

Ground-source pump system for heating and cooling: Review and thermodynamic approach

Original

Ground-source pump system for heating and cooling: Review and thermodynamic approach / Lucia, Umberto; Simonetti, Marco; Chiesa, Giacomo; Grisolia, Giulia. - In: RENEWABLE & SUSTAINABLE ENERGY REVIEWS. - ISSN 1364-0321. - STAMPA. - 70:(2017), pp. 867-874. [10.1016/j.rser.2016.11.268]

Availability:

This version is available at: 11583/2666875 since: 2017-03-12T16:48:15Z

Publisher:

Elsevier Ltd

Published

DOI:10.1016/j.rser.2016.11.268

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

Ground-source pump system for heating and cooling: review and thermodynamic approach

Umberto Lucia^{a,1,*}, Marco Simonetti^{a,2}, Giacomo Chiesa^{b,3}, Giulia Grisolia^{a,4}

^a Dipartimento Energia, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

^b Dipartimento di Architettura e Design, Politecnico di Torino, Viale Mattioli 39, 10125 Torino, Italy

¹ umberto.lucia@polito.it

² marco.simonetti@polito.it

³ giacomo.chiesa@polito.it

⁴ giulia.grisolia@studenti.polito.it

* Corresponding author

Abstract

Ground source heat pump (GSHP) is an innovative and perspective technology able to use the ground as a thermal sink or heat source. If combined with system operating at relatively low temperature, it represents a high efficiency solution for the heating of buildings. Complementarily, during cooling operation it has a good advantage with respect to air-cooled systems, because the ground temperature is stably lower than the outdoor air one. Geothermal heat pump systems are able to reduce the environmental impact of buildings for space heating and cooling by using the ground as an energy renewable source. This paper presents a review on the GSHP systems presenting both a summary of different ground-source typologies of heat pumps and a thermodynamic approach for their modeling. The irreversible thermodynamic approach is here summarized and exposed for a complete GSHPs system. This analytical approach is particularly useful for implementing an optimization design tool for GSHP systems. Recently many works have

been published about exergy analysis of these systems. Those works suggest that future lines of development may be considered: a) the optimization based on the transient performance of GSHP systems and not on the sole design condition; b) the integration of irreversible thermodynamic optimization approach into the algorithms of control systems. The diffusion of optimized GSHP systems is essential in order to reduce fossil fuel consumption and CO₂ emissions, complying with the EU's directive.

Keywords: ground source heat pumps, renewable energy, geothermal heating and cooling, thermodynamic model, dynamic optimization.

1. Introduction

On April 23rd 2009, The European Parliament and the Council adopted the Directive 2009/28/EC on the promotion of the use of energy from renewable sources: it represents the European Union common basis for the promotion of renewable energy [1]. Moreover, economic strategy for the sustainable development suggest both to improve energy efficiency and to introduce a rational use of energy in all the member states of the European Union [2].

Globally, the energy required in buildings for lighting, heating, cooling and air conditioning, is around the 40% of the total world annual consumption, with a considerable environmental impact due to the related CO₂, NO_x and CFCs emissions [3]. Nowadays, heat use for space heating and hot water generation requires around the 80% of the energy demand in houses and utility buildings. Moreover, during the last decades, a considerable increase of the global electrical consumption due to air conditioning demand and the related peak power demand has been pointed out in summer season [4-6]. Consequently, new power plants for electrical energy production are required. Moreover, an increase in the peak electricity cost has been pointed out.

Since 1997, when Montreal Protocol has been approved, governments agreed to phase out refrigerants which potentially destroys stratospheric ozone, to reduce energy consumption, to

decrease the rate of energy reserves use and of pollution. Consequently, a renewed interest has increased in cooling and heating technologies in order to reduce their environmental impact [3].

So, buildings can represent a fundamental topic of investigation in order to use its cost effective potential for energy savings, also related to the reduction of green house gas emissions. The fundamental way for building energy consumption reduction for heating, lighting, cooling, ventilation and hot water supply, is to a more accurate energy design buildings [3-7]. Innovative renewable would contribute to preservation of the environment by reducing the emissions at local and global levels. A new theoretical and design approach is required to integrate renewable energies in high performance building [3,8].

Heat pump is a thermal installation which is based on a reverse Carnot thermodynamic cycle which yields thermal energy at a higher temperature. Heat pumps enable the use of ambient heat at useful temperature level need electricity or other form of energy to function. The above-mentioned directive could open new opportunities for the diffusion of heat pumps for heating and cooling in buildings. Among the different kinds of heat pumps for heating and cooling of buildings, the ground source heat pumps (GSHP), known also as geothermal heat pump systems or geo-exchange systems, represent a new modern and perspective technology. Indeed, they use the heat stored beneath the earth surface as a thermal sink. GSHPs represent an alternative energy source for buildings heating and cooling applications. The GSHP applications are characterized by their relatively low operative temperatures. Their applications [15,16] can be in one of the three following categories of geothermal energy resources:

1. high-temperature ($> 150^{\circ}\text{C}$) } electric power production,
2. intermediate- and low- temperature ($<150^{\circ}\text{C}$) direct-use applications;
3. GSHP applications ($<32^{\circ}\text{C}$).

They can be considered a next future technology for saving primary energy as well as for heating and cooling cost reduction. Their fundamental components are the ground side, the heat

pump and the building, designed by taking care of the whole system, such that achieving the most effective operation for a good building comfort [9-14].

During the last years, GSHP have seen a market increase in some European countries among them Sweden and Switzerland are leading since the first 1980s.

This paper wish to review the GSHP systems. They use ground-source as a heat source or sink. To do so, in Section 2 a summary of the GSHP technologies is developed, Section 3 review the ground heat exchanger (GHE) modelling state of the art, in Section 4 the irreversible thermodynamic approach for their modeling is recalled.

2. Ground-source heat pumps technologies

In this section, a brief description of the present GSHP technologies is developed. The design and the relative cost of the system is affected by the geological properties, the subsurface temperatures, the thermal and the hydrological properties of the site. Consequently, system performance depends on the uncertainty in design input parameters, with particular regards to the temperature and thermal properties of the source. The GSHP systems general scheme is represented in Figure 1. It is composed by [15,16]:

1. The load side with an air-water or a water-water loop in relation to the application considered;
2. The refrigerant loop of the water source heat pump;
3. The ground loop in which water exchanges heat with the refrigerant and the earth.

The system absorb heat at a low temperature level and reject it to a higher temperature level [15,16]. The GSHPs use the thermal energy stored in the earth through two main different geometries of the circuits, vertical or horizontal heat exchange systems buried in the ground, as represented in Figure 2. The system can work both as a refrigerator and as a heating system, with the possibility of obtaining a dual-mode GSHP systems by using a reversing valve to switch

between heating and cooling modes, by reversing the refrigerant flow direction. In relation to the technology used, the GSHP systems can be classified in four categories [8]:

1. GWHP, ground-water heat pump systems, also known as open-loop systems, are the original type of GSHP system, first installed in the late 1940s [11]. They are vertical GWHP systems, which involve wells and well pumps in order to supply ground water to a heat pump or directly to the applications. The used ground water is discharged to a suitable receptor. Designing is based on the knowledge of some conditions related to the ground-water availability and its chemical quality. They are interesting systems for their low cost, simplicity in realization and small amount of ground area necessary. Disadvantages and problems are related to the possible limited availability and poor chemical quality and to ground water withdrawal and re-injection;
2. GCHP, ground-coupled heat pump systems, known as closed-loop GSHP systems [17]. They were developed during the 1970s with the advantage of overtaking the problems related to the ground water quality and availability. Moreover, they use less pumping energy than the previous systems because of the less elevation required [18]. In these systems, heat rejection and extraction is obtained by a high-density polyethylene pipe heat exchanger buried in vertical boreholes (Figure 2a) or horizontal trenches (Figure 2b). This fluid used can be water or an antifreeze solution. In the case of vertical borehole GCHP systems, the ground heat exchanger can be composed of (30.5-120 m)-deep and (76-127 mm)-diameter boreholes, backfilled with a material that prevents contamination of ground water, and with a (19-38 mm)-diameter U-shaped pipe through which the heat exchange fluid flows [19]. One of the difficulty in the vertical GCHP design consists in the appropriate sizing the depth of boreholes [20]. In horizontal GCHP systems, ground heat exchanger is composed of a series of (19-38 mm)-diameter and (121.9-182.9 m)-length parallel pipe, per ton of heating and cooling capacity, in horizontal (0.91-1.83 m)-deep boreholes. This superficial soil layer has an ample temperature swing: during fall season it is

at a higher temperature than the deeper soil (>10m depth), because of the summer solar irradiation; at the end of the winter it is typically at a lower temperature, due to the ground surface heat losses. For this reason, a drawback of this system is a less stable heat source temperature and a variable COP during the heating season

3. SWHP, surface water heat pump systems, in two different configurations:

- the closed-loop in which heat rejection-extraction circulating system is positioned at an optimized depth within a lake, pond, reservoir, or, in general, open channel. The thermal systems use pipes of (19÷38 mm)-diameters and a (30.5÷91.4 m)-length per ton of heating or cooling capacity;
- the open-loop type, in which screened intake area is used to extract water from the surface-water body. Then, the water is discharged to a receptor;

At the present, this technology is still in developing;

4. SCW, standing column well systems (Figure 3), in which water is pumped out and in a standing column in a deep well bore. The borehole, which allows the heat exchange fluid to be in direct contact with the earth, has diameters of about 15.2 cm with a depth of 457.2 m.

They have very significant installation costs

Table 1 summarizes and compares this category.

Initially, ground-coupled heat pumps were introduced in rural, residential applications [22,23], while their improvements for high level of comfort and low operating costs have allowed the market to be expanded to urban and commercial applications. For example, in USA, in 1985, the GSHPs installed in residential and commercial applications were 14,000, in 1990 around 100,000, in 1999 about 400,000: between the years 2000 and their annual energy use grew at a rate of 30.3%, while their installed capacities increased by 23.8% [24].

Their coefficient of performance (COP) is usually in the range 3÷3.8 because these systems work using the sink earth temperature which can be considered constant (the geothermal gradient is

around $30^{\circ}\text{C km}^{-1}$) at its working depth (6÷100 m). Moreover, they use water as a heat transfer medium which has a high heat capacity. The usual method of ground coupling consists in burying thermally fused plastic pipe in horizontal or vertical accommodation, using a circulator pump for water or antifreeze solution as thermal working fluid in heat exchanger such that no water enters the system from the ground. A less used system consists in a direct expansion such that a refrigerant lines are buried in the ground and the intermediate heat exchanger and fluid are eliminated [15]. Another rarely applied system, for vertical application only, uses heat pipes filled with phase changing CO_2 . The principal difficulty to rapid implementation of the GSHP is represented both by the technology involved and by their costs, even if some progresses have been made in their use for system integration, with the result of reducing the cost of the ground heat exchanger (GHE), of improving collector configuration and their control systems [15].

3. Thermodynamic analysis of the GHE (Ground Heat Exchanger)

Previously, the growing technological interest for the GSHP has been highlighted. Single borehole systems are generally used in residential applications, while multiple borehole systems for energy storage for commercial applications.

One of the fundamental key for their optimization is to obtain precise theoretical model for their designing. Indeed, their modelling is very complex because it requires a long-term steady-state temperature response; consequently, many simplified assumptions are usually introduced [25-32], even if these systems present transient responses, which would be taken into account. Moreover, their temperature response depends on the heat transfer inside the borehole and its heat conduction [26,27]. The borehole thermal mass and heat transfer resistance are the fundamental heat transfer quantities interesting in the heat transfer process. Indeed, its resistance may be conductive, if it is filled with viscous liquid, or conductive-convective if there is advection or thermally induced convection in a water-filled hole [25]. Moreover, the heat flow depends also on other factors, i.e.

the location and the boreholes thermal relative interaction. The two most critical design quantities are the appropriate length and the balance of the ground loads [32].

Many analytical and numerical models of different complexity have been introduced to design and optimize [33-47]:

- the heat transfer mechanism inside a borehole;
- the conductive heat transfer from a borehole;
- the thermal interferences between boreholes .

It is important to highlight that numerical models [33,34] are useful both to obtain very accurate solutions and to develop parametric analysis, but they aren't so flexible and they require long computational times. Moreover, building energy simulation software cannot incorporate these numerical models, with a consequent limited practical application for these numerical method.

A possible useful solution is to use hybrid models [35,37,39], used to calculate numerically particular temperature response functions that can be incorporated into the building simulation software.

But, the preferred models for practical applications are the analytical models [41,43,44,46,47]; indeed, even if they are less precise than the previous ones, they present small computational times and great flexibility for parameterized design. Their sole imprecision is related to the theoretical assumptions introduced.

All the model for the thermodynamic analysis of GHE are based on the evaluation of a relation of the kind:

$$T = T_0 + \frac{\dot{q}_b}{\lambda} f(\text{Fo}) \quad (1)$$

where T is the temperature of the borehole, surrounded by an infinite homogeneous medium at temperature T_0 , \dot{q}_b is the thermal power exchanged with the borehole, λ the thermal conductivity, f is a function of the Fourier number $\text{Fo} = a \tau / r_b^2$ is the Fourier number, a is the thermal diffusivity, τ

is the characteristic time, r_b its radius. The physical mathematical problem consists in obtaining the expression of the function $f(\text{Fo})$. The most used models are:

1. The analytical infinite length line source [23]: the Kelvin's theory on line source [48] has been implemented in order to obtain a radial heat transfer model. The ground heat exchanger is represented with a infinite length line source. It is assumed that the ground heat exchanger has a constant heat output. The result of this model is the following temperature difference [25]:

$$T = T_0 - \frac{\dot{q}_b}{4\pi\lambda} \text{Ei}\left(\frac{1}{4\text{Fo}}\right) \quad (2)$$

where Ei is the exponential integral function. Ei can be extended on the whole complex plane as [49]:

$$\begin{aligned} \text{Ei}(-x) &= -\text{E}_1(z) \quad , \quad x \in \mathbf{R}, z \in \mathbf{C}, \arg(z) < \pi \\ \text{E}_1(z) &= \int_z^\infty \frac{\exp(u)}{u} du \quad , \quad u \in \mathbf{C} \end{aligned} \quad (3)$$

In our case we use the Fourier number Fo, which is a real number, consequently the equation (2) results:

$$T = T_0 + \frac{\dot{q}_b}{4\pi\lambda} \text{E}_1\left(\frac{1}{4\text{Fo}}\right) \quad (4)$$

Last, if we need to use this equation in a building energy simulation software we can use its numerical expression [49]:

$$\text{E}_1\left(\frac{1}{4\text{Fo}}\right) = \gamma + \ln\left(\frac{1}{4\text{Fo}}\right) + \sum_{k=1}^{\infty} \frac{1}{k!k} \left(\frac{1}{4\text{Fo}}\right)^k \quad (5)$$

being γ the Euler-Mascheroni constant [50]:

$$\gamma = \lim_{n \rightarrow \infty} (H_n - \ln n) \quad (6)$$

and H_n the n -th harmonic number [51]:

$$H_n = \sum_{k=1}^n \frac{1}{k} \quad (7)$$

Consequently, remembering the expression of the natural logarithm, the expression for equation (2) for a building energy simulation software results:

$$T = T_0 + \frac{\dot{q}_b}{4\pi\lambda} \lim_{n \rightarrow \infty} \left\{ \sum_{k=1}^n \frac{1}{k} \left[1 + \frac{1}{k!} \left(\frac{1}{4\text{Fo}} \right)^k + (-1)^{k+1} \left(\frac{1}{4\text{Fo}} - 1 \right)^k \right] - \ln n \right\} \quad (8)$$

by using the useful approximation for the designing needs;

2. The analytical cylindrical source: the borehole is represented by a cylinder with constant heat flow across its boundary, from its infinite homogeneous environment. The result of this approach is the following relation:

$$T = T_0 - \frac{1}{\pi^2} \frac{\dot{q}_b}{\lambda} \int_0^\infty \frac{J_0(r_b^* \xi) Y_1(\xi) - J_1(\xi) Y_0(r_b^* \xi)}{J_1^2(\xi) + Y_1^2(\xi)} [1 - \exp(\text{Fo} \xi)] d\xi \quad (9)$$

where J_x are the x -th order Bessel function of the first kind, defined considering the Bourget-Giuliani functions [52,53]:

$$J_{n,k}(z) = \frac{1}{\pi} \int_0^\pi \cos^k(\vartheta) [\cos(n\vartheta) - z \sin(\vartheta)] d\vartheta \quad , \quad n \in \mathbb{Z}, k \in \mathbb{N} \quad (10)$$

with $k = 0, n = 0, 1$, so:

$$\begin{aligned} J_0(r_b^* \xi) &= J_{0,0}(r_b^* \xi) = \frac{1}{\pi} \int_0^\pi [1 - r_b^* \xi \sin(\vartheta)] d\vartheta = \sum_{n=0}^\infty \frac{(-1)^n}{(n!)^2} \left(\frac{r_b^* \xi}{2} \right)^{2n} \\ J_1(\xi) &= J_{1,0}(\xi) = \frac{1}{\pi} \int_0^\pi [\cos(\vartheta) - \xi \sin(\vartheta)] d\vartheta = \sum_{n=0}^\infty \frac{(-1)^n}{(n+1)!n!} \left(\frac{\xi}{2} \right)^{2n+1} \end{aligned} \quad (11)$$

In the relation (9) Y_x are the x -th order Bessel function of the second kind, named Neumann functions, defined as [54]:

$$Y_\alpha(z) = \frac{J_\alpha(z) \cos(\alpha\pi) - J_{-\alpha}(z)}{\sin(\alpha\pi)} \quad (12)$$

The integral in relation (9) is known as G -factor and it is usually evaluated as an approximated and tabular value [23,36]:

$$G = - \frac{1}{\pi^2} \int_0^\infty \frac{J_0(r_b^* \xi) Y_1(\xi) - J_1(\xi) Y_0(r_b^* \xi)}{J_1^2(\xi) + Y_1^2(\xi)} [1 - \exp(\text{Fo} \xi)] d\xi \quad (13)$$

3. The analytical finite length line source: the GHE thermal response is numerically modelled by the finite difference approach of a non-dimensional thermal response functions, called g -functions:

$$T = T_0 + \sum_i \frac{\dot{q}_i}{2\pi\lambda} g\left(\frac{t-t_i}{H^2/9a}, \frac{r_b}{H}\right) \quad (14)$$

where t is the time, \dot{q} is the heat power extracted, H active borehole dept and a is ground thermal diffusivity. The temperature response of the boreholes is obtained from a sum of step responses, which represent the response to any heat input. The explicit analytical g -function, of which the shape is represented in Figure 4, was obtained by introducing a finite length line heat source, it results [39]:

$$g\left(\text{Fo}, \frac{r_b}{H}\right) = \frac{1}{2} \int_0^1 \left[\left(\frac{r_b}{H}\right)^2 + \left(0.5 - \frac{z}{H}\right)^2 \right]^{-1/2} \text{erfc} \left\{ 0.5 \text{Fo}^{-1/2} \left[\left(\frac{r_b}{H}\right)^2 + \left(0.5 - \frac{z}{H}\right)^2 \right]^{-1/2} \right\} d\left(\frac{z}{H}\right) - \frac{1}{2} \int_0^1 \left[\left(\frac{r_b}{H}\right)^2 + \left(0.5 + \frac{z}{H}\right)^2 \right]^{-1/2} \text{erfc} \left\{ 0.5 \text{Fo}^{-1/2} \left[\left(\frac{r_b}{H}\right)^2 + \left(0.5 + \frac{z}{H}\right)^2 \right]^{-1/2} \right\} d\left(\frac{z}{H}\right) \quad (15)$$

4. Analytical Buried Electrical Cable Analogy: this approach allows us to evaluate the short-term response of the GHE, obtained by extending the non-dimensional temperature response functions.

4. GSHP efficiency analysis: first law and irreversible thermodynamic approaches

The best system, from an energy point of view, is the one which uses less energy to obtain the same useful output [55]. In the vast majority of GSHP application, driving energy for the heat pump is electricity, whose production depend on the energy mixes of each country. Thus, the thermodynamic efficiency of a GSHP is also related to the technological and ecological development of the single country of application.

In order to evaluate the energy efficiency, two different thermodynamic approaches must be considered:

1. The first law analysis, known also as the net energy analysis: it allows tracing the energy flows useful to produce products or services. Its mathematical expression is the energy balance:

$$\sum_{in} G_{in} (h + e_k + e_p)_{in} - \sum_{out} G_{out} (h + e_k + e_p)_{out} + \sum_i Q_i - W = 0 \quad (1)$$

where G is the mass flow, h is the specific enthalpy, e_k and e_p are the kinetic and the potential specific energy, Q is the exchanged heat and W the work done. From this equation a useful formulation of the first law efficiency was proposed [56] as:

$$\eta_I = \frac{H_{out}^{useful}}{H_{in}} \quad (2)$$

where H_{out}^{useful} represents the raw energy resource converted to useful energy, met downstream as final or end-use demand [57], while H_{in} is the input enthalpy;

2. The second law analysis, also known as the entropy or the exergy analysis: this law allows taking into account the degradation of the energy due to irreversible processes. In relation to this analysis the exergy balance equation:

$$\sum_{in} G_{in} ex_{in} - \sum_{out} G_{out} ex_{out} + \sum_i (Ex_Q - Ex_W)_i - I = 0 \quad (3)$$

where G is the mass flow, ex is the specific exergy, Ex_Q is the exergy associated with the exchanged heat Q , Ex_W is the exergy associated with the work done W and $I = Ex_{in} - Ex_{out}$ is the exergy loss for irreversibility. From this equation, a useful formulation of the second law efficiency was proposed [58] as:

$$\eta_{II} = \frac{Ex_{out}}{Ex_{in}} \quad (4)$$

First law analysis does not consider the energy quality, while the second law allows pointing out that not all the heat input can be converted into useful work, because of irreversibility. This law

requires the definition of parameters that allow quantifying the maximum amount of work achievable in a given system with different energy sources: this quantity is the exergy Ex defined as the available energy for conversion from a reservoir with a reference to the ambient environmental temperature [59]. So it represents the thermodynamic quality of the energy of a system [56].

In the last decades, the irreversible thermodynamic analysis of natural and engineering systems has been developed [60-85]. In this section, the entropy generation approach to the GSHPs will be summarized and developed.

To do so, we consider the system represented in Figure 5, composed by a compressor, a condenser, an evaporator, a fan-coil unit and a ground heat exchanger [81]. In order to develop this approach any component is considered and the exergy, entropy and mass flows. In relation to Figure 5, it follows:

1. for the compressor:

$$\begin{aligned}
 \dot{m}_1 &= \dot{m}_2 = \dot{m}_c \\
 \dot{W}_c &= \dot{m}_c (h_2 - h_1) \\
 Ex_{\lambda c} &= \dot{m}_c (ex_2 - ex_1) + \dot{W}_c = \dot{m}_c [(ex_2 - ex_1) + (h_2 - h_1)]
 \end{aligned} \tag{15}$$

where \dot{m} is the mass flow, \dot{W}_c is the mechanical power of the compressor, h is the specific enthalpy, Ex_{λ} is the exergy lost by the compressor, ex is the specific exergy defined as:

$$ex = (h - h_0) - T_0(s - s_0) \tag{16}$$

where s is the specific entropy and 0 means environmental;

2. for the condenser:

$$\begin{aligned}
 \dot{m}_5 &= \dot{m}_6 = \dot{m}_w \\
 \dot{Q}_{cd} &= \dot{m}_w (h_6 - h_5) \\
 Ex_{\lambda cd} &= \dot{m}_c (ex_2 - ex_3) + \dot{m}_w (ex_6 - ex_5)
 \end{aligned} \tag{17}$$

where cd means condenser and w means water;

3. for the lamination valve:

$$\begin{aligned}\dot{m}_3 &= \dot{m}_4 = \dot{m}_c \\ Ex_{\lambda v} &= \dot{m}_c (ex_3 - ex_4)\end{aligned}\quad (18)$$

where v means valve;

4. for the evaporator:

$$\begin{aligned}\dot{m}_4 &= \dot{m}_1 = \dot{m}_c \\ \dot{Q}_e &= \dot{m}_c (h_1 - h_4) \\ Ex_{\lambda e} &= \dot{m}_c (ex_4 - ex_1) + \dot{m}_{wv} (ex_8 - ex_7)\end{aligned}\quad (19)$$

where wv means the water evaporated;

5. for the fan-coil unit:

$$\begin{aligned}\dot{Q}_f &= \dot{m}_a (h_{a,out} - h_{a,in}) \\ Ex_{\lambda f} &= \dot{m}_w (ex_5 - ex_6) + \left(1 - \frac{T_0}{T_{a,in}}\right) \dot{Q}_e\end{aligned}\quad (20)$$

where a means air, T is the temperature, in means inflow and out means outflow;

6. for the ground heat exchanger (GHE):

$$\begin{aligned}\dot{m}_7 &= \dot{m}_8 = \dot{m}_{wv} \\ Ex_{\lambda GHE} &= \dot{m}_{wa} (ex_7 - ex_8) + \dot{m}_{wv} (h_8 - h_7)\end{aligned}\quad (21)$$

So the 2nd law efficiency can be obtained as the ratio of the sum of all the exergy flows flowing out of the system to the sum of all the exergy flows flowing into the system:

$$\eta_{II} = \frac{Ex_{out}}{Ex_{in}}\quad (22)$$

In the recent past some works reported exergy analysis of GSHP [86].

Akpinar and Hepbasli [87] performed a comparative exergy analysis of two types of GSHP systems installed in Turkey-based on operational data. Hepbasli and Akdemir [88] reported energy and exergy analyses of an experimental GSHP system, which was found to have coefficient of performance (COP) values ranging between 1.45 and 2.88. A GSHP drying system was also analyzed to determine drying performance parameters from an exergetic point of view [89] and

[90]. Ozgener and Hepbasli [91] modeled a solar-assisted vertical GSHP greenhouse heating system, determining an average exergy efficiency of 68.1%, while its COPs was ranging from 2.27 to 3.14. Bi et al. [92] presented a comprehensive exergy analysis of a GSHP system. This work showed that the GSHPs normally have considerably low exergy efficiency and thermodynamic perfection, suggesting a great potential for design enhancement through thermodynamic optimization.

Li and Lai [93] applied the entropy generation minimization (EGM) method for the design optimization of a vertical GHE. In their study, the analytical expressions were developed to determine both the optimal borehole depth and flow velocity. Su et al. [94] used the same EGM method, numerically solving the problem by using a genetic algorithms. The results showed that the total system cost (i.e. the upfront cost plus the first 10-years operation cost) of the system optimized by mean of EGM was 5.5% lower than the originally designed one.

All these optimization studies considered design working condition. In a GSHP system there are many transient variables: the temperature of the water flowing out from the borehole could have variation of some Kelvin degrees during an hour, and heating or cooling loads of buildings can vary hourly, as well. Intermittent working GSHPs have been proved to be more effective than systems working in continuous mode. The comparison of the coefficient of performance of the GSHP, between intermittent and continuous modes, denotes that the average COP of the GSHP system, when operating in heating and intermittent mode, is larger than that in the continuous mode by a factor that may range from 9%, after 100 h of operation, up to 12%, after 40 h of operation [95]. This fact suggests that optimization based on design conditions should evolve into dynamic optimization over a year cycle. In a recent work, Baccoli et al. [96] performed a time-profile calculation of exergy consumptions of two heat pump systems, one exploiting GHE and one harvesting heat from air. They found a relation for the instantaneous differences of the two system's exergy consumptions in heating and in cooling mode.

The studies reviewed in this paragraph demonstrated the reliability of the irreversible approach, which is based on analytical, but has been implemented in different tools for designing or for analyzing GSHP.

However, these works did not optimize configuration on the base of time-dependent exergy calculations, but they optimized the configuration parameters under a design condition or they performed time-dependent exergy analysis, after final dimensioning. Moreover, they did not consider the possibility of a variable configuration of the system. For example, a variable mass flow rate could be easily considered, both for GHE exchanging fluid and for refrigeration gas. Whenever a variable configuration is envisaged, a dynamic exergy optimization could be leveraged. A future category of dynamic control systems, which implement entropy generation minimization methods into their operating algorithm, could foster variable working parameter GSHP.

5. Conclusions

This paper reviews the available different GSHP technologies, the thermodynamic analysis of these solutions and the application of entropy generation approach to GSHP.

GSHP are increasingly affirming technologies. Their COP (Coefficient of Performance) is usually in the range 3-3.8. Different configurations of the ground heat exchanger exploit ground heat source from the surface down to a depth of 450m.

Several models of the ground heat exchanger of different complexity were introduced, in order to better design and optimize these system configurations. The precision of the theoretical models is an important parameter for correctly optimizing these solutions. The presented models are analytical, considering their better practical application if compared to the more precise numerical models. These last ones, in fact, are not so flexible and requires high timing and working efforts. Additionally, numerical models are not interoperable with software used for building energy simulations.

The paper has then reviewed the entropy generation approach for GSHP systems. This analytical approach is particularly useful since it allows a simple implementation in design tools, considering the possibility to automatically optimize the design process. The general application of this approach to the GSHP is explained and recent works on the topics are recalled. The seasonal average exergy efficiency of GSHP has been calculated around 68%, which suggests a huge optimization potential. Moreover, the entropy generation optimization can reduce by a 5.5% the installation costs of the system.

From this review, it emerges that two possible lines of evolutions can be considered for future development:

1. 2nd law optimization can be considered under a dynamic approach, since the design operating conditions could vary significantly, during a single day and during the season;
2. The 2nd law optimization could be implemented into a control algorithm, operating on a set of variable configuration parameters, such as mass flow rate into the U-tube borehole, on the basis of a time-running calculation of minimum entropy.

These improvements could likely enhance the efficiency of GSHP systems and increase their potential for reduction of CO₂ emission, following the global target of sustainability.

References

- [1] European Union, Promotion of the use of energy from renewable sources, December 11th, 2014: http://europa.eu/legislation_summaries/energy/renewable_energy/en0009_en.htm
- [2] Sarbu I, Sebarchivici C. General review of ground-source heat pump systems for heating and cooling of buildings. *Energy and Buildings* 2014; 70: 441-54.
- [3] Omer AM. Direct expansion ground source heat pumps for heating and cooling. *International Research Journal on Engineering* 2013; 1(2): 27-48.
- [4] Chiesa G, Simonetti M, Grosso M. A 3-field earth-heat-exchange system for a school building in Imola, Italy: Monitoring results. *Renewable Energy* 2014; 62: 563-70.

- [5] Givoni B. *Passive and low energy cooling of buildings*. New York: Van Nostrand Reinhold; 1994.
- [6] Santamouris M. Preface: why passive cooling? In. Santamouris M Ed. *Advances in passive cooling*. London: Earthscan; 2007: xix-xxxii.
- [7] Cantrell J, Wepfer W. Shallow Ponds for Dissipation of Building Heat: A case Study. *ASHRAE Trans*. 1984; 90(1): 239-46.
- [8] ASHRAE. *Commercial/Institutional Ground Source Heat Pump Engineering Manual*. American Society of heating, Refrigeration and Air-conditioning Engineers, Inc. Atlanta, GA: USA; 1995.
- [9] ASHRAE Handbook-HVAC Applications: Geothermal Energy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta: ASHRAE; 2007; 32: 1-29.
- [10] Breger D, Hubbell J, Hasnaoui H, Sunderland J. Thermal energy storage in the ground: comparative analysis of heat transfer modeling using U-tubes and boreholes. *Solar Energy* 1996; 56(6): 493-503.
- [11] Kavanaugh S, Rafferty K. *Ground-source heat pumps, design of geothermal systems for commercial and institutional buildings*. Atlanta: ASHRAE; 1997.
- [12] Omer AM. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews* 2008; 12(2): 344-71.
- [13] Yang H, Cui P, Fang Z. Vertical-borehole ground-coupled heat pumps: a review of models and systems. *Applied Energy* 2010; 87(1): 16-27.
- [14] EGEC, European Geothermal Energy Council. *Geothermal Heat pumps – Ground source Heat pumps*. December 11th, 2014: <http://ecec.info/wp-content/uploads/2011/01/EGEC-Brochure-GSHP-2009.pdf>
- [15] Omer AM. Direct expansion ground source heat pumps for heating and cooling. *International Research Journal on Engineering* 2013; 1(2): 27-48.

- [16] Do SL, Haberl J. A review of ground coupled heat pump models used in whole-building computer simulation programs. Proceedings of the 17th Symposium for Improving Building Systems in Hot and Humid Climates Austin Texas August 24-25, 2010.
- [17] Breger D, Hubbell J, Hasnaoui H, Sunderland J. Thermal energy storage in the ground: comparative analysis of heat transfer modeling using U-tubes and boreholes. *Solar Energy* 1996; 56(6): 493-503.
- [18] Claesson J. 1991. PC design model for thermally interacting deep ground heat exchangers. Proceeding WS on GSHP Montreal, HPC-WR-8, Sittard; 1991; 95-104.
- [19] Claesson J, Eskilson P. PC design model for heat exchanger boreholes. Proceeding. 4th International Conference Energy Storage JIGASTOCK 88, Paris; 1988; 135-7.
- [20] Claesson J, Eskilson P, Hellström G. PC design model for heat extraction boreholes. Proceeding 3rd WS on SAHPGCS Göteborg, CIT; 1990; 3: 99-102.
- [21] DOE 2010. EnergyPlus Energy Simulation Software. Retrieved July 2010, from Energy Efficiency & Renewable Energy: <http://apps1.eere.energy.gov/buildings/energyplus/>
- [22] Ingersoll L, Plass H. Theory of the Ground Pipe Heat Source for the Heat Pump. *ASHVE Transactions* 1948; 54: 119-22.
- [23] Ingersoll L, Zobel O, Ingersoll A. Heat Conduction with engineering, geological, and other applications. New York: McGraw-Hill; 1954.
- [24] Lund JW, Freeston DH, Boyd TL. Direct application of geothermal energy: 2005 Worldwide review. *Geothermics* 2005; 34(6): 691-727.
- [25] Javed S, Fahlén P, Claesson J. Vertical ground heat exchangers – A review of heat flow models. Proceedings of 11th International Conference on Thermal Energy Storage, Effstock 2009, Stockholm, Sweden, 2009.
- [26] Javed S, Fahlén P. Thermal response testing of a multiple borehole ground heat exchanger. *International Journal of Low Carbon Technologies* 2011; 6(3): 141-148.

- [27] Javed S, Claesson J. New analytical and numerical solutions for the short-term analysis of vertical ground heat exchangers. *ASHRAE Transactions* 2011; 117(1): 3-12.
- [28] Javed S, Spitler J, Fahlén P. An experimental investigation of the accuracy of thermal response tests used to measure ground thermal properties. *ASHRAE Transactions* 2011; 117(1): 13-21.
- [29] Claesson J, Javed S. An analytical method to calculate borehole fluid temperatures for time-scales from minutes to decades. *ASHRAE Transactions* 2011; 117(2): 279-288.
- [30] Liebel H, Javed S, Vistnes G. Multi-injection rate thermal response test with forced convection in a groundwater-filled borehole in hard rock. *Renewable Energy* 2012; 48(2012): 263-268.
- [31] Javed S, Nakos H, Claesson J. A method to evaluate thermal response tests on groundwater-filled boreholes. *ASHRAE Transactions* 2012; 118(1): 540-549.
- [32] Claesson J, Javed S. A load-aggregation method to calculate extraction temperatures of borehole heat exchangers. *ASHRAE Transactions* 2012; 118(1): 530-539.
- [33] Al-Khoury R, Bonnier P, Brinkgreve B. Efficient finite element formulation for geothermal heating systems. Part I: steady state. *International Journal for Numerical Methods in Engineering* 2005; 63(7): 988-1013.
- [34] Al-Khoury R, Bonnier P. Efficient finite element formulation for geothermal heating systems. Part II: transient. *International Journal for Numerical Methods in Engineering* 2006; 67(5): 725-45.
- [35] Bandyopadhyay G, Gosnold W, Mann M. Analytical and semi-analytical solutions for short-time transient response of ground heat exchangers. *Energy and Buildings* 2008; 40(10): 1816-24.
- [36] Bernier MA. Ground-coupled heat pump system simulation. *ASHRAE Transactions* 2001; 106(1): 605-16.

- [37] Bernier MA, Labib R, Pinel P, Paillot R. A Multiple load aggregation algorithm for annual hourly simulations of GCHP systems. *HVAC&R Research* 2004; 10(4): 471-87.
- [38] Carslaw HS, Jaeger JC. *Conduction of heat in solids*. Oxford: Oxford University Press; 1959.
- [39] Eskilson P, Claesson J. Simulation model for thermally interacting heat extraction boreholes. *Numerical Heat Transfer* 1988; 13: 149-65.
- [40] Hart P, Couvillion R. *Earth coupled heat transfer*. National Water Well Association, Dublin, OH; 1986.
- [41] Ingersoll LR, Plass HJ. Theory of the ground pipe heat source for the heat pump. *Heating, Piping & Air Conditioning* 1948; 20(7): 119-22.
- [42] Ingersoll LR, Zobel OJ, Ingersoll AC. *Heat conduction with engineering, geological and other applications*. New York :McGraw-Hill; 1954.
- [43] Lamarche L, Beauchamp B. A new contribution to the finite line-source model for geothermal boreholes. *Energy and Buildings* 2007; 39(2): 188-98.
- [44] Lamarche L, Beauchamp B. New solutions for the short-time analysis of geothermal vertical boreholes. *International Journal of Heat and Mass Transfer* 2007; 50(7-8): 1408-19.
- [45] Lund JW, Freeston DH, Boyd TL. Direct application of geothermal energy: 2005 Worldwide review. *Geothermics* 2005; 34(6): 691-727.
- [46] Nagano K, Katsura T, Takeda S. Development of a design and performance prediction tool for the ground source heat pump system. *Applied Thermal Engineering* 2006; 26(14-15): 1578-92.
- [47] Zeng HY, Diao NR, Fang ZH. Heat transfer analysis of boreholes in vertical ground heat exchangers. *International Journal of Heat and Mass Transfer* 2003; 46(23): 4467-81.
- [48] Kelvin TW. *Mathematical and physical papers*. London: Cambridge University Press; 1882.
- [49] Harris FE. Spherical Bessel Expansions of Sine, Cosine, and Exponential Integrals. *Appl. Numer. Math.* 2000; 34: 95-98.
- [50] Havil J. *Gamma: Exploring Euler's Constant*. Princeton: Princeton University Press; 2003.

- [51] Graham RL, Knuth DE, Patashnik O. Concrete Mathematics. Cummings: Addison-Wesley; 1990.
- [52] Bourget J. Mémoire sur les nombres de Cauchy. J. Math. Pures App. 1861; 6: 33-54.
- [53] Giuliani G. Alcune osservazioni sopra le funzioni sferiche di ordine superiore al secondo e sopra altre funzioni che se ne possono dedurre. Giornale di Matematiche di Battaglini 1888; 26: 155-171.
- [54] Bayin SS. Mathematical Methods in Science and Engineering. Hoboken: Wiley; 2006
- [55] Chicco G. Sustainability challenges for future energy systems. J. Sustainable Energy 2010; 1(1): 6-16.
- [56] Hammond G, Stapleton AJ. Exergy analysis of the United Kingdom energy system. Proceedings of the Institution of Mechanical Engineers, part.A: Journal of Power and Energy 2001; 215(A2): 141-162.
- [57] Slessor M. Energy in the Economy. London: Macmillan, 1978.
- [58] Van Gool W. The value of energy carriers. Energy 1987; 12(6): 509–518.
- [59] Sciubba E. Modelling the energetic and exergetic self-sustainability of societies with different structures. Transactions of ASME: Journal of Energy Resource Technology 1995; 177: 75–86.
- [60] Lucia U. Entropy generation: Minimum inside and maximum outside. Physica A 2014; 396: 61-65.
- [61] Lucia U. Overview on fuel cells. Renewable & Sustainable Energy Reviews 2014; 30: 164-169.
- [62] Lucia U. Entropy generation: From outside to inside!. Chemical Physics Letters 2013; 583: 209-212.
- [63] Lucia U. Carnot efficiency: Why?. Physica A 2013; 392(17): 3513-3517.
- [64] Lucia U. Adsorber efficiency in adsorption refrigeration. Renewable & Sustainable Energy Reviews 2013; 20: 570-575.

- [65] Lucia U. Entropy and exergy in irreversible renewable energy systems. *Renewable & Sustainable Energy Reviews* 2013; 20(1): 559-564.
- [66] Lucia U. Stationary open systems: A brief review on contemporary theories on irreversibility. *Physica A* 2013; 392(5): 1051-1062.
- [67] Lucia U. Entropy generation in technical physics. *Kuwait Journal of Science and Engineering* 2012; 39(2A): 91-101.
- [68] Lucia U. Maximum or minimum entropy generation for open systems?. *Physica A* 2012; 391(12): 3392-3398.
- [69] Lucia U. Second law analysis of the ideal Ericsson magnetic refrigeration. *Renewable & Sustainable Energy Reviews* 2011; 15(6): 2872-2875.
- [70] Lucia U. and Gervino G. Hydrodynamic cavitation: from theory towards a new experimental approach. *Central European Journal of Physics* 2009; 7(3): 638-644.
- [71] Lucia U. General approach to obtain the magnetic refrigeration ideal coefficient of performance COP. *Physica A* 2008; 387(14): 3477-3479.
- [72] Bejan A. Entropy generation through heat and mass fluid flow. New York: Wiley & Sons; 1982.
- [73] Bejan A. Entropy generation minimization. Boca Raton: CRC Press; 1995.
- [74] Bejan A. Method of entropy generation minimization, or modeling and optimization based on combined heat transfer and thermodynamics. *Revue Générale de Thermique* 1996; 35: 637-646.
- [75] Bejan A., Tsatsaronis A. and Moran M. Thermal design and optimization. New York: Wiley & Sons; 1996.
- [76] Bejan A. Convection Heat Transfer. New York: Wiley; 2000.
- [77] Bejan A. Shape and Structure, from Engineering to Nature. Cambridge: Cambridge University Press; 2000.

- [78] Bejan A. and Lorente S. The constructal law and the thermodynamics of flow systems with configuration, *International Journal of Heat and Mass Transfer* 2004; 47: 3203-3214.
- [79] Bejan A. *Advance Engineering Thermodynamics*. New York: John Wiley; 2006.
- [80] Bejan A. and Lorente S. The constructal law of design and evolution in nature. *Phil. Trans. R. Soc. B* 2010; 365: 1335-1347.
- [81] Sciubba E. and Wall G. A brief Commented History of Exergy From the Beginnings to 2004. *Int. J. Thermodynamics* 2007; 10(1): 1-26.
- [82] Bergles A.E. Some perspectives on enhanced heat transfer – 2nd-generation heat transfer technology. *J. Heat Transfer, Transaction of the ASME* 1988; 110(4B): 1082-1096.
- [83] Bergles A.E., Heat transfer enhancement – the encouragement and accommodation of high heat fluxes, *J. Heat Transfer, Transaction of the ASME* 1997; 119(1): 8-19.
- [84] Hesselgreaves J.E., Rationalization of Second Law analysis of heat exchangers, *Int. J. Heat and Mass Transfer* 2000; 43(22): 4189-4204.
- [85] Shah R.K. and Skiepko T. Entropy generation extrema and their relationship with heat exchanger effectiveness – Number of transfer unit behavior for complex flow arrangements, *J. Heat Transfer – Transaction of the ASME* 2004; 126(6): 994-1002.
- [86] Hepbasli A. Thermodynamic analysis of a ground-source heat pump system for district heating. *International J. of Energy Research* 2005; 29: 671-687.
- [87] Akpınar, E.K., Hepbasli, A. Comparative study on exergetic assessment of two ground-source (geothermal) heat pump systems for residential applications. *Building and Environment* 42, 2004–2013.
- [88] Hepbasli, A., Akdemir, O. Energy and exergy analysis of a ground source (geothermal) heat pump system. *Energy Conversion and Management* 45(5), 737–753.
- [89] Kuzgunkaya, E.H., Hepbasli, A., Exergetic evaluation of drying of laurel leaves in a vertical ground-source heat pump drying cabinet. *International Journal of Energy Research* 2007; 31(3): 245–258.

- [90] Kuzgunkaya, E.H., Hepbasli, A. Exergetic performance assessment of a ground-source heat pump drying system. *International Journal of Energy Research* 2007; 31(8): 760–777.
- [91] Ozgener, O., Hepbasli, A. A parametrical study on the energetic and exergetic assessment of a solar assisted vertical ground-source heat pump system used for heating a greenhouse. *Building and Environment* 2007; 42: 11–24.
- [92] Bi, Y., Wang, X., Liu, Y., Zhang, H., Chen, L. Comprehensive exergy analysis of a ground-source heat pump system for both building heating and cooling modes. *Applied Energy* 2009; 86(12): 2560–2565.
- [93] Li M, Lai AKC. Thermodynamic optimization of ground heat exchangers with single Utube by entropy generation minimization method. *Energy Convers Manage* 2013; 65: 133-139.
- [94] Huang , S., Ma, Z. & Cooper, P. Optimal Design of Vertical Ground Heat Exchangers by Using Entropy Generation Minimization Method and Genetic Algorithms. *Energy Conversion and Management* 2014; 87: 128-137.
- [95] Man, Y., Yang, H., Wang, J., Fang, Z. In situ operation performance test of ground coupled heat pump system for cooling and heating provision in temperate zone, *Appl. Energy* 2012; 97: 913-920
- [96] Baccoli, R., Mastino, C. and Rodriguez, G. Energy and exergy analysis of a geothermal heat pump air conditioning system, *Applied Thermal Energy* 2015; 86: 333-347

Table 1 – GSHP technologies comparison

Category Initialisms	Category description	Sub categories	Heat source	Heat source recharge	Typical working depth [m]
GWHP	Ground-water heat pumps or open loop systems	-	Ground water	Geothermal	6-100
GCHP	Ground-coupled heat pumps or closed loop systems	Vertical	Soil	Geothermal	6-120
		Horizontal	Soil	Solar irradiation + geothermal	1.5
SWHP	Surface water heat pumps	Closed-loop	Surface water	Solar irradiation + balance with atmosphere + geothermal	0-5
		Open-loop			
SCW	Standing column well systems	-	Ground water	Geothermal	up to 450

Figure 1. General design of GSPS

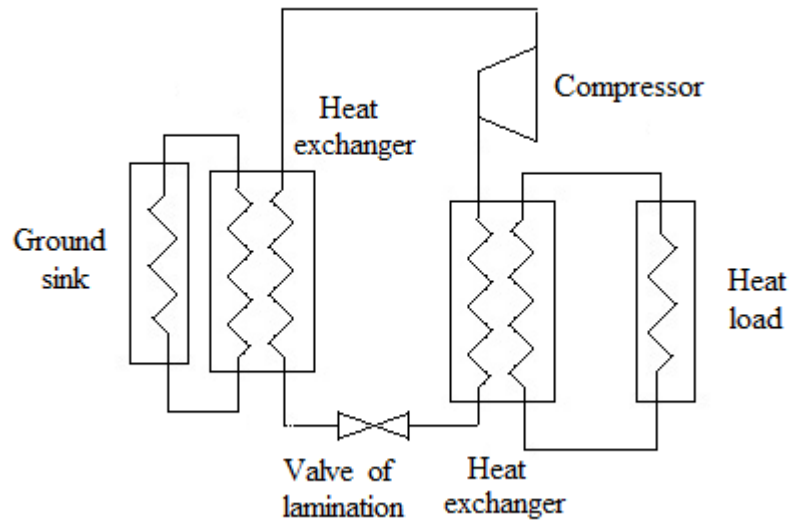


Figure 2. Geometric well systems

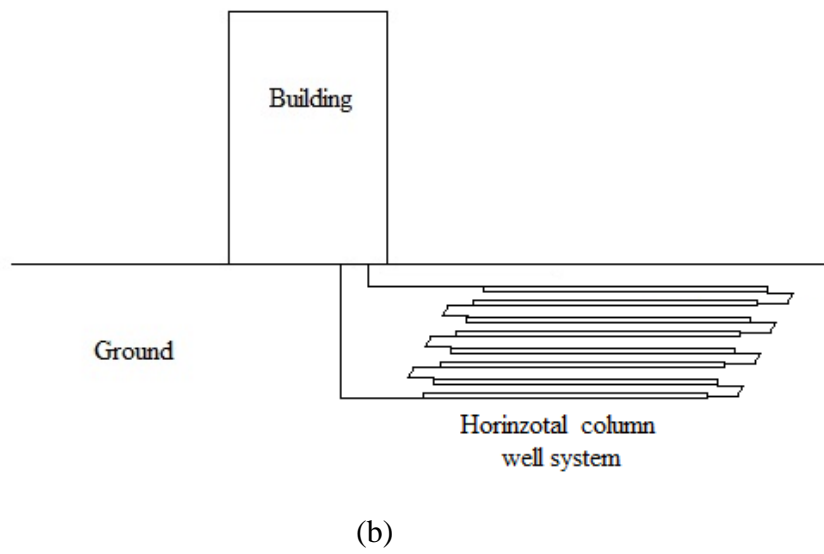
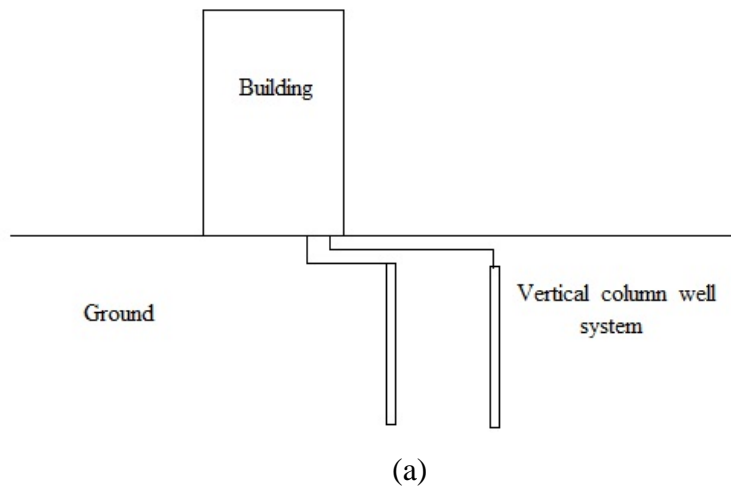


Figure 3. SCW system scheme

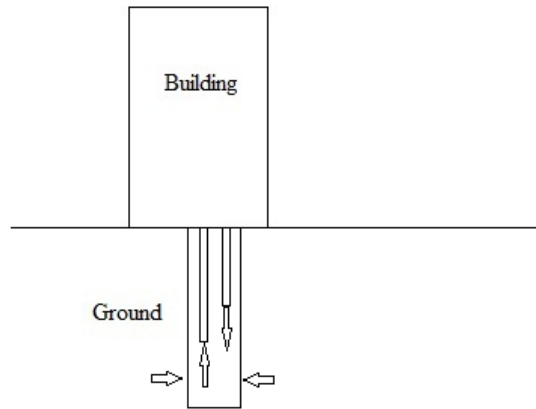


Figure 4. g factor

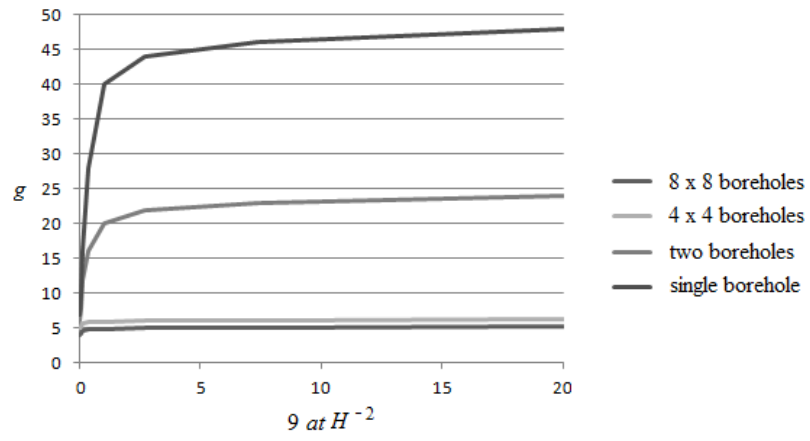


Figure 5. The main component of the GSHS

