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Efficiency Investigation and Energy Saving of Vertical Ground Source Heat Pump

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Ključne riječi
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Dizalica topline s bušotinskim izmjenjivačem topline
Simulacija
Štednja energije
Uredska zgrada

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Original scientific paper
The paper presents results of an optimal design process of a ground-source heat pump system including thermal modelling of the system and selection of optimal design parameters which affect the system performance and operational costs. An integrated building and system simulation program was built for this purpose. The results were compared with a predefined “reference” installation defining energy savings, environmental benefits and economical results. It was found that a primary energy saving and CO_2 emission reduction of 31 % was obtained. Decreasing the borehole resistance leads to an increased natural cooling fraction of 48 % to 61 %. Operational costs were higher for the reference installation (86 %) than for the heat pump system (73 %). Over a lifetime, the ground source heat pump system is a far more economical choice.

Istraživanje učinkovitosti dizalice topline s bušotinskim izmjenjivačem topline

Izvornoznanstveni članak
Ovaj rad predstavlja rezultate optimiranja rada dizalice topline s bušotinskim izmjenjivačem topline, te uključuje termodinamički model sustava, odabir optimalnih parametara koji utječu na učinkovitost sustava te njegovih pogonskih troškova. U tu svrhu izgrađena je simulacija cjelovite zgrade s prethodno navedenim sustavom. Rezultati su uspoređeni s ranije definiranom referentnom instalacijom, definirajući uštede energije, pozitivan utjecaj na okoliš, te ekonomske rezultate. Rezultati su pokazali da je ostvarena ušteda primarne energije i smanjenje CO2 emisije od 31 %. Smanjenje toplinskog otpora bušotine vodi do porasta udjela prirodnog hlađenja s 48 % na 61 %. Operativni troškovi su bili veći za referentni sustav (86 %) za razliku od sustava s dizalicom topline s bušotinskim izmjenjivačem topline.(73 %). Obzirom na vijek trajanja, dizalica topline s bušotinskim izmjenjivačem topline predstavlja ekonomski isplativiju opciju.

1. Introduction

In the European Union 40 % of the total final energy consumption is related to the building sector [1]. A ground source heat pump (GSHP) in combination with vertical borehole heat exchangers (BHE) is an environmental option in various European countries for reducing the consumption of ‘conventional’ energy sources, primary energy and indirect CO_2 emissions [2, 3]. GSHP system performance is furthermore determined by the heat pump (HP) characteristics itself and thermal interaction between the ground and the BHE. The ground is used as a sink (cooling mode) or source (heating mode) of thermal energy and is nearly unlimited by using BHEs. The ground temperature at a suitable depth is independent from the ambient temperature but is strongly a function of soil type [4]. For sizing BHEs, local ground properties as thermal conductivity, borehole thermal resistance, undisturbed ground temperature, specific heat capacity, etc. are needed to deliver heat at a proper temperature [5]. The BHE thermal efficiency depends on the soil properties, temperature and characteristics of the heat exchanger itself (geometry, borehole spacing, grouting material, pipe thermal conductivity, etc.) [6-9]. The BHE costs are vital for the economical competitiveness of GSHP systems [10]. Sufficient thermal contact between borehole wall and the water circulation system is needed to limit vertical movements of water in the borehole [11]. In literature, one can find numerous references on design, performance, economic analysis, handbooks and standards of GSHPs and BHEs. Despite the fact that this technology has been for since almost 50 years, market penetration of GSHPs in Belgium is in the preliminary stage. This is in contrast to the large numbers of GSHPs in other European countries (Germany, Austria, Sweden, Norway and Switzerland) [2]. This paper provides an overview of the results from a feasibility study for a Belgian office building concerning energy savings, borehole configuration, economic and environmental benefits offered by using vertical BHEs in combination with GSHPs.

Symbols/Oznake

BHE	- Borehole heat exchanger - Bušotinski izmjenjivač topline
GSHP	- Ground source heat pump - Dizalica topline s bušotinskim izmjenjivačem topline
SPF	- Seasonal performance factor - Sezonski faktor djelovanja
TRT	- Thermal response test - Test toplinskog odziva

Indices / Indeksi

b	- borehole - bušotina
c	- cooling - hlađenje
h	- heating - grijanje

2. Description of case study

2.1. The office building

The office building is situated in Ghent (Belgium) and is the new headquarters of an electricity distribution company (gross floor area: 16363 m², occupied ground surface 3000 m²). The building has five storeys and an atrium. 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 the BHEs in natural cooling mode (without use of the heat pump), the heat pump working as a cooling machine and additionally by a cooling machine. Heating energy is provided by the heat pump and additionally by condensing gas-fired boilers. 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.

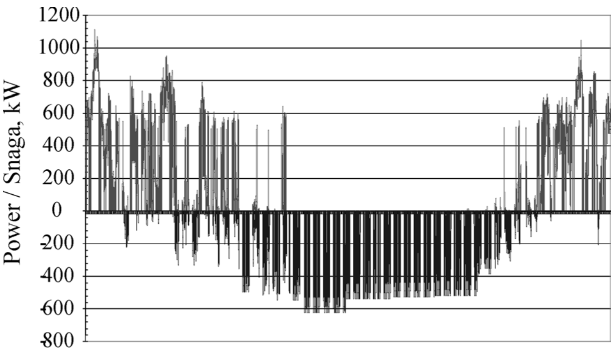

Figure 1. Heating (+) and cooling (-) loads of the building

Slika 1. Toplinsko (+) i rashladno (-) opterećenje zgrade

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. These parameters can be measured in-situ by a thermal response test (TRT). The principle of TRT is based on a known amount of heat injected into a borehole over a certain period of time, by letting a heat carrier fluid circulate through the borehole tubing while transferring the heat to the ground. The temperature response of the ground is measured by recording the inlet and outlet temperatures. The main aim of TRT should be to achieve data from steady state operation of sufficient length without avoiding extra costs in longer test duration and cumbersome data processing.

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 [12]. Different types in TRNSYS 16 such as a ground model, heat pump model, building model, control type, etc., were combined into one model and references were found to their validation [10, 13]. With this simulation model different sizing of BHEs and GSHPs can be simulated. Figure 1 show the heating and cooling loads of the building.

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, 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, 1190 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. Table 1 gives the sizing of the system.

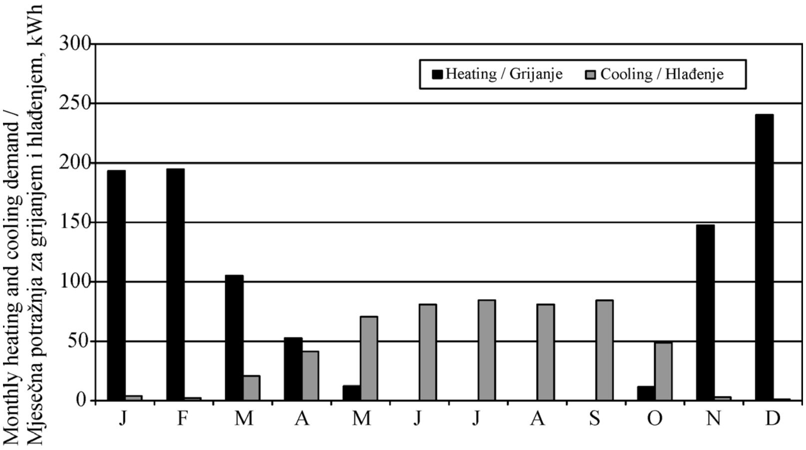

Figure 2. Monthly heating and cooling demand

Slika 2. Mjesečna potražnja za grijanjem i hlađenjem

Table 1. Sizing of the whole system

Tablica 1. Dimenzioniranje cijelog sustava

Component / Komponenta	Thermal power / Toplinska snaga, kW
Gas-fired boilers / Plinski bojleri	1900
Chiller / Rashlađivač	1200 (refrigeration)
BHEs (cooling) / (hlađenje)	350
GSHPs (condenser) / (kondenzator)	500

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 2 shows the main characteristics of the ground heat exchangers. The GSHP system using R-134a as refrigerant is a water-to-water vapour compression heat pump system. The heat pump consists of two plate heat exchangers used, evaporator and condenser, a vapour compression, an expansion valve and a regulation module. Working conditions are 0/5°C evaporator side (inlet/outlet temperature) and 35/45°C condenser side (inlet/outlet temperature).

The efficiency investigation in this paper is done following the method in [3, 14].

Table 3 gives the energy balance for the yearly heating (Q_h), cooling (Q_c) and electricity (E) demand for the office building (only HVAC no equipment or lighting demand included) for a system with 90 boreholes.

Table 2. Characteristics of the ground heat exchanger

Tablica 2. Karakteristike bušotinskog izmjenjivača topline

Parameter / Parametar	Value / Vrijednost
Borehole depth / Dubina bušotine	125 m
Number of boreholes / Broj bušotina	90, 100 or 110
Distance between boreholes / Udaljenost među bušotinama	5 m
Number of U-tubes / Broj U-cijevi	4
U-tube pipes / Dimenzije U-cijevi	26/32 mm
Borehole diameter / Promjer bušotine	180 mm
Ground thermal conductivity / Toplinska provodljivost tla	1.86 W/m K
Ground heat capacity / Toplinski kapacitet tla	2.45 MJ/m³·K

Table 3. Energy balance for the office building (90 boreholes)

Tablica 3. Energetska bilanca uredske zgrade (90 bušotina)

Energy balance for the office building / Energetska bilanca uredske zgrade			
	Q_h, MWh_t	Q_c, MWh_t	E, [MWh_e
Gas-fired boilers / Plinski bojleri	290	-	1
Chillers / Rashlađivači	-	143	45
BHEs	-	400	9
GSHPs (cooling) / (hlađenje)	-	281	88
GSHPs (heating) / (grijanje)	900	-	220
Total / Ukupno	1190	824	363

A heat pump with a thermal power of 500 kW (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 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 chiller (-60 %) and obviously the electricity needed to operate the chiller (-83 %) can be reduced in comparison with the reference installation.

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

In comparison with 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.

3.3. Influence of borehole resistance

One important factor on designing borehole heat exchangers is the borehole resistance [15]. 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 the 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 realization of this installation special attention was given to ensure that the refilling of the boreholes was done correctly.

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 taking 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. LCC analysis is a process of evaluating the economic performance of a building or installation over its entire life [16 – 18]. LCC balances initial investments with long-term expenses of owing and operating the building or installation. Figure 4 give the net present value (NPV) of the reference installation and the GSHP system with BHEs over a 30 year 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.

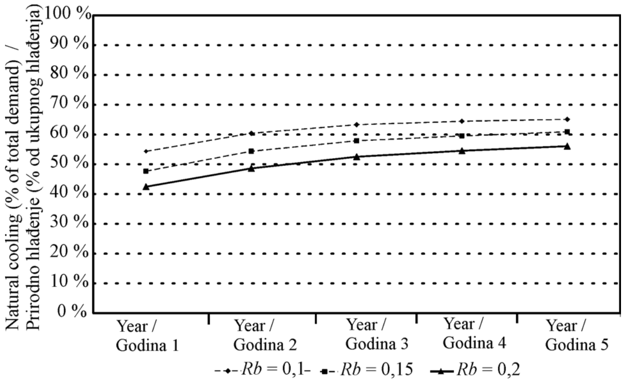

Figure 3. Influence of borehole resistance on results (5 years simulation)

Slika 3. Utjecaj toplinskog otpora bušotina na rezultate (simulacija za 5 godina)

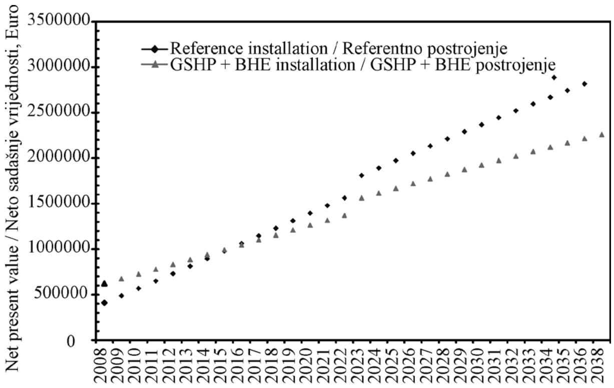

Figure 4. Net present value of reference and GSHP installation with 90 boreholes

Slika 4. Neto sadašnje vrijednosti referentnog i GSHP postrojenja s 90 bušotina

The initial investment costs with GSHP and BHE are higher but the line is more flat during the lifetime compared 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 BHEs (73 %). Over the lifetime of the system the GSHP and BHEs are a far more economical choice than 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, 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 is becoming a growing market.

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