ENERGY SAVINGS, SIMULATIONS AND ECONOMIC ANALYSIS OF A GROUND SOURCE HEAT PUMP WITH VERTICAL BOREHOLE HEAT EXCHANGERS FOR A BELGIAN OFFICE BUILDING

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Abstract: Since recent years cooling in office buildings is increasing due to higher internal heat production and higher thermal comfort requirements. This results in a higher electricity demand. Vertical borehole heat exchangers (BHEs) with a heat pump can reduce the primary energy consumption and CO_2 emissions if correctly designed. This paper presents simulation results of a whole integrated building and HVAC TRNSYS model with 90, 100 and 110 boreholes. The results are compared with a predefined “reference” installation defining energy savings, environmental benefits and economical results.

A primary energy saving and CO_2 emission reduction of 31% can be obtained compared to the reference installation. Attention should be given to the borehole filling during the installation process. The natural cooling fraction increases from 48% to 61% by decreasing the borehole resistance. The operational costs are higher for the reference installation (86%) than for the BTES (Borehole Thermal Energy Storage) system (73%). Over the lifetime of the system the GSHP and BHE is a far more economical choice than the reference installation. The recent interest in renewable energy is expected to further enhance their application.

Key Words: ***simulation, heat pump, borehole heat exchanger, office building***

1 INTRODUCTION

Energy consumption in the building sector is constantly expanding. In the European Union 40% of the total final energy consumption is related to that sector (EU 2006). This fact shows the importance of efficient design and construction in the development of energy efficient buildings for the future. To reduce greenhouse gases (GHG) emitted by heating and cooling plants the public sector needs to shift away from the use of conventional techniques towards renewable energy sources. The use of shallow geothermal energy combined with heat pumps can reduce the consumption of ‘conventional’ energy sources, primary energy and CO_2 emissions.

In the literature one can find numerous references on design, performance, economic analysis, handbooks and standards of GSHPs and BHEs. Despite the fact that this technology is known since almost 50 years, market penetration of GSHPs in Belgium is in preliminary stage. This is in contrast to the large numbers of GSHPs in other European countries (Germany, Austria, Sweden, Norway and Switzerland) (Sanner et al. 2003).

In Belgium, due to hydro geological limitations, the most interesting regions and cities of the country are not suitable for the technology of aquifer thermal energy storage (ATES) - an open loop system. An alternative solution for these regions could be borehole thermal energy storage (BTES) - a closed loop system. This technology can be considered as complementary to ATES where aquifers aren’t available. BTES systems are advantageous regarding their installation and operation, compared to ATES systems. By extending the heat pump system from a heat extraction system to a heat storage system, the BTES system has very interesting advantages (natural cooling, regeneration, high efficiency, low operational costs). Nevertheless the use of a geothermal heat pump with BHEs to heat or to cool buildings can create annual imbalances in the ground loads and detailed simulations are therefore necessary.

This paper provides an overview of the results from a feasibility study for a Belgian office building concerning the energy savings, optimal configuration and environmental benefits offered by using vertical BHEs in combination with GSHPs.

2 DESCRIPTION OF CASE STUDY

2.1 The Office Building

The office building is situated in Ghent (Belgium) and is the new headquarter of an electricity distribution company (gross floor area: 16,363 m², occupied ground surface 3000 m²). The building has five storeys and an atrium (see Figure 1). The building characteristics (insulation walls, windows, roof, and floor) are in accordance with Belgian legislation.

The air-conditioning is achieved by ventilation air and cooling coils in the office buildings. Cooling energy is provided by BHEs in natural cooling mode (without use of the heat pump), the heat pump working as cooling machine and additionally by a cooling machine. Heating energy is provided by the heat pump and additionally by condensing gas-fired boilers. The focus of the innovative system lies in the use of low temperature heating by the heat pump. By extracting heat from the ground cold is built up in the ground. The cold stored in the ground during the winter period is used in the summer to cool the building (natural cooling). This gives a double effect: a high energy-efficient cooling system and good performance of the heat pump during winter. The building has an insulation level in accordance with the energy requirements of the Flemish region.

Figure 1: View of the office building during construction

2.2 Ground Characteristics

When designing BHEs with GSHPs the knowledge of ground thermal properties (thermal conductivity, borehole thermal resistance, undisturbed ground temperature, specific heat capacity) are important for correct functioning of the system. Due to the higher investments costs, over-sizing of BHEs and GSHPs pays a higher penalty than in conventional applications. Obtaining accurate values for thermal ground properties requires detailed survey on site by a thermal response test (Gehlin 1997 and Zeng et al. 2003) or literature values (Hoes 2004). Parameters that can have an influence on the result are the building load, borehole spacing, borehole fill material and the on-site characteristics.

At the site of the office building the ground, up to a depth of 125 m, consists mainly of heavy clay with a large upper part of sand. Based on a thermal response test, the local thermal conductivity is measured as 1.86 W/m·K and the specific heat capacity to 2.45 MJ/m³·K. The undisturbed soil temperature is 12°C.

2.3 Computational Model of the Building and Installation

In this case study a model of the office building and simplified HVAC installation was built with the software program TRNSYS 16 (Klein 2000). Different types in TRNSYS 16 such as a ground model, heat pump model, building model, control type, etc., were combined into one model. With this simulation model different sizing of BHEs and GSHPs can be simulated.

For the energy simulation the following numerical assumptions are made:

- compression chiller efficiency $SPF_{cooling}$ = 3,2;
- heat pump efficiency $SPF_{heating}$ = 4,1;
- gas-fired boiler seasonal thermal efficiency η = 85%.

Knowing the thermal ground properties and hourly heating and cooling load one can start designing BHEs. With thermal energy storage systems, the determination of heating and cooling energy consumption is much more crucial compared to other conventional applications (boilers, compression chillers). The design method is based on the building loads calculated throughout the whole year, not just the peak heating and cooling demands. In the design methodology annual and multi year simulation becomes an invaluable tool – both in terms of calculating annual building loads, and long-term ground thermal response.

3 SIMULATION RESULTS

3.1 Building Simulation

Simulation provided the following general results: total heating power (not installed power) 1.9 MW, total cooling power is 1.2 MW. The corresponding density values are: 50 kWh/m² for cooling, 73 kWh/m² for heating, 73 W/m² maximum cooling power density, 116 W/m² maximum heating power density, 1,190 MWh_t per year heating demand and 824 MWh_t per year cooling demand. The monthly results of the energy simulation for the office building are shown in Figure 2.

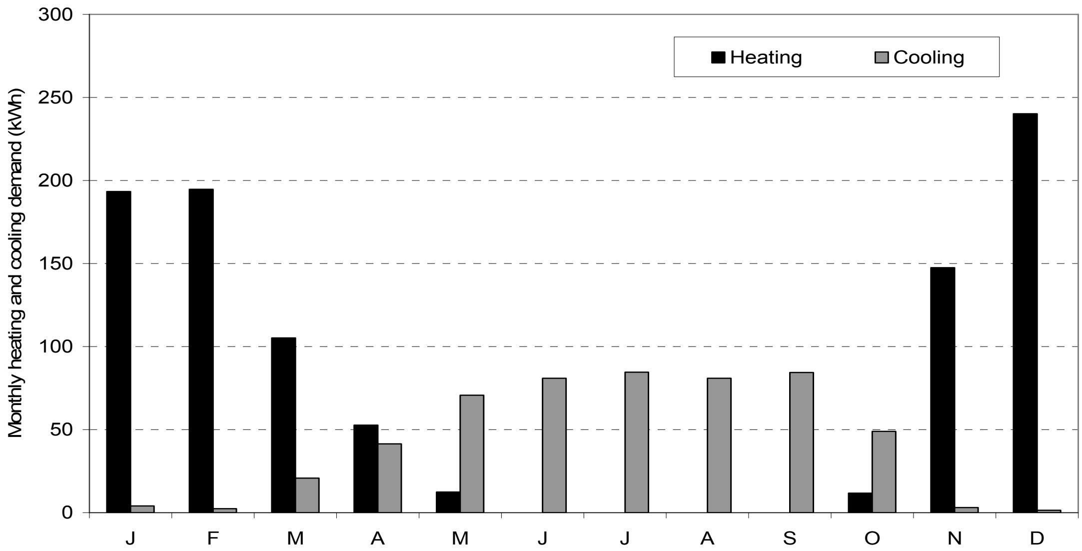

Figure 2: Monthly heating and cooling consumption

3.2 Borehole Heat Exchanger

By considering the hourly heating and cooling loads, the GSHPs and BHEs were chosen to supply only a part of the maximum peak cooling and heating demand. Ground loop heat exchanger configurations of 90, 100 and 110 boreholes of a depth 125 m were simulated in order to illustrate the effect of the ground loop on system performance. Only the results from the 90 borehole system are presented here. The borehole configurations are in each case the same, a square configuration with borehole spacing of 5 m. A monopropylene glycol (25% volume) solution is circulated throughout the boreholes. All simulations started at the 1st of January and were done for a period of 10 years.

Table 1 gives the energy balance for the yearly heating (Q_h), cooling (Q_c) and electricity (Q_e) demand for the office building (only HVAC no equipment or lighting demand included) for a system with 90 boreholes.

Table 1: Energy balance for the office building (90 boreholes)

Energy balance for the office building			
	Q_h [MWh_t]	Q_c [MWh_t]	Q_e [MWh_e]
Gas-fired boilers	290	-	1
Chillers	-	143	45
BHEs	-	400	9
GSHPs (cooling)	-	281	88
GSHPs (heating)	900	-	220
Total	1190	824	363

A heat pump with a thermal power of 500 kW_t (26% of total heating power) could deliver 76% of the total heating demand of the office building during the first year. In the 10th year this drops down to 69%. The BHEs (situation with 90 boreholes) can deliver 48% of the total cooling demand in the first year and this increase to 65% in the 10th year. With the BHEs and GSHPs the size of the compression chiller (-60%) and obviously the electricity needed to operate the compression chiller (-83%) can be reduced in comparison with the reference installation.

The total electricity consumption of the whole system (gas-fired boilers, compression chiller and heat pump) is higher (+28%) than in the reference installation, mainly because of electricity needs for the heat pump.

In comparison with compression chillers, the BHEs and GSHPs produces cooling energy at a higher efficiency ($SPF_{cooling}$ = 6) but also at a much higher temperature regime, typically 14/18°C instead of 6/12°C. The BHEs deliver cold (as natural cooling) at an efficiency of 44%.
An optimum design was found that faces energy needs of the heat pump and optimal simulation benefits. The simulation showed that 90 BHEs are needed at a depth of 125 m. The storage is formed by 9 rows of 10 boreholes arranged in a rectangular pattern. With a borehole configuration of 90 boreholes the swing in temperature is much more modest. The borehole spacing is 5 m, the borehole diameter is 150 mm and thus given a storage volume of 243,535 m³. The polyethylene (PE100) double U-tubes has an inside/outside diameter of 26/32 mm and a thickness of 3 mm. A specific heat extraction rate of 31 W/m of borehole depth was calculated. It must be noted that (Sanner 1995) reported much higher values, average specific heat extraction rates from 55 to 77 W/m.

One important factor on designing borehole heat exchangers is the borehole resistance (Verone and Czurda 2007). Figure 3 shows the simulation results for 3 different borehole resistances (0.1, 0.15 and 0.2 K/(W/m)) during 5 years of simulation. The effect of a good borehole resistance is very clear on the figure. The natural cooling fraction increases from 48% to 61% by decreasing borehole resistance. The lower the borehole resistance the better the system is working given high fraction of heating and cooling demands. During the realization of this installation special attention was given to ensure that the refilling of the boreholes was done correctly.

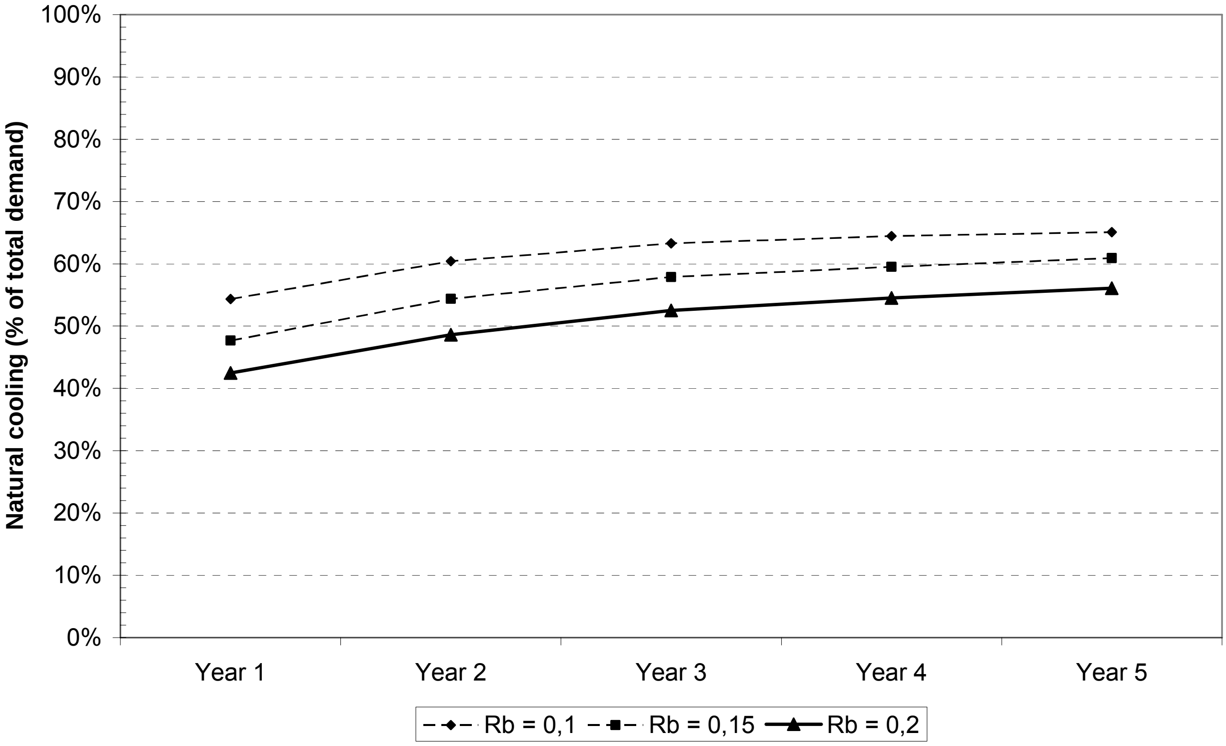

Figure 3: Influence of borehole resistance on results (5 years simulation)

4 ENVIRONMENTAL RESULTS

The primary energy consumption is compared to a reference installation with classical technologies (chiller and gas-fired boiler). A primary energy reduction of 31% per year can be reached compared to the reference installation. The CO_2 emission from each of the selected systems has been calculated. In the scenarios with BHEs and GSHPs the CO_2 emissions were lower; a CO_2 reduction of 128 tons per year can be realized or 31% in comparison with conventional applications.

5 ECONOMICAL RESULTS

A more economic selection can be made based on life cycle cost (LCC) of the different borehole systems taken into account the initial investments, reinvestments after their life time, the energy and maintenance costs. In this paragraph the results for only the system with 90 boreholes are presented in comparison with a classical heating and cooling installation (chillers and gas-fired boiler). LCC analysis is a process of evaluating the economic performance of a building or installation over its entire life (NIST 2003, IEA 2005, Yang 2005). LCC balances initial investments with long-term expenses of owing and operating the building or installation.

The end of life costs (residual value and demolition costs) and the costs needed to supply the heat and cold in the buildings were not taking into account. The HVAC installation in the building is the same for the 4 systems so the results of the LCC are the same. No salvage value was assumed for any of the systems at the end of the life time, but it is likely that the BTES / HP system would have some salvage value if the decision was made to install similar equipment but this would not significantly affect the LCC comparison. The life time calculation starts at 2008 until 2038 (30 years). The total net present value (NPV) is calculated as the sum of investment costs plus the NPV of the running costs and the NPV of the reinvestment. All mentioned costs and (re)investments were without Belgian taxes and subsidies.

Figure 4 give the NPV of the reference installation and the GSHP system with BHEs over the 30 years lifetime. These calculations were done based on a discount rate of 4%, an inflation rate of 2% and an energy price change factor of 2.1% per year.

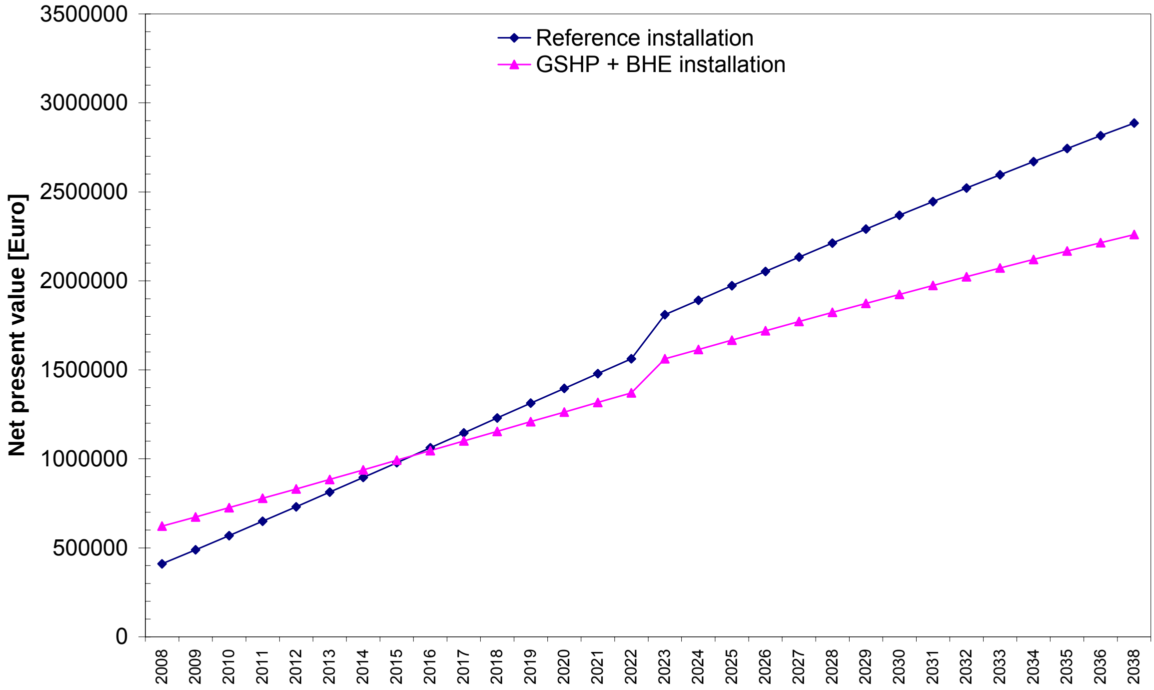

Figure 4: Net present value of reference and GSHP installation with 90 boreholes

The initial investment costs with GSHP and BHE are higher but the line is more flat during the life time comparing to the NPV of the reference installation. The graph showed that despite the higher initial investment costs this resulted in a dynamic payback period of 8.5 years. The operational costs in relation to the total NPV for the reference installation is higher (86%) than with the BTES system (73%). Over the lifetime of the system the GSHP and BHE is a far more economical choice then the reference installation.

6 CONCLUSIONS

The simulation model presented here can be used to model the performances of BHEs and GSHPs on a sub-hourly, annual and multi-year period. An important factor is the calculation of the heating and cooling energy demand. An over-estimation of the energy demand could damage the benefits of GSHPs by severely increasing initial investments and energy costs. This effect is more enhanced than with conventional installations (gas-fired boilers, compression chillers), where over-dimensioning is not rare and often encountered.

The simulation results showed that with a wisely designed system, a primary energy saving and CO_2 emissions reduction of 31% can be obtained compared to classic primary energy consuming technologies.

BHEs and GSHPs are a promising technique for Belgian office buildings. The recent interest in renewable energies is expected to further enhance their application. In general one may conclude that application of BHEs and GSHPs in Belgian office buildings becomes a growing market.

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