from the combination of representative (average) months from different actual climate years. Warm climate conditions have been represented by the actual climate data for the Bilt in the year 1995.

The reference years include different relevant climate data, like hourly outdoor temperature, irradiation, and relative humidity.

4.3. Heat exchanger and soil

In the Netherlands, the most common type of heat exchanger in the soil is a double U-tube; this type therefore has been assumed for the simulation effort. For the reference house 3 boreholes, each with a double U-tube, have been taken into account; separation between these boreholes has been set at 5 meter (see figure 4). For transport medium water with 25% monopropylene glycol has been taken.

In line with the underlying assumptions of EED the soil has been modeled as vertically homogeneous silt. Together with clay and sand this is one of the three different soil types that exist in the Netherlands. In reality the soil mostly consists of layers of all three types; however, silt has average properties and therefore can be used to represent all layers.

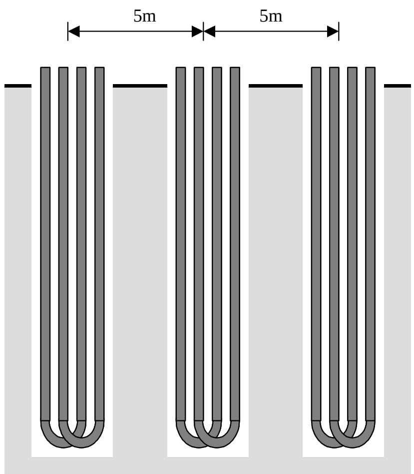

Figure 4 Bore hole and U-tube schematic

5. RESULTS

The following sections describe the computational results for the building simulation, assessment of condensation risk, earth storage simulation, CFD-efforts, and the findings from the actual project.

5.1. Building simulation

For a number of building variants the heating and cooling load have been calculated using the VA114 program. Variants are based on the applied climate year (average or warm), the application of simple passive cooling measures (application of simple sun shading devices to limit the chance of overheating and of summer night ventilation to reduce the cooling load at daytime), and different cooling set point values (24°C and 22°C). Regarding the cooling set point values a relatively high value of 24°C has been selected as default value, since houses in the Netherlands typically do not have cooling systems. However, most offices do have cooling systems, often using a set point value of 22°C. The results are presented in Table I.

Table I Heating and cooling loads

Variant	Climate year	Simple passive measures	Cooling set point (°C)	Heating load (kWh/yr)	Cooling load (kWh/yr)
1	average		24	5104.9	779.3
2	average	X	24	5104.9	286.9
3	warm		24	4493.7	1572.3
4	warm	X	24	4493.7	1244.7
5	average		22	5110.5	1573.0
6	average	X	22	5110.5	917.9
7	warm		22	4510.7	2418.8
8	warm	X	22	4510.7	2003.8

These results demonstrate that, for the given variation of climate, cooling measures and set points, the cooling load of the reference house varies between 300 and 2400 kWh/yr. For the same variation the heating load varies between 4500 and 5000 kWh/yr. This means that the relation between heating and cooling load is subject to large differences, and varies from 1:2 to 1:20.

Lowering the cooling set point from 24°C to 22°C clearly has a huge effect on the cooling load, which almost gets twice as high in an average year. Note that a lower cooling set point also results in a small increase of the heating load (a byproduct of storing less energy in warm days).

5.2. Assessment of condensation risk

The temperature differences between the indoor air and the surface temperatures of floors or walls that are cooled in order to prevent overheating might result in a risk of condensation. In general this risk can be assessed by studying surface temperatures and comparing those with the dew point temperature.

When using a low-temperature heating system for cooling purposes, the surface temperatures depend on the cooling load and corresponding temperatures of the cooling water coming from the heat pump. Therefore the relationship between dew point temperature and cooling demand has been plotted in figure 5. In figure 5, the diagonal line represents the cases where the surface temperature needed to match the cooling load equals the dew point temperature; there is no condensation in the areas above this line (A and B), while condensation occurs for all points under this line (areas C and D).

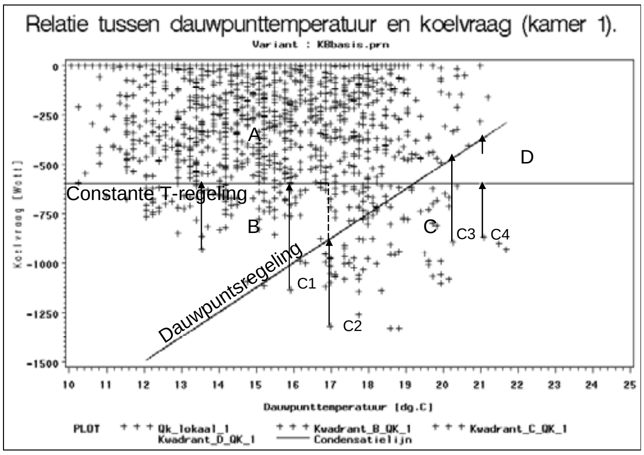

Figure 5 Cooling load versus dew point temperature

In practice, two control mechanisms are applied to prevent condensation: a simple limitation of the cooling water to a given, minimal value (constant temperature regulation, CTR). This effect is represented by the horizontal line in figure 5. The other option is to control the temperature of the cooling water according to the current dew point temperature (dew point regulation, DPR); in this case cooling power is limited as represented by the same diagonal line.

When assessing the effect of the CTR, it is obvious that there is a number of cases where cooling power is limited while the surface temperature is still above the dew point temperature (area B). There is also a small area (area D) where the dew point temperature is higher than the cut-off temperature, resulting in a small condensation risk. The impact of using DPR prevents condensation in all cases.

When using CTR, the temperature difference between water and air is limited to 5 K and the specific cooling power is limited to 12 W/m^2; according to general calculation procedures for floor heating in the Netherlands (ISSO 49, 2003). The limited cooling power is 600 W for zone 1 and 2 of the reference house, and 300 W for zone 3. This is a reduction of approximately 10% in relation to DPR. The limitation of the cooling power has been included in the simulations described in the next section, which demonstrate that even when using limited cooling power (due to CTR) the system of a heat exchanger in the soil, heat pump, and low-temperature heating system can limit overheating to acceptable numbers.

5.3. Earth storage simulation

Required dimensions of the thermal storage system in the soil have been calculated by the tool E.E.D., based on the heating and cooling demands as found from the simulation of the reference house.

Table II presents the results for basic variations, that is the dimensions needed to either heat or cool the house in an average or a warm year, without use of simple cooling measures and without consideration of peak loads.

Table II Dimensions for basic variations

Variant	Climate year	Heating	Cooling	Depth of borehole (m)	Length of heath exchanger (m)
	average	X		22.1	66.3
	average		X	21.8	65.4
	warm	X		21.9	65.8
	warm		X	28.8	86.3

Results show that for an average year the capacity of a system as needed for heating in the winter period is sufficient for cooling purposes in the summer. In a warm year however the cooling load increases, and more capacity is required.

Table III shows the impact of using simple passive cooling measures on the required dimensions for cooling purposes.

Table III Dimensions for cooling, including simple passive cooling measures

Variant	Climate year	Cooling	Simple passive measures	Depth of borehole (m)	Length of heath exchanger (m)
1	average	X		21.8	65.4
	average	X	X	21.5	64.5
2	warm	X		28.8	86.3
	warm	X	X	22.8	68.5

The results show that the use of simple cooling measures helps to bring down the dimensions as needed for cooling in a warm year to the same order of magnitude as required for heating purposes in the winter.

The effect of dimensioning the cooling capacity on peak loads is shown in Table IV. For the calculations peak loads of 2.5 kW have been assumed, which occur for a period of 4 hours in June, 6 hours in July, and 4 hours in August.

Table IV Dimensions for cooling, including peak loads

Variant	Climate year	Cooling	Peak loads	Simple passive measures	Depth of borehole (m)	Length of heath exchanger (m)
	average	X			21.8	65.4
	average	X	X		40.1	120.2
	average	X	X	X	35.6	106.8
	warm	X			28.8	86.3
	warm	X	X		55.6	166.6
	warm	X	X	X	49.8	149.4

These results show that fully dealing with peak loads requires the dimensions of the borehole to be almost tripled.

In order to study the impact of peak loads on the thermal comfort inside the house, additional VA114 work has been carried out. Results are presented in Table V. For an average and a warm year overheating hours have been analyzed for the variants that employ simple cooling measures. For these options the new set of simulations shows the effect of using the thermal storage in the soil with limited cooling capacity, which has been set to 600 W for zones 1 and 2, and 300 W for zone 3.

Table V Overheating (hours of exceeding given comfort temperatures)

Variant x: average year, simple cooling measures

Zone	h>24°C	h>26°C	h>28°C	h>30°C
1	743	126	5	0
2	575	77	0	0
3	675	120	1	0

Variant x: warm year, simple cooling measures

Zone	h>24°C	h>26°C	h>28°C	h>30°C
1	1521	1211	513	45
2	1487	1169	447	23
3	1508	1202	530	62

(Table VI continued)

Variant x: average year, simple cooling measures and limited cooling power

Zone	h>24°C	h>26°C	h>28°C	h>30°C
1	266	0	0	0
2	270	0	0	0
3	414	0	0	0

Variant x: warm year, simple cooling measures and limited cooling power

Zone	h>24°C	h>26°C	h>28°C	h>30°C
1	986	8	0	0
2	1025	0	0	0
3	112	41	0	0

These results show that in an average year the temperature exceeds a value of 26°C for only a limited number of hours. However, this number explodes in a warm year. The combination of limited cooling power (by the earth storage, heat pump and low-temperature heating system) and simple cooling measures returns overheating to acceptable levels.

5.4. CFD simulation

CFD-simulation with the tool WISH-3D (Lemaire et al. 1993) has been used to calculate the convective heat flow from the surfaces enclosing zone 1 (living room). Three different cases have been considered: A - floor cooling; B - wall cooling; and C - floor cooling with a sunspot (which results in mixing of the air). Results are presented in Table VII. Positive values indicate heat transfer from surface to air (heating), while negative values indicate heat transfer from the air to the surface (cooling).

Table VII Convective heat flows (W/m^2)

	Case A	Case B	Case C
floor	-1.2	3.5	-4.7
facade fr	0.8	5.6	-18.2
facade bck	0.8	5.6	-10.8
wall (l)	0.8	-7.4	-12.1
wall (r)	0.8	-7.4	-12.1
ceiling	0.0	0.5	-5.8
sunspot	0.0	0.0	1312.0

Results show that the convective heat exchange is very limited; the working of the cooling system therefore is predominantly through radiative heat exchange between the cooled surface and the other walls, floor and ceiling.

As can be expected, the effect of embedding a low-temperature in the wall produces slightly higher convective effects than embedding it in the floor where stratification limits the movement of air. As is demonstrated by the impact of adding a sunspot on the floor, additional movement of the air improves convectional heat exchange.

The results of the CFD-simulations also have been used to assess thermal comfort. A crude first overview can be obtained by the study of temperature fields in the zone; see for instance figure 6, presenting temperature fields for case B. See figurwe 6. From this figure it is clear that in this case (B) there are some temperature gradients near the wall and ceiling, indicating some stratification. However, overall air temperatures around the zone are balanced and no problems for thermal comfort are expected.

For more detailed analysis PPD-values, operative temperatures and draught risk have been calculated as well. The results are that PPD values are between -10% and +10%, operative temperatures are between 22.5°C and 24.5°C, and that draught risk is smaller than 15%. Each of these parameters has been plotted in the zone, see for instance the example of operative temperatures in figure 7. However, since differences are small no special effects are observed in these plots. Note that, as the cooling is mainly achieved by radiative heat transfer, it is important to avoid radiative asymmetry, as well as to avoid large temperature differences between floor and indoor air (that might result in the effect of cold feet, warm body).

5.5. Findings from the actual project Hofstad

Findings from the actual houses in the Hofstad project identify a number of issues that need attention when applying this technology in real practice:

- Occupants have high expectations of the cooling system, but are not aware of the differences between conventional air-conditioning units and the passive cooling system. Therefore information must be provided about the peculiarities of the system, preventing wrong operation and disappointment with system performance.
- People in the Netherlands in general do not heat their bedrooms; to this end they close the heating loops during winter. However, if they do not reopen these loops in spring, this prevents using the system for cooling during the summer. It would be advantageous to have some automated control on this issue, preventing unintentional shut-down of cooling loops.

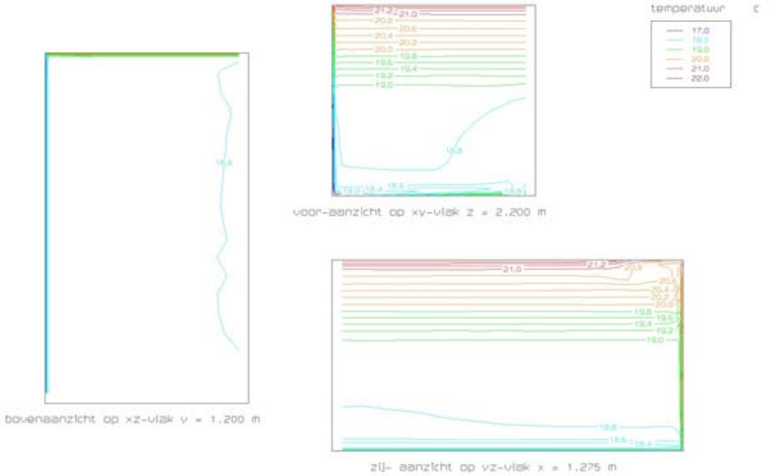

Figure 6 Temperature field in zone 1
(two symmetry planes applied)

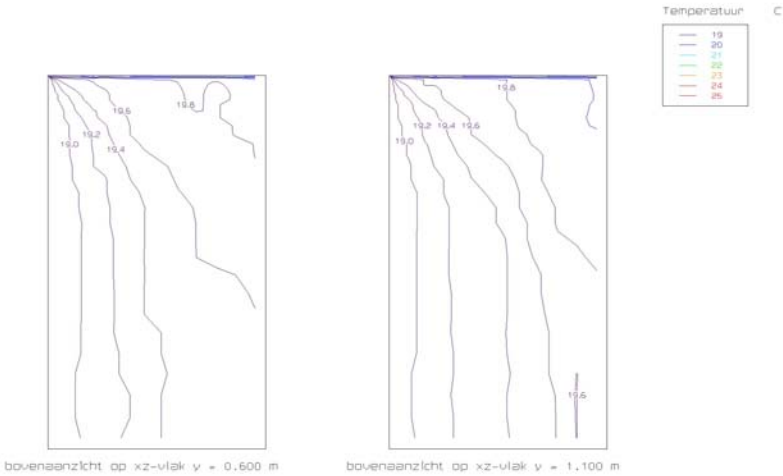

Figure 7 Operative temperature field in zone 1

- Metering data from the actual houses indicates that there might be days in spring and autumn where the system is used for both heating (in the early morning and evening) as well as for cooling (during the day). As the system has long warm-up and cool-down periods this is counterproductive and might result in a high loss of energy. Predictive control mechanisms might offer a solution to prevent this from happening.

6. CONCLUSIONS AND REMARKS

The findings of the work as presented in this paper lead to conclusions about both the system under consideration as well as to conclusions about the simulation efforts.

Cooling with low-temperature heating systems

Regarding cooling with a system consisting of a heat exchanger in the soil, a heat pump, and a low-temperature heating system the following has been concluded:

1. In the Netherlands the cooling of houses is gaining momentum. Cooling loads of course are strongly dependent on actual climate, sun shading, occupant behavior etc. In favorable conditions the cooling load of a reference house is limited to approximately 5% of the heating load; in unfavorable conditions however the cooling load can become in the order of magnitude of 50% of the heating load.

2. Cooling of floors and walls in summer periods introduces a condensation risk. To prevent condensation two control strategies can be applied: constant temperature regulation and dew point regulation. The first option is the easiest to apply, but limits cooling capacity with roughly 10%. However, this still greatly improves thermal comfort in the house. The second option removes all condensation risk without reduction of the cooling capacity, but requires a more complex control mechanism.

3. The use of a heat exchanger in the soil, a heat pump, and a low-temperature heating system for cooling purposes can only be successful when this system is used in combination with traditional cooling measures like sun shading and summer night ventilation.

4. The capacity of a storage system in the soil that has been dimensioned for heating purposes of the reference house is sufficient to meet the cooling demands of an average year. If the system is to cover the cooling load of a warm year or years with cooling peaks this capacity is insufficient; to fully cover corresponding demands the system capacity would have to be tripled.
   However, if a limited cooling power (and a small number of overheating hours) is accepted, the application of the system results in a large increase of thermal comfort, preventing overheating above 28^{o}C and strongly limiting the number of hours that the temperature exceeds 26^{o}C.

5. Cooling through a low-temperature heating system mainly works by means of radiative heat exchange between the cooled floor or wall and the other surfaces enclosing the room. Convective heat exchange between the system and the indoor air is limited due to stratification effects. Correspondingly the impact on thermal comfort in the rooms is mainly obtained by means of the radiative temperature rather than through a reduction of the mean air temperature. Radiation asymmetry and temperature differences due to stratification effects are within acceptable comfort boundaries (PMV-value, draught risk).

6. Occupants of houses that are equipped with a heat exchanger in the soil, a heat pump, and a low-temperature heating system which is used for cooling need to get proper information about the peculiarities, operation and performance of the system. Furthermore, a control system should be included that prevents mixed heating and cooling in spring and autumn.

Simulation efforts

Regarding the simulation efforts as discussed in this paper the following conclusions have been made:

1. In this computational study the simulation of the house and the earth storage have been de-coupled, meaning that building simulation has resulted in heating and cooling loads which have been used to drive subsequent earth storage simulations. This approach seems valid but requires that the effects of the actual cooling capacity of the storage on the temperature development in the building are checked. Nevertheless, this allows the use of adequate tools for each individual simulation effort.

2. In the CFD-simulations applied in this study the water temperature of the cooling wall or floor is a given (fixed) input parameter, and is not determined by studying the energy transfer between water, concrete and the indoor air, limiting the view on real world complexity. To overcome this limitation a (run-time) coupled approach should be applied (Djuneady et al. 2005).

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