Ground Source Heat Pump Systems

Yao Yu and Gaylord Olson

Contents

Abstract

A Ground Source Heat Pump (GSHP) system is a type of energy system that usually consumes electricity to provide cooling and heating in buildings. The

---

Y. Yu (✉)
Department of Construction Management and Engineering, North Dakota State University, Fargo, ND, USA
e-mail: yao.yu@ndsu.edu

G. Olson
Seasonal Storage Technologies, Princeton, NJ, USA
e-mail: gg_olson@yahoo.com

R. Wang, X. Zhai (eds.), *Handbook of Energy Systems in Green Buildings*,
https://doi.org/10.1007/978-3-662-49120-1_3

most outstanding feature of a GSHP is the use of ground resources, which distinguishes GSHPs from other heat pump systems. A GSHP may be considered as a "green" system, mainly because of its use of geothermal energy that, as a type of renewable energy, has enormous potential for reducing CO_2 emissions and fossil fuel consumption. In general, a higher system performance may be achieved by using a GSHP system compared with an air source heat pump system, due to the relatively small temperature variation of the ground compared with the ambient air. In a typical GSHP system, there are several main components: indoor distribution systems and ground source heat exchangers along with the ground as a heat sink/source. The role of indoor distribution systems is to handle building cooling and heating loads by absorbing room heat gains or providing heat to rooms through indoor heat pump units. The thermal energy carried by heat pumps is distributed to the ground through ground source heat exchangers buried underground or to the building through pipes/ducts.

In this chapter, in-depth discussions regarding GSHP systems are given including the topics of geothermal resources, ground source heat exchangers, indoor distribution systems, heat storage technologies of GSHP systems, as well as their economics and environmental impacts. Additionally, the most updated concepts, designs, and technologies for GSHPs are covered in this chapter.

Keywords

Ground source heat pump (GSHP) · Geothermal heat pump (GHP) · Ground source heat exchangers · Ground loops · Direct-exchange system · Open-loop system · Closed-loop system · Hybrid system · Vertical loop · Horizontal loop · Lake and pond loop · Aquifer Thermal Energy Storage (ATES) · Borehole Thermal Energy Storage (BTES)

Introduction to Ground Source Heat Pump Systems

Introduction

A ground source heat pump (GSHP) system is a type of energy system that usually consumes electricity to provide cooling and heating in buildings. The most outstanding feature of a GSHP is the use of ground resources, which distinguishes GSHPs from other heat pump systems, such as air source heat pumps. A GSHP may be considered as a "green" system, mainly because of its use of geothermal energy that, as a type of renewable energy, has enormous potential for reducing CO_2 emissions and the consumption of fossil fuel. Additionally, in general, a higher system performance may be achieved by using a GSHP system compared to an air source heat pump system, due to the relatively small temperature variation of the ground compared with the ambient air. In a typical GSHP system, there are several main components: indoor distribution systems and ground source heat exchangers along with the ground as a heat sink/source. The role of indoor distribution systems

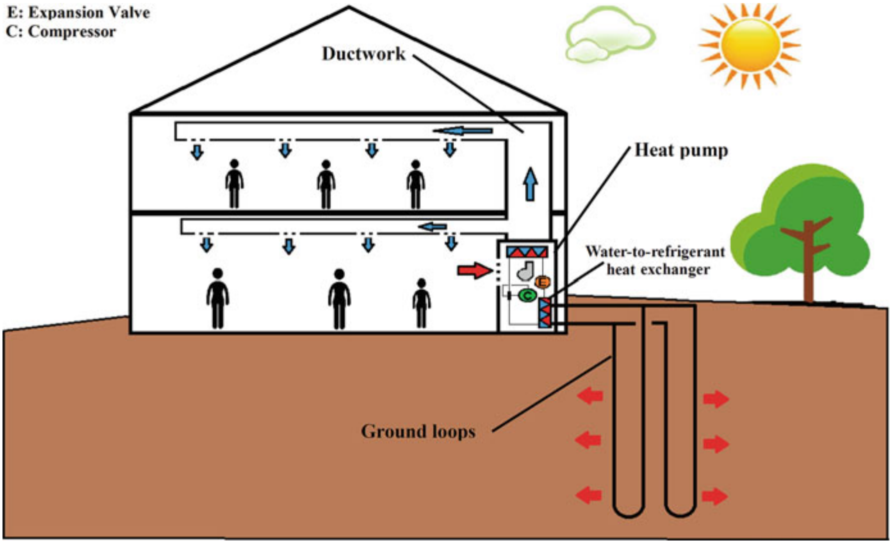


Fig. 1 A typical GSHP system

is to deal with building cooling and heating loads by absorbing room heat gains or providing heat to rooms through indoor heat pump units. Ground source heat exchangers (or ground loops) are the parts that are typically buried underground. The main components are connected in a way, for example, as shown in Fig. 1, to allow the heat (building heat or ground heat) to transfer between them through the working fluid (refrigerant, water, or a water-antifreeze solution). Figure 1 illustrates a typical GSHP system used in a building, including its ground loops, indoor heat pump units, and ductworks. In this figure, the heat transfer between the ground loop and the indoor distribution system takes place at the water-to-refrigerant heat exchangers embedded in the heat pump units.

In this chapter, in-depth discussions regarding GSHP systems are given, including the topics of geothermal resources, ground source heat exchangers, indoor distribution systems, and heat storage technologies of GSHP systems, as well as their economics and environmental impacts. In addition, this chapter covers the most updated concepts, designs, and technologies for GSHP systems.

Geothermal Resources

The definition of the word "geothermal" in the dictionary [1] is "of, relating to, or using the natural heat produced inside the Earth." According to this definition, geothermal energy should be the energy contained and stored within the Earth, including the Earth's core, mantle, and crust. Nowadays, geothermal energy is, however, typically defined as the thermal energy stored in the crust of the Earth, due to its easier access and exploitation by human beings.

The thermal energy contained within the Earth's crust has been utilized in various ways depending on the available power. Similar to the temperature classification typically used in geothermal industries [2], in this chapter, three categories are classified according to the available ground (or underground fluids) temperature (T):

- High ground temperature application: $T \geq 150\ ^\circ C$
- Intermediate ground temperature application: $32\ ^\circ C < T < 150\ ^\circ C$
- Low ground temperature application: $T \leq 32\ ^\circ C$

When the ground temperature is high (150 °C or greater), the available heat is suitable for electric power generation that can be accomplished by using conventional steam or binary power plants. Typically, higher ground temperatures (at least 150 °C) are required to produce high-temperature fluids in order to economically and efficiently drive conventional steam turbines. The most recent development of geothermal electricity generation technology allows the use of lower ground temperatures (around 90 °C or even lower) in binary power plants that consist of small individual modular units linked up together to produce required electric power. Although the capital cost of geothermal electricity generation may be much higher than other conventional power plants, the tremendous potentials on the use of renewable energy and the reduction of greenhouse emissions still make this type of energy application attractive and competitive in the market. Additionally, the wide application of this type of geothermal energy is significantly restricted by the availability of such high ground temperatures at reasonable depths of drilling.

When the available ground temperature is relatively low ($32\ ^\circ C < T < 150\ ^\circ C$), it is less efficient for electric power generation. Instead, this type of geothermal energy can be used directly, for example, to provide heating for systems or buildings without any supplemental input power or energy. This is the oldest application of geothermal energy and has been used for hundreds of years. Typically, fluid with relatively high enthalpy from underground is produced and pumped to user sites and then transferred into distribution systems through heat exchangers. Finally, the distribution systems carry the heat to user loads. Space and domestic hot water heating are the most common applications of this direct-use geothermal system. Free heating is supplied from underground, which significantly reduces the system energy consumption, compared to conventional systems, in which heat is provided by consuming nonrenewable energy through furnaces or boilers. Free cooling can be accomplished by using the direct-use geothermal system as well, in which the underground heat is converted into cooling effect through absorption refrigeration systems. The capital cost is the major investment of direct-use geothermal systems, including the expenses of the production of wellbores, transmission and distribution systems, associated equipment, and labor. Compared to the initial investment, the operational cost of direct-use geothermal systems is much lower, due to the free source of heat from the deep earth. Although it is known that the available temperature lower than 150 °C is not suitable for efficient electricity generation, a new product (Climeon Ocean™) has recently been designed and developed, which converts low-temperature heat into electricity with the efficiency up to 14% at a temperature of about 120 °C. This new technology allows the use of the intermediate-temperature free heat (<150 °C) (such as industrial waste heat, geothermal energy, etc.) to produce electric power, which avoids fossil fuel use and leads to zero emissions.

Typically, when the available ground temperature is lower than 32 °C, it is difficult to be utilized directly, and thus additional energy has to be provided in order to efficiently take advantage of this type of ground thermal energy, which is widely distributed on the Earth and relatively easy to access. The ability of the earth to store heat is significant due to its large volume and thermal capacitance. Therefore, underground temperatures at sufficient depths are typically constant throughout the year. At different depths, there exists a geothermal gradient, representing the underground temperature increase with depth. The deeper the ground is (below the frost line), the warmer the temperatures are. The thermal behavior of the deeper ground is less disturbed and influenced by outside weather conditions. The efficient utilization of this nearly constant ground temperature below the frost line is typically accomplished by using geothermal heat pumps (GHPs) or GSHPs. As its name implies, the ground is regarded as the heat/cool source for GSHPs, which reject building heat into the ground during summer and conversely extract heat from the ground to provide heating effect to buildings during winter. In this chapter, only the low-temperature application will be discussed, in which GSHPs are typically used to exploit this type of sustainable energy.

Ground Source Heat Pump Systems

Specifically, a GSHP system includes indoor heat pump units, outdoor ground source heat exchangers (ground loops), and associated indoor and outdoor distribution equipment, such as heat exchangers (water-to-refrigerant, water-to-water, etc.), pipes, ducts, pumps, etc., as shown in Fig. 2. During summer, building heat is absorbed by heat pumps, transferred from indoor distribution systems to outdoor

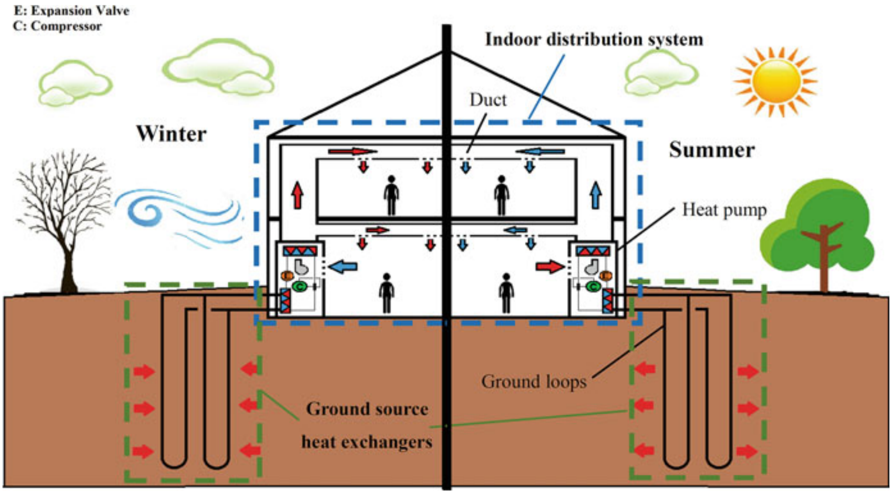


Fig. 2 A typical GSHP system used in winter and summer

ground loops through heat exchangers, and eventually rejected into the ground. During winter, the process is opposite. Ground heat is extracted by the ground loops and then supplied to the inside of buildings through heat pump units. The ground is regarded as a heat source during winter and a heat sink during summer.

The outdoor ground loops, also known as ground source heat exchangers, play a significant role in the exploitation of underground energy. According to the different types of ground source heat exchangers, GSHP systems can be categorized as direct-exchange systems, closed-loop systems, open-loop systems, and hybrid systems.

As the oldest type of GSHP systems, direct-exchange systems (type A in Fig. 3) are those, in which refrigerant is utilized as the working fluid in ground heat exchanger loops to carry heat and transfer it between the terminal heat pumps and the shallow ground. Unlike the direct-exchange systems, water (or a mixture of water and antifreeze) is typically used in open- and closed-loop systems, as shown in Fig. 3 (types B, C, and D). As their names imply, the difference between open- and closed-loop systems depends on whether the working fluid is directly exposed to the ambient medium or not. In a typical open-loop system, as shown in Fig. 3, the groundwater is pumped from wells and circulated directly through heat pumps (type C) or indirectly through water-to-water heat exchangers (type D) and then to transfer heat to each heat pump unit.

To date, closed-loop systems, including horizontal loops, vertical loops, and lake/pond loops (Fig. 4), are the most commonly used systems, especially the vertical-loop GSHP systems when the available land is scarce. In a typical vertical-loop GSHP system, as shown in Fig. 4a, ground source heat exchanger pipes are buried vertically in boreholes that are typically 15–140 m in depth with a separation distance of at least 4.5 m between each borehole. Unlike vertical-loop systems, the heat exchanger pipes of horizontal loops, as shown in Fig. 4b, are typically buried horizontally in the shallow ground, below the frost line but not as deep as vertical loops. Horizontal loops have different piping layouts, including single pipe, multiple pipes, slinky pipes, and horizontally bored pipes. Therefore, designers have more options when using horizontal-loop GSHP systems, depending on the different requirements of buildings and the availability of land. Horizontal-loop systems are typically less expensive than vertical-loop systems, but require larger ground areas for piping layouts. In lake/pond-loop systems, the heat source/sink becomes water bodies, such as lake, pond, river, etc., instead of the ground. This type of system (Fig. 4c) is more likely to be influenced by surrounding environments, especially when small and shallow bodies of water are involved. Hybrid systems typically use more than one type of heat source/sink. In addition to the underground thermal resource, the ambient air is usually used as another heat source/sink in hybrid systems for building heat exchange through fluid coolers or cooling towers (type E in Fig. 3). This integration of ground source loops with ambient air heat exchange units allows the optimization of system efficiency and performance by balancing the heating and cooling loads of buildings. For example, the ground loop may be designed to handle the entire building heating load but a small portion of building cooling load. The rest of the cooling load would be handled by using fluid coolers or cooling towers. This kind of system combination is particularly beneficial to cooling-dominated buildings

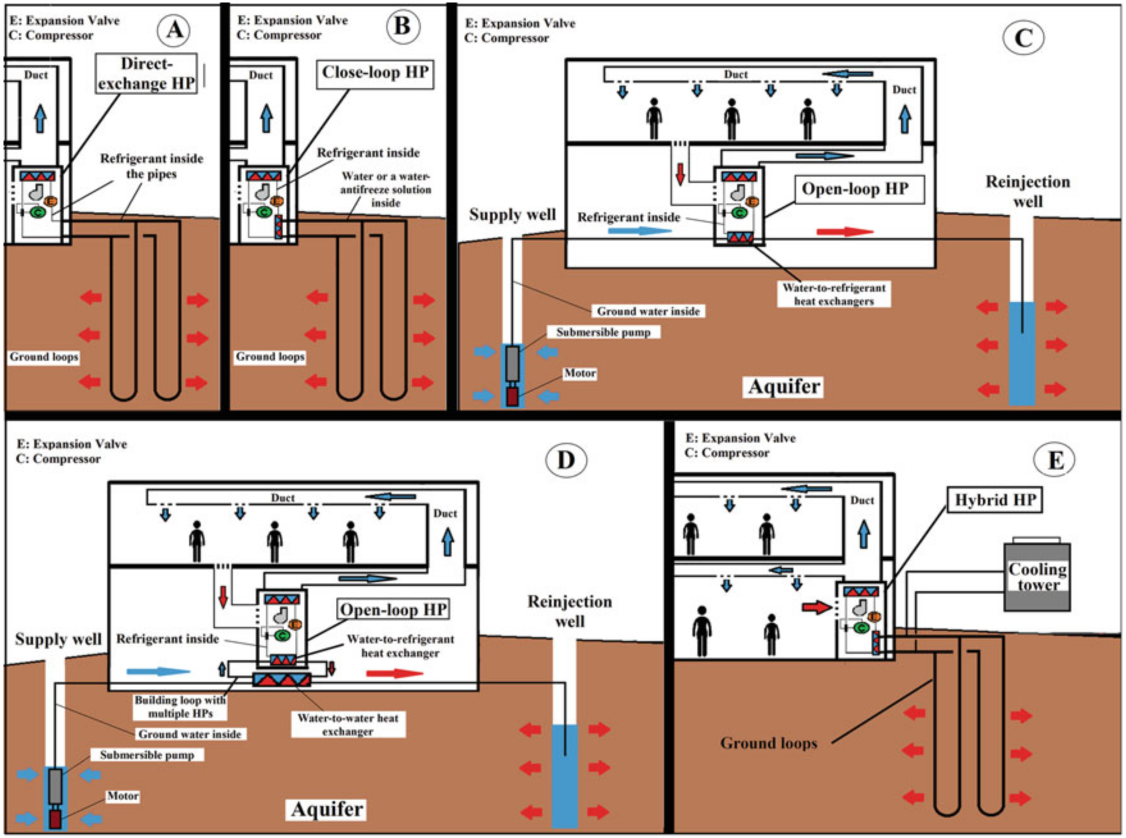


Fig. 3 Different types of GSHP systems

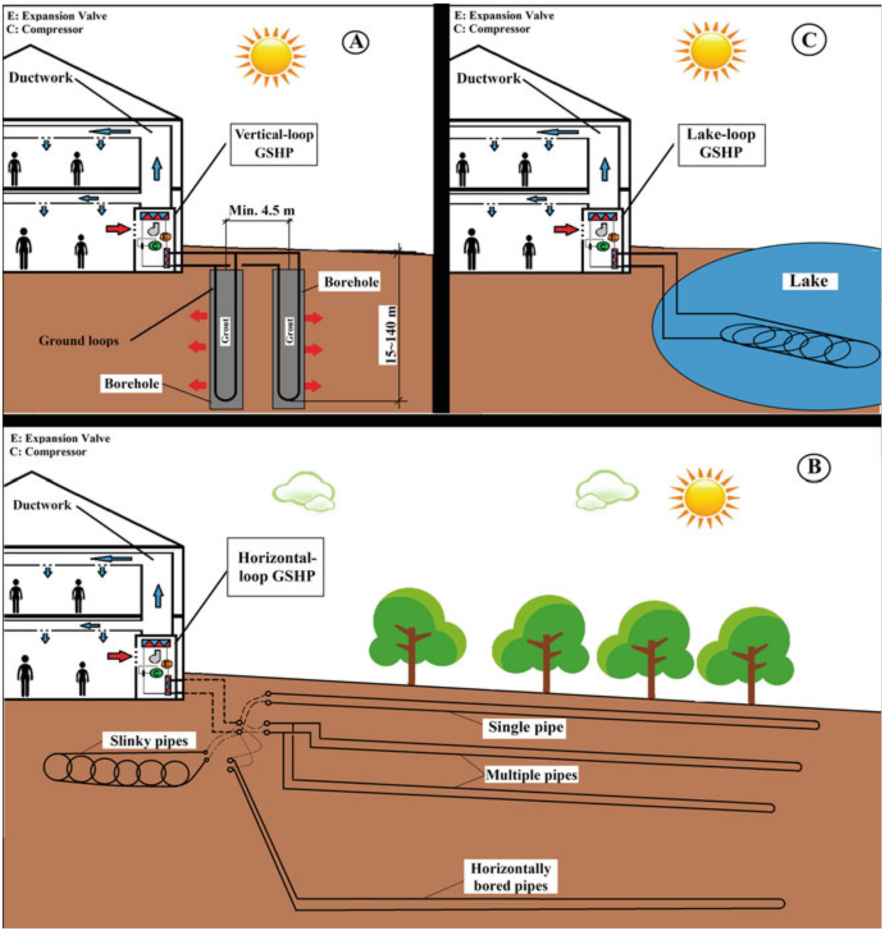


Fig. 4 Closed-loop ground source heat exchangers

because the use of auxiliary air source heat rejection units contributes to balancing the heating and cooling effects of the ground loops, downsizing the ground system, and therefore reducing the capital cost.

Overview

Although the concept of a heat pump was proposed around 1853 by Lord Kelvin, the use of a heat pump with underground loops was carried out by Robert C. Webber nearly 100 years after, who built the first ground source (direct-exchange) heat pump system in the world in the late 1940s [3]. Open-loop groundwater heat pump systems were firstly commercialized by J.D. Kroeker in Portland, Oregon, around 1948.

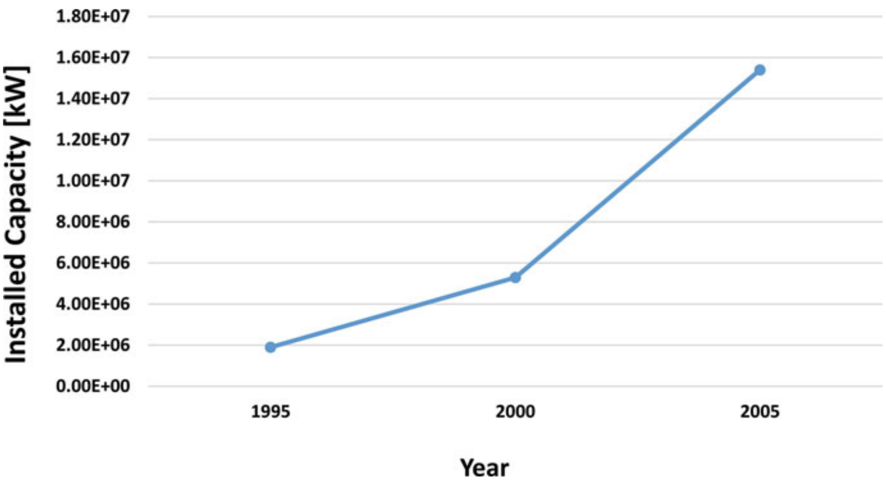


Fig. 5 GSHP worldwide capacities (Source: Lund et al. [4])

Since then, the market for ground source heat pumps was dominated by open-loop systems until the late 1970s when the use of polybutylene pipes provided an opportunity for the wide development and commercialization of closed-loop GSHP systems [3]. With the outbreak of the global energy crisis in the early 1970s, people paid more attention to technologies for energy savings, for example, the use of geothermal energy, directly or indirectly resulting in the establishments of the Geothermal Resources Council, the Geothermal Energy Association, the US Department of Energy (DOE), etc. in 1970s.

The worldwide development and application of GSHP systems were slow, due to the fact that it takes time to gain wide commercial acceptance. GSHP systems had a significant increase in use since 2005. As shown in Fig. 5, the global GSHP installed capacity has been growing quickly from 5.3×10^6 kW in 2000 to 15.4×10^6 kW in 2005, at which time the application of GSHP systems (Fig. 6) was focused on Europe (39%) and North America (56%) [5, 4].

In Europe, Sweden is the country with the greatest use of GSHPs. The installed GSHP units in Sweden accounted for 44% of the total European installations in 2008 [5, 6]. In North America, the United States has the largest GSHP market, and according to IGSHPA (International Ground Source Heat Pump Association) [7], about 1.5 million units have been installed in the United States as of 2010. Per US EIA (Energy Information Administration) [8], the total geothermal heat pump shipments in the United States were 35,581 units in 2000, and this number was increased by about three times in 2009 with 115,442 units.

Although the Asian market for GSHP systems was developed relatively late compared with Europe and North America, it contains enormous potential. For example, in China, the use of GSHP has demonstrated a continued rapid growth since 2005 [9], as shown in Fig. 7, which represents the annual accumulative building floor areas conditioned by using GSHPs in China.

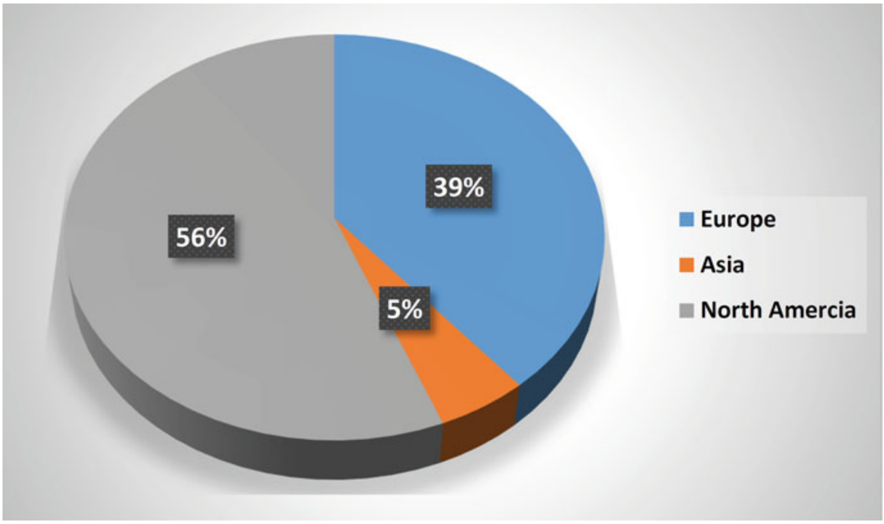


Fig. 6 Chart for GSHP installed capacities of the world in 2005 (Source: Lund et al. [4])

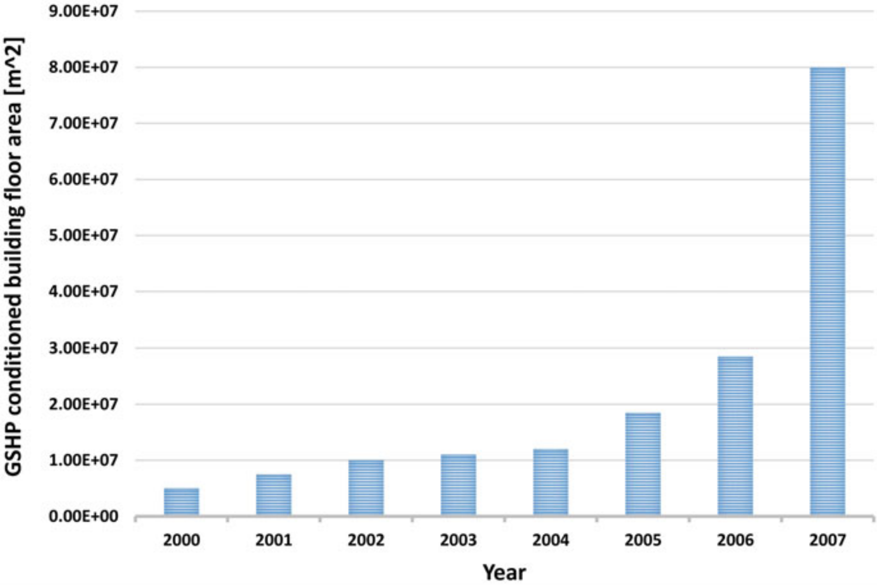


Fig. 7 Annual cumulative building floor areas conditioned by using GSHPs in China (Source: Liu et al. [9])

Low-Temperature Geothermal Resources

Nowadays, the low-temperature geothermal energy (32 °C or less) is one of the most common applications of renewable energy, due to its wide distribution in shallow grounds and relatively easy access and exploitation. For example, in the United States, the groundwater temperatures are typically between 8.0 °C and 27 °C, as shown in Fig. 8. Low and high groundwater temperatures are distributed in the north and south of the United States, respectively. Therefore, unlike the high- or intermediate-temperature geothermal energy, the application of this type of renewable energy is not restricted by the availability of the higher temperatures from local geologic formations.

Temperature gradients exist underground, indicating the rise of temperature with depth in the deep earth. The average gradient is approximately 2.5 °C/100 m in depth. For example, if the average ground temperature near the surface is 15 °C, the underground temperature at a depth of 300 m would be around 22.5 °C and 30 °C at a depth of 600 m. In fact, the deeper the ground is, the less the ground thermal behavior is disturbed by ambient environments. Although the deeper ground means relatively higher available temperatures and smaller temperature fluctuations, it also implies more capital costs and larger risks of failure during installation.

The thermal characteristics of geologic formations play a significant role in the application of geothermal energy. These characteristics include ground temperature, earth thermal conductivity, and diffusivity, which are dependent on geographic locations, earth types, and ground depth. In shallow grounds, the geologic formations consist of different types of sands, gravels, clays, and rocks, for example, as shown in Fig. 9 and Table 1. The thermal characteristics of these geologic formations vary with the effects of ground temperatures and moisture content, and thus a method involving on-site test and evaluation (thermal response test) [2, 15, 16] is typically suggested in order to obtain accurate ground properties, especially for large commercial projects. On-site tests are relatively easy for horizontal piping layouts which are typically buried in near-surface grounds, even though the ground thermal behaviors at this depth vary significantly depending on the moisture content. Compared to horizontal loops, the on-site tests for vertical loops are relatively difficult and expensive, in which vertical boreholes (one or more) have to be installed at the beginning for the evaluation purpose. A test device is typically used to measure the ground thermal properties, as shown in Fig. 10. An accurate measurement and knowledge of the local ground thermal properties contribute to avoiding the over- or undersizing of the ground heat exchanger loops and improving the operational performance and efficiency of the entire GSHP system.

For smaller commercial or residential projects, however, traditional methods involving the use of tables and maps for estimating the thermal properties of the geologic formations are acceptable due to the relatively high cost of on-site tests compared to the limited budget for these projects, even though this method is less accurate than on-site tests or evaluations. Table 1 shows the thermal properties of the commonly existing sands, clays, as well as rocks in the shallow ground or the Earth's crust. Remund and Carda [17] proposed an approximate formula for estimating

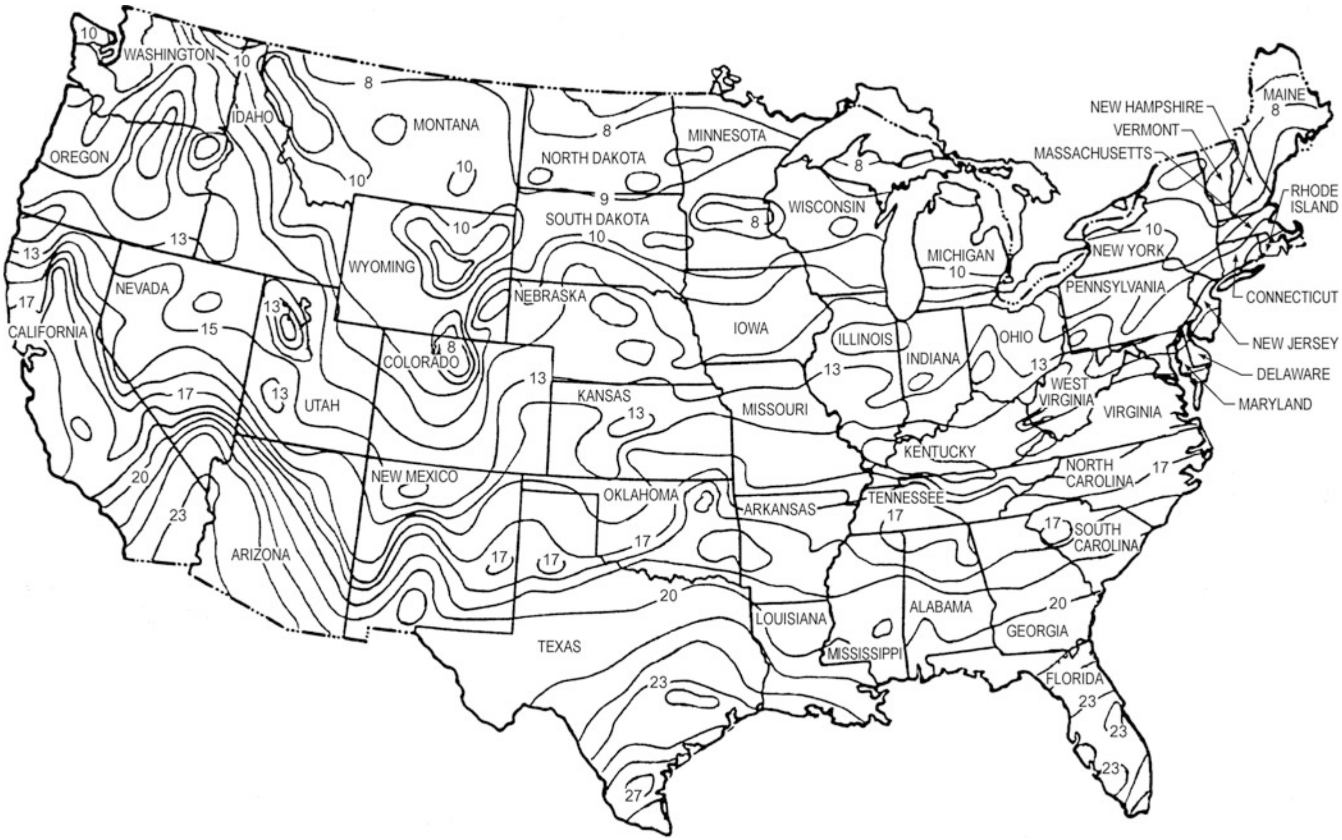


Fig. 8 Approximate groundwater temperature (°C) in the United States [2] (©ASHRAE, www.ashrae.org. *2013 ASHRAE Handbook – HVAC Applications*)

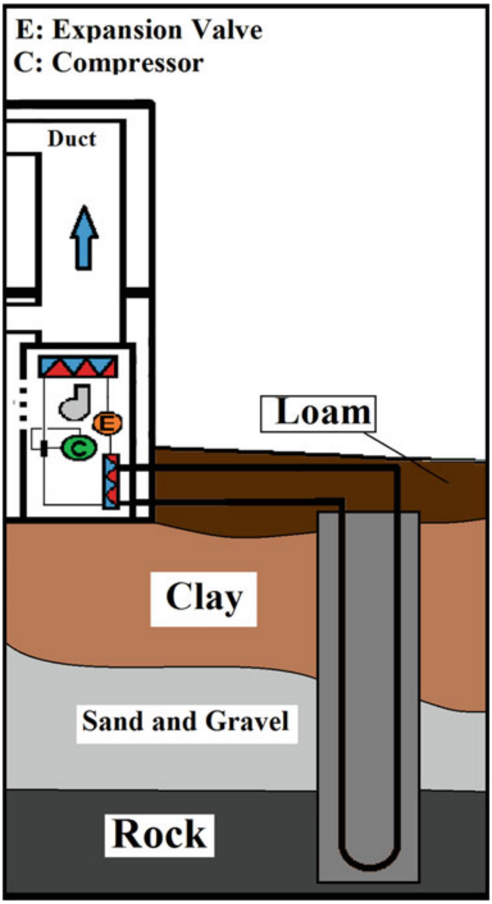


Fig. 9 An example for geologic formations

ground temperatures at shallow depths, which is shown in Eq. 1. This equation is an acceptable estimation for temperatures (T_{ground}) deeper than 10 m in shallow grounds and is typically used for smaller commercial or residential projects:

$$T_{\text{ground}} = T_{\text{mean}} - A_s \cdot \exp\left(\left(-d\left(\frac{\pi}{365\alpha}\right)^{0.5}\right) \cdot \cos\left(\left(\frac{2\pi}{365}\right)\left(\tau_d - \tau_{\min} - 0.5d\left(\frac{365}{\pi\alpha}\right)^{0.5}\right)\right)\right) \tag{1}$$

where T_{mean} [°C] is the mean earth temperature at the surface (or average annual air temperature); A_s [°C] is annual daily average temperature variation at the surface above and below T_{mean}; d [m] is the depth below the surface; α [m^2/day] is the thermal diffusivity; τ_d [days] represents the number of days after January 1; and $\tau_{\min}$ [days] represents the number of days after January 1 when the minimum ground/air temperature takes place. Please note that if T_{mean}, A_s, and $\tau_{\min}$ are not available, they can be obtained from Chap. 14 of *2013 ASHRAE Handbook – Fundamentals* [18], where the

Table 1 Thermal properties of rocks, sands, and clays

	Moisture [%]	Density (or dry density for sands/clays) [kg/m^3]	Thermal conductivity [W/m-K]	Thermal diffusivity [m^2/day]	Specific heat [kJ/kg-K]
Rocks[a]					
Amphibolite	–	2800–3120	2.6–3.8	–	–
Andesite	–	2560	1.6–2.4	0.13	0.5
Basalt	–	2880	2.1–2.4	0.07	0.71–0.88
Claystone	–	–	1.9–2.9	–	–
Diorites	–	2880	2.1–2.9	0.08	0.92
Dolomite	–	2720–2800	2.8–6.2	0.16	0.88
Dry shale (25% quartz)	–	2080–2640	1.4–2.4	0.08	0.88
Dry shale (no quartz)	–	2080–2640	0.9–1.4	0.05	0.88
Gabbro (Cen. Plains)	–	2960	1.6–2.8	0.08	0.75
Gabbro (Rocky Mtns.)	–	2960	2.1–3.6	0.11	0.75
Gneiss	–	2560–2800	2.2–3.5	0.10	0.92
Granodiorites	–	2720	2.1–3.5	0.10	0.88
Granite (10% quartz)	–	2640	1.9–5.2	0.10	0.88
Granite (25% quartz)	–	2640	2.6–3.6	0.11	0.88
Limestone	–	2400–2800	1.7–5.2	0.11	0.92
Marble	–	2720	2.1–5.5	0.09	0.92
Quartzite	–	2560	5.2–6.9	0.24	0.84
Rock salt	–	2080–2160	6.4	–	0.84
Sandstone	–	2560–2720	2.1–3.5	0.09	1.00
Schist	–	2720–3200	2.1–4.5	–	–
Siltstone	–	–	1.4–2.4	–	–
Slate	–	2720–2800	1.6–2.6	0.07	0.92
Wet shale (25% quartz)	–	2080–2640	1.7–3.1	–	0.88
Wet shale (no quartz)	–	2080–2640	1.0–4.0	0.05	0.88
Sands (various moistures and dry densities)[b]	5	1280	1.38	0.088	–
	10	1280	1.47	0.079	–
	15	1280	1.56	0.070	–
	20	1280	1.64	0.066	–
	5	1600	1.90	0.097	–
	10	1600	2.51	0.096	–
	15	1600	2.42	0.093	–
	20	1600	2.68	0.086	–
	5	1920	2.68	0.114	–
	10	1920	2.94	0.104	–
	15	1920	3.29	0.099	–

(*continued*)

Table 1 (continued)

	Moisture [%]	Density (or dry density for sands/clays) [kg/m^3]	Thermal conductivity [W/m-K]	Thermal diffusivity [m^2/day]	Specific heat [kJ/kg-K]
Clays (various moistures and dry densities)^b	5	1280	0.69	0.045	–
	10	1280	0.73	0.039	–
	15	1280	0.81	0.037	–
	20	1280	0.87	0.034	–
	5	1600	0.95	0.049	–
	10	1600	0.95	0.041	–
	15	1600	1.13	0.039	–
	20	1600	1.21	0.045	–
	5	1920	1.21	0.052	–
	10	1920	1.21	0.043	–
	15	1920	1.64	0.051	–

Source: Kavanaugh and Rafferty [10], Farouki [11], Toulokian et al. [12], Robertson [13], Carmichael [14]

[a] Rock thermal properties at the temperature of 25 °C

[b] Sands with the size of 0.075 ~ 5 mm and clays with the size of 0.075 mm or less

annual temperature shown in the monthly climatic design condition table may be used for T_{mean}; the maximum and minimum values for monthly climatic design conditions may be used to determine A_s; and the 15th day of the month when the minimum temperature occurs according to the monthly climatic design conditions is used to determine $\tau_{\min}$ [10].

Compared to wind, tides, waves, and solar, low-temperature geothermal energy is one of the most commonly used applications of renewable energy. It is widely available and less restricted by local geographic and climate conditions. Typically, the low-temperature ground energy is harvested by using GSHP systems, in which heat transfer between the system and ground occurs through ground source heat exchangers buried underground with various loops or layouts, as shown in Figs. 3 and 4. It is possible to combine the use of different types of renewable energy in order to maximize the benefit of this clean energy, instead of using fossil fuels, and to reduce the associated greenhouse gas emissions. In practice, geothermal energy is typically combined with aboveground solar heat that can be regarded as a supplemental/main heat source depending on the availabilities of the on-site geothermal and solar energy and the allocation of building cooling and heating loads to balance the ground temperature, especially for heating-dominated buildings.

Types of Ground Source Heat Exchangers

GSHP systems typically consist of outdoor ground source heat exchangers and indoor distribution systems (Fig. 2). The thermal heat absorbed or supplied by indoor heat pump units would be distributed to the ground, representing heat sink

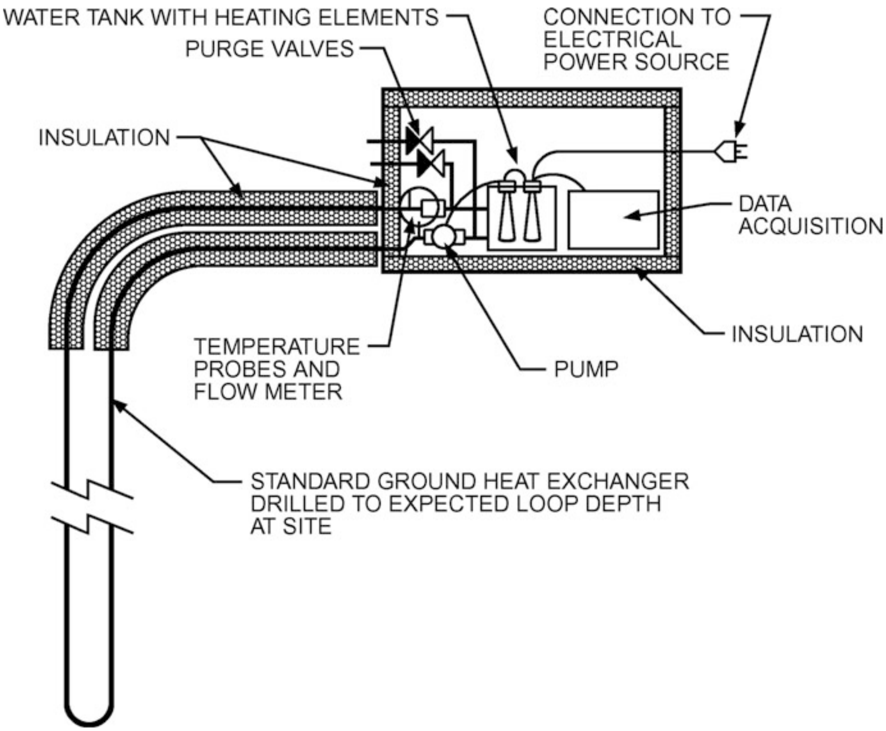


Fig. 10 The apparatus for testing ground thermal properties [2] (©ASHRAE, www.ashrae.org. *2013 ASHRAE Handbook – HVAC Applications*)

or source in cooling or heating mode, respectively, through pipes that are buried underground. These pipes are known as ground source heat exchangers where heat transfer between the fluid in the heat exchangers and the ground takes place (e.g., as shown in Fig. 11). According to the various underground piping layouts, configurations, and/or working fluids, ground source heat exchangers can be categorized into four groups, including direct-exchange systems, closed-loop systems, open-loop systems, and hybrid systems.

Direct-Exchange System (Also Called Direct-Expansion or DX System)

Compared to other ground source heat exchange systems, direct-exchange systems are not widely or frequently used and have a small market share. In direct-exchange systems, thermal energy is typically carried by a refrigerant circulated in copper pipes buried underground. As shown in Fig. 3a, the refrigerant is the only working fluid (no intermediate fluid involved), and it is circulated through the entire direct-exchange GSHP system. After the refrigerant in indoor heat pump units transfers the thermal heat to/from the inside of buildings, it is distributed into an underground

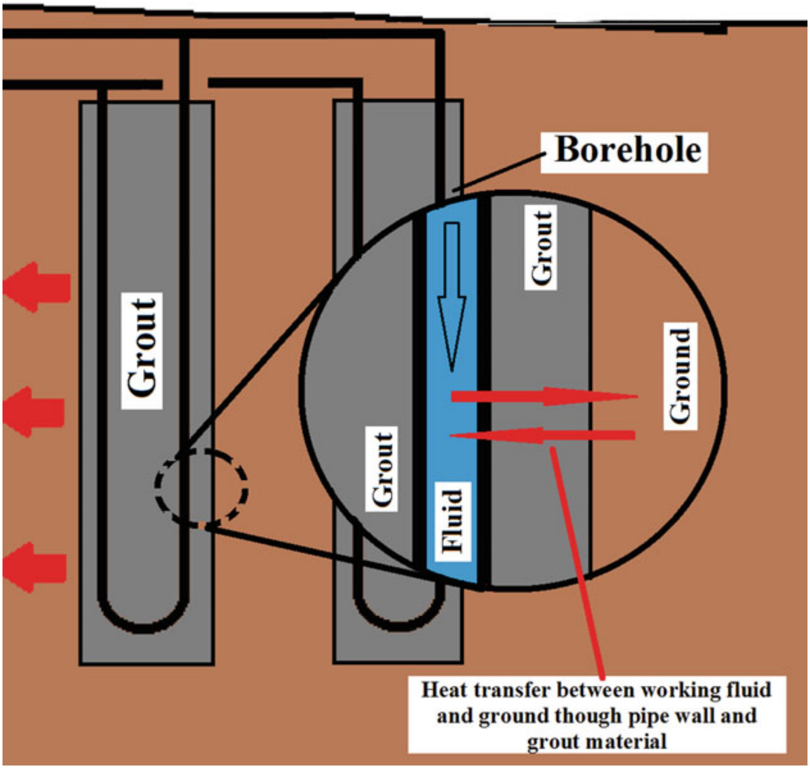


Fig. 11 Heat transfer between the working fluid and the ground in vertical boreholes

piping network in order to directly exchange its carried thermal heat with the ground. Given its characteristics of direct heat exchange between the refrigerant and the ground without the use of any intermediate fluid (water or a mixture of water and antifreeze that is typically used in conventional systems), the direct-exchange systems can also be named as direct-expansion (DX) systems. The efficiency of DX systems is typically greater than closed/open-loop systems, owing to:

- The avoidance of using water-to-refrigerant heat exchangers
- The latent heat related to the phase change of refrigerants, which takes place in underground heat exchangers
- The enhanced heat transfer between the working fluid and the ground because of the use of copper pipes, instead of plastic

In conventional systems, water-to-water or water-to-refrigerant heat exchangers are typically used to carry out the heat transfer between the working fluids in the ground loops (water or a mixture of water and antifreeze, such as a water-glycol mixture) and in the indoor heat pump units or indoor distribution systems (water or a refrigerant, e.g., R134a), as shown in Fig. 3b–d. The use of heat exchangers in conventional systems is intended to separate two different working fluids, such as water and refrigerant, meanwhile carrying out the heat transfer between them. The absence of such water-to-refrigerant (or water-to-water) heat exchangers in DX GSHP systems contributes to eliminating the heat transfer loss caused by the heat exchangers and therefore improves the system efficiency.

The lack of water-to-refrigerant heat exchangers in DX systems allows the refrigerant to flow directly from indoor terminals to underground heat exchange loops and to transfer heat to the ground. Unlike other ground source heat exchange systems, this unique design of DX underground systems maximizes the use of refrigerant latent heat. The phase change of the refrigerant between liquid and gas without the change of its temperature in the underground tubes produces energy that is known as latent heat, which is one of the most important reasons for the enhanced efficiency of DX systems. Depending on the operation mode (cooling or heating), the ground is either heat sink or source. For example, as shown in Fig. 12, in the cooling mode, the refrigerant gas entering the underground loop is converted to

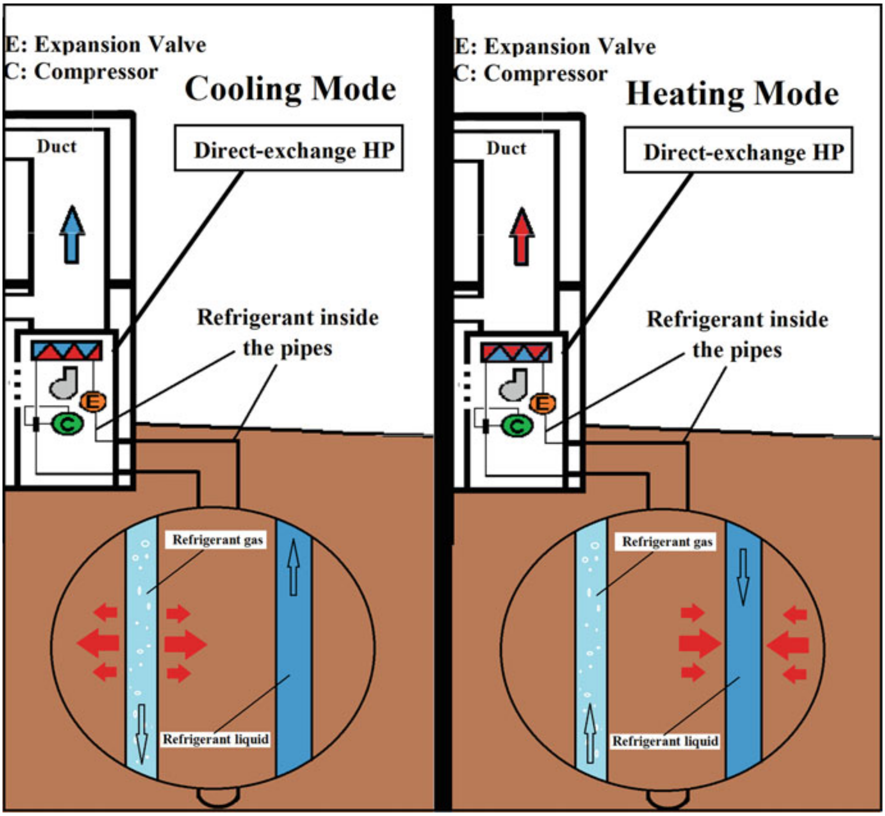


Fig. 12 Refrigerant phase change in underground heat exchangers

liquid by giving off heat to the ground, and conversely the entering refrigerant liquid to the loop is converted to gas by absorbing heat from the ground in the heating mode. The refrigerant used in DX GSHP systems includes, but is not limited to, R-22, R-407c, R-410a, and R-744, whose thermal characteristics can be found in Chap. 30 of *2013 ASHRAE Handbook – Fundamentals* [19].

Using copper as the material of underground heat exchange pipes is one of the reasons for the higher efficiency of DX GSHP systems. Copper pipes have a high thermal conductivity (about 401.5 W/m·K) compared to the polyethylene pipes typically used in closed-loop systems with a thermal conductivity of around 0.33 W/m·K. Therefore, the performance of heat transfer between the refrigerant and the ground is enhanced by this high thermal conductivity material (Fig. 11).

Compared with other ground source heat exchange systems, the higher efficiency of DX systems allows a shorter line of underground loop and therefore less need for excavation and drilling. However, the applications of DX systems are usually restricted to small projects, due to the considerable requirement of copper tubing and refrigerant for larger projects, which may significantly increase the capital cost.

In a DX system, the power to circulate the working fluid (refrigerant) in the entire system is provided by a compressor, eliminating the use of circulation pumps. Therefore, DX systems can be regarded as the simplest configuration of ground source heat exchangers in contrast with conventional and hybrid systems.

System Design

Several considerations should be taken into account when designing DX systems, such as ground condition, underground loop layout, and refrigerant selection.

Ground Condition

On-site test and evaluation of the local geologic formations are suggested in order to obtain accurate knowledge of the thermal characteristics of the ground, which is conducive to optimizing the design of underground loops, including the pipe size and installation depth. The associated cost for on-site tests is usually affordable because the underground loops of this type of system are typically buried in relatively shallow ground with small ground areas. DX loops need to be located in underground regions that are unlikely to be disturbed, since any ground shift and movement could damage the piping and cause serious refrigerant leaking issues.

The direct contact of copper piping with acidic soils may cause the risk of corrosion. Appropriate protections to shield underground pipes [20] should be considered if the installation in the ground with acidic soils is unavoidable.

Underground Loop Layout

Theoretically, DX underground loops may be installed in vertical, horizontal, or radial (diagonal) configurations, as shown in Fig. 13. Due to the omission of circulation pumps in this type of system, the compressor in the heat pump unit provides the power for circulating the refrigerant throughout the entire system. It follows that the location of the compressor should not be far from the underground loops. Additionally, the installation depth of underground heat exchangers is limited

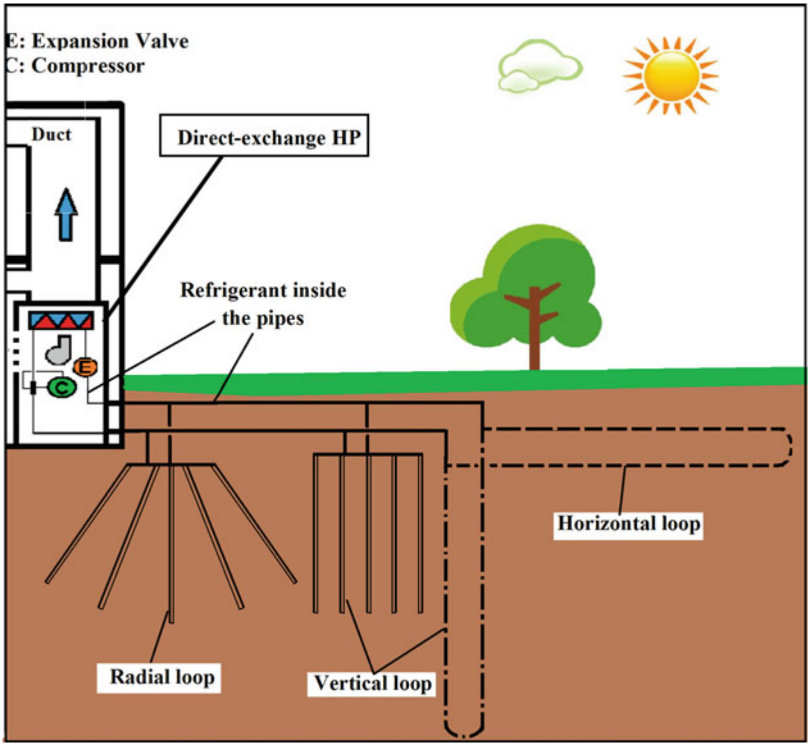


Fig. 13 DX underground loop layouts

to shallow grounds. For example, the installation of horizontal loops is typically below the frost line and around 1.5–3 m in depth from the ground surface. The typical land areas required by horizontal loops may be estimated using 13 square meters per cooling kilowatt, and smaller land areas are required by using vertical loops with approximately 2.6–4 m^2/kW [21]. The typical length of horizontal heat exchangers buried underground is about 30 m/kW, even though shorter loops may be used if advised by the manufacturers. Ochsner [22] gave a suggested value for horizontal pipe spacing, i.e., at least 0.5 m for damp and well-packed soils and 0.8 m for dry and loose soils. The depth for vertical DX loops is usually between 3 and 30 m. Deeper vertical boreholes mean larger capacity and higher efficiency, but also greater investment. The radial (diagonal) underground layout may be regarded as an intermediate configuration between vertical and horizontal layouts. As shown in Fig. 13, each borehole may be tilted up at a certain angle (e.g., 60°). Multiple pipes may be intersected together at one point near the ground surface. Each borehole is required to be grouted after the insertion of pipes. Compared to a horizontal layout, a radial underground layout reduces the required land area and surface disturbance. DX GSHP systems are not typically manufactured in a very large capacity. They are commonly used in residential or small commercial projects. Therefore, the available capacities of this type of system in the current market are typically limited to approximately 50 kW or lower. Although this type of system is infrequently used in large buildings, installing multiple heat pumps together in line is a solution to handle larger building loads.

Selection of Refrigerant

Several considerations have to be taken into account in order to select refrigerant properly for DX GSHP systems. One of the major concerns of using refrigerant is its environmental impact. R-22 was used to replace chlorofluorocarbons (CFCs) because of its relatively low ozone depletion potential (ODP) and thus has been used as a refrigerant for a number of years. However, it is being phased out and not allowed to be used in new equipment in some countries. Therefore, R-22 is now rarely used in DX GSHP systems, especially for new installations in the United States. Alternatively, other refrigerants may be used in DX systems, such as R-134a, R-407c, R-410a, and R-744. The ODP and GWP (global warming potential) of these refrigerants are shown in Table 2. More information for each popularly used refrigerant, including the environmental and physical properties, can be found in Chaps. 29 and 30 of *2013 ASHRAE Handbook – Fundamentals* [19].

As replacements for R-22, R-134a, R-407c, and R-410a have been widely used in refrigeration systems for many years. As shown in Table 2, the ODPs of R-134a, R-407c, and R-410a are very low (nearly zero), but with relatively high GWPs of 1370 for R-134a, 1700 for R-407c, and 2100 for R-410a. In order to further reduce the global warming impact of refrigerant, carbon dioxide (R-744), as a natural refrigerant, may be an appropriate substitute for R-134a, R-410a, or R-407c. The potential of using carbon dioxide as the refrigerant in DX GSHP systems is being explored and studied. For example, Brian and Sumathy [23] confirmed the potential of using R-744 in DX systems to improve the performance. Most recently, a numerical analysis has been done by Hu et al. in 2016 [24], in which a DX GSHP system with R-744 as the refrigerant was coupled with air- or water-cooled gas coolers aiming to reduce the unbalance degree of the earth's energy caused by unbalanced cooling and heating requirements of buildings. They found that the R-744 DX GSHP system may reduce the unbalance to zero and maintain lower investment and operation costs compared to a GSHP system with R-134a.

Another concern is the large amount of refrigerant required in DX systems. The volume of refrigerant used in DX GSHP systems is typically much higher than

Table 2 ODP and GWP for selected refrigerants

	ODP[a]	GWP[a]$_{100}$
R-22	0.040	1790
R-134a	0.000	1370
R-407c	0.000	1700
R-410a	0.000	2100
R-744	0.000	1

[a] Source: Chap. 29 of *2013 ASHRAE Handbook – Fundamentals* [19]

conventional (non-DX) GSHP systems. With the same system capacity, the required volume of refrigerant in a DX GSHP could be about ten times more than a typical GSHP system that uses water in its underground loops. For example, Egg et al. mentioned in their book [20] that a typical (non-DX) GSHP system with an average capacity of 17.6 kW may have 1.8 or 2.3 kg of refrigerant, while the required amount of refrigerant in DX systems would be 23 kg or even more in order to maintain the same capacity of 17.6 kW. The considerable requirement of refrigerant is caused by the longer refrigerant pipe length than non-DX GSHP systems. A DX system with an average capacity of 17.6 kW would need approximately 180 m of copper pipes buried underground, which have to be filled with refrigerant in order to maintain the normal operation of the system.

System Installation

One of the major problems of this type of system involves the leakage of refrigerant. Refrigerant leaking would reduce the system capacity and performance and most importantly cause serious environmental issues considering the large amount of refrigerant enclosed in DX systems. Therefore, the installation of underground tubing should be undertaken very carefully by professional contractors following the manufacturer's installation guideline, in order to eliminate any potential problems and imperfections that could cause the leak of refrigerant.

System Control and/or Operation

As shown in Fig. 14, in a cooling mode, the building heat absorbed by the refrigerant in the evaporator of the system changes the phase from liquid to vapor. Then the low-pressure vapor refrigerant goes through the reversing valve and compressor and becomes a high-pressure vapor with a relatively high temperature before it is eventually transferred to the condenser that is buried underground to reject the heat. The phase change of the refrigerant from gas to liquid takes place in the underground loops (Fig. 12). The returned refrigerant (a high-pressure liquid) from underground will lose its pressure and temperature when it transfers through the expansion valve before it goes to the evaporator again with a low-pressure low-temperature liquid.

In a heating mode, the operation sequence is reversed, which is controlled and accomplished by using the reversing valve shown in Fig. 14, and the ground heat is harvested through the underground loops and then transferred to the indoor heat exchanger coil (shown as condenser in Fig. 14) that is usually located inside of the building to provide heating effect. It is noticed that the terms "condenser" and "evaporator" correspond to their functions in both cooling and heating modes, i.e., condenser is used to reject heat, and evaporator is to absorb heat.

The performance rating of DX GSHPs, such as the test, rating and operating requirements, etc., is included in the standard of ARI/AHRI 870 [25] by the American Refrigerant Institute (ARI)/Air-Conditioning, Heating, and Refrigeration Institute (AHRI), which provides guidance for the industry in the use of this type of system.

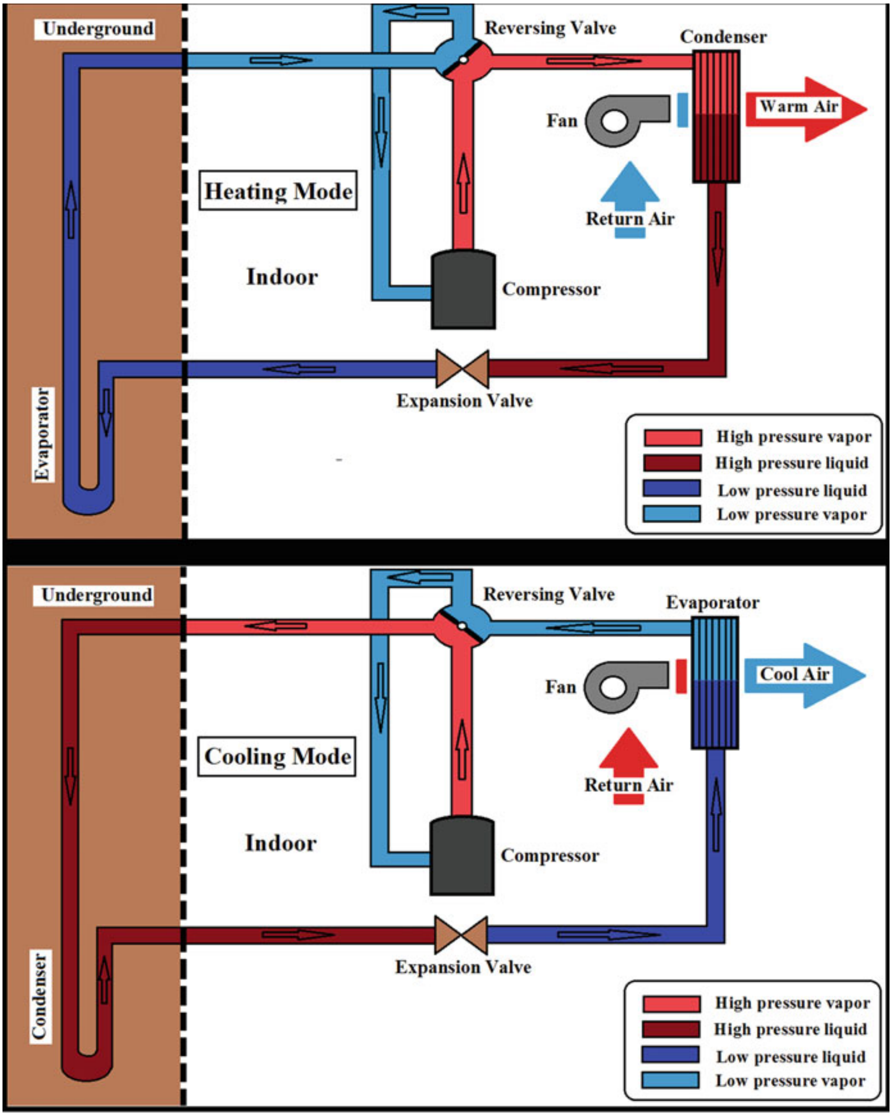


Fig. 14 DX GSHP heating and cooling cycles

System Trouble Shooting

The challenges in the design and use of DX GSHP systems may include, but are not limited to, the following:

- Ensuring sufficient refrigerant oil return from underground heat exchangers
- Avoiding the potential of refrigerant leakage and the associated environmental issues
- Detecting and repairing underground pipe leaks

The use of refrigerant oil is aimed to provide lubrication to compressors. Adequate refrigerant oil is necessary to maintain a normal operation of compressors as well as the entire DX GSHP system. Typically, the liquid refrigerant and the oil can be fully mixed. The oil, however, is not able to mix with the vapor refrigerant, which would cause the separation of the oil and refrigerant vapor when the phase change occurs in underground heat exchangers. It follows that when the system is in a heating mode, the refrigerant oil could be trapped and accumulated at the lowest point of underground heat exchanger loops (Fig. 15), which would cause insufficient oil return back to the compressors and eventually an abnormal system operation or a system shutdown. To solve this problem, it was proved by Mei and Baxter in 1991 [26] that a smaller underground pipe size contributes to eliminating the insufficient oil return problem. Additionally, Wang et al. in 2013 [27] designed a special underground loop, as shown in Fig. 15, by adding an oil return circle to each loop in order to enhance the oil return back to the compressors. This design allows the oil accumulation point to move up from

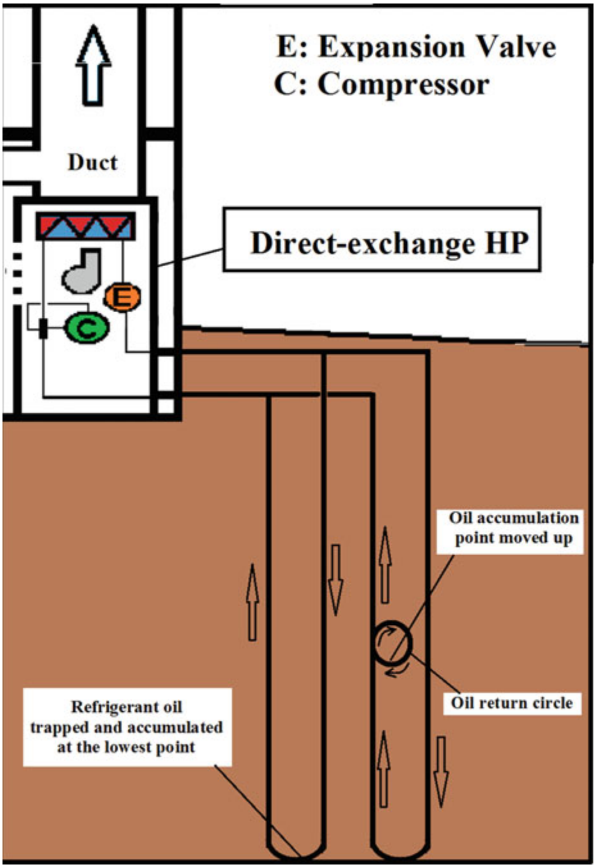


Fig. 15 Refrigerant oil accumulation

the bottom of the loop to the middle where the oil return circle is located and thus further improve the potential of the refrigerant oil to feed back to the compressors.

Unlike other underground heat exchange systems, in which liquid water (or a liquid water and antifreeze mixture) exists, DX systems contain refrigerant that could exist in the system in the form of vapor or liquid depending on its phase change during the system operation. Refrigerant vapor is much easier to escape through small imperfections of underground tubing than liquid water/refrigerant, and thus the underground brazed copper pipes are typically coated with polyethylene or polypropylene to ensure seamless leak-free connectivity. Moreover, the use of environment-friendly refrigerants, such as R-744, reduces its environmental threat, in case of the leak of refrigerant.

If a pressure or refrigerant loss in a DX GSHP system is detected indicating that leaking is likely occurring, the system should be shut down automatically, in order to minimize the leak of refrigerant. A pressurization test is typically needed by feeding the underground loops with water/air at a certain pressure in order to detect the leaking location(s) and to fix the problem eventually by repairing or replacing the leaking loop(s). The detection and repair of leaking loop(s) may be time-consuming and expensive due to the needs for tests and excavations.

Closed-Loop System

Closed-loop systems are isolated from the ambient environment without a direct contact. High-density polyethylene (HDPE) pipes are typically used to carry out the heat transfer between their enclosed fluid and the surrounding environment, such as the ground or water bodies (Fig. 4). Although DX systems can be regarded as a special case of closed-loop systems, these two systems are described separately in this chapter, mainly because of the use of different types of working fluid in their ground heat exchangers, which may cause significantly different system performances. Unlike a DX system that uses refrigerant in its ground loop, a mixture of water and antifreeze is typically used as the working fluid in the ground heat exchangers of a conventional system. Depending on the layouts of heat exchange loops, closed-loop systems are typically categorized into three types, i.e., horizontal loop, vertical loop, and lake/pond loop, as shown in Fig. 4.

Vertical Loop

To date, vertical closed-loop systems (VCS) may be considered as the most commonly used geothermal heat pump systems. Typically, plastic pipes (usually HDPE) of VCS are vertically inserted underground in boreholes whose depths typically vary from 15 to 140 m or even more. Each borehole is usually configured with a pair of pipes (single U-tube) that are joined by a U-bend at the bottom of the hole, as shown in Fig. 16. Other configurations include two pairs of pipes (double U-tube), simple

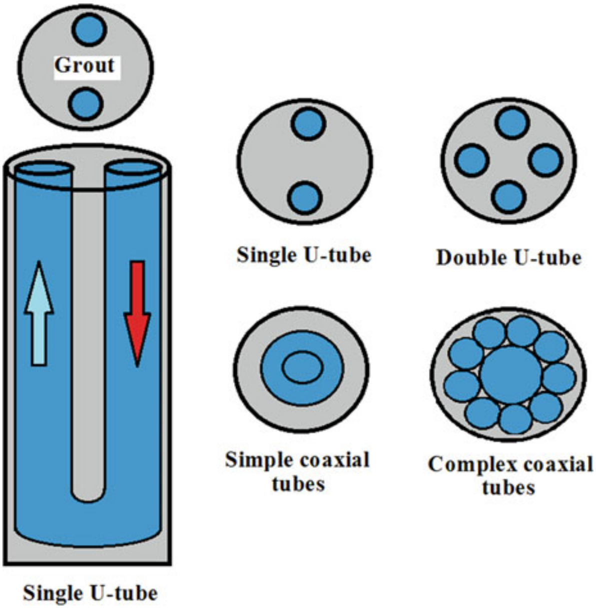


Fig. 16 Vertical loop configurations in boreholes

coaxial tubes, and complex coaxial tubes (Fig. 16). Regardless of the configurations, each borehole is filled with grout (usually a bentonite clay or bentonite-cement mix) to enhance the heat transfer performance as well as to seal the borehole in order to avoid contamination to groundwater. The working fluid (usually a mixture of water with 20–25% antifreeze) is circulated through each underground loop, where heat transfer takes place between the fluid and the surrounding soils through the pipe walls and grout material (Fig. 11).

The advantages of VCS may include the following:

- Less need for land area than horizontal-loop systems, especially for projects where the land resource is scarce.
- Less pump power than open-loop systems.
- Less threat to the surrounding environment than DX systems that use refrigerant as the underground circulation fluid.
- Fewer restrictions and requirements on the underground environment, such as water quality, bedrock, etc., than open-loop systems, and thus the use of VCS may avoid the potential problems that open-loop systems are facing regarding corrosion.

One of the largest obstacles that may limit the application of VCS is the high investment, especially the cost for drilling. A ground loop capital cost comparison done by Rafferty [28] indicates that the ground loop cost of typical commercial closed-loop systems is approximately 30–75% higher than open-loop systems with the same system capacities between 176 and 1760 kW, respectively.

System Design

The first step to design a vertical closed-loop heat pump system is usually to estimate the loads (heating and cooling) of the proposed building. Once the building heating and cooling requirements have been determined, the design of its corresponding VCS may start. In the design of a VCS, multiple key points have to be taken into account, including the configuration of the piping circuit, pipe size and length, pump capacity, as well as borehole diameter, depth, and separation. These design aspects are interrelated, and therefore comprehensive integration, optimization, and evaluation of the design are suggested to find the most appropriate design scheme for each specific project, in consideration of its first cost, system performance, and environmental impacts. Kavanaugh and Rafferty [10] gave a detailed description about the design procedure (10 steps) for VCS. Minimum deliverables for GSHP system installations are described in Chap. 34 of the *2015 ASHRAE Handbook – HVAC Applications* [2], including:

- Heat pump specifications at rated conditions
- Water pump specifications, expansion tank size, and air separator
- Fluid specifications
- Design operating conditions
- Pipe header details with ground heat exchanger layout
- Bore depth and approximate bore diameter
- Piping material specifications and visual inspection and pressure testing requirements
- Grout/fill specifications
- Purge provisions and flow requirements
- Instructions on connecting to building loop(s) and coordinating building and ground heat exchanger flushing
- A drilling report, if applicable, for the borehole thermal response test
- Sequence of operation for controls

Configuration of Piping Circuit

In addition to the different piping configurations within each borehole (single/double U-tube or simple/complex coaxial tubes), the network of underground piping circuits can vary from case to case, mainly including two layouts, i.e., series and parallel.

Series piping circuits, as shown in Fig. 17, are simple to design. The working fluid is circulated through each borehole one after another. The disadvantage of this type of circuit involves the relatively high pump power compared to parallel piping circuits that typically have a main reverse-return piping header with several branch loops evenly distributed, as shown in Fig. 17. A requirement for parallel circuits is to have an equal length of each branch loop, in order to ensure an equal flow in each borehole.

Pipe Size and Length

Underground pipes are one of the most important parts in a VCS. The typical design water flow rate in a VCS is approximately between 2.7 and 3.2 L/min/kW [10]. The

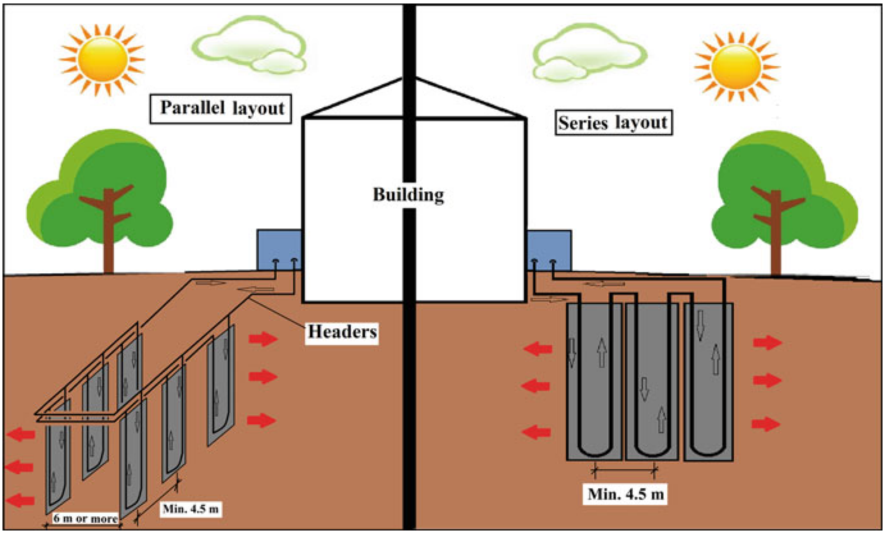


Fig. 17 Series and parallel vertical piping layouts

nominal pipe diameter used in the series layout may range from 20 to 50 mm. The nominal pipe diameter between 20 and 32 mm with a relatively larger size (e.g., 40 mm) for headers is typically used for the parallel layout.

The performance of a VCS is largely determined by the depth of boreholes and the corresponding length of underground pipes. Generally speaking, a value between 26 and 43 m/kW is a reasonable approximation for a typical pipe length for the single U-tube configuration (parallel layout), and a series layout may have a smaller value of m/kW for pipe length.

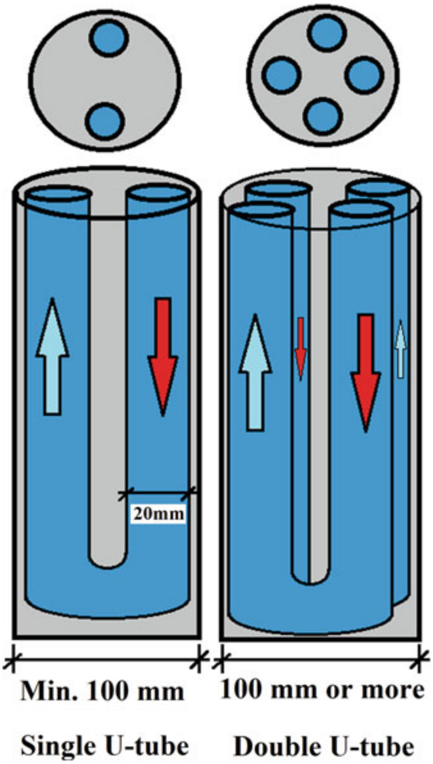
Borehole Diameter, Depth, and Separation

The purpose of drilling boreholes in a VCS is to allow the insertion of underground pipes. Therefore, the borehole diameter and depth are closely related to the pipe size and length. The minimum borehole diameter is typically 100 mm for a single U-tube in one borehole with its inserted nominal pipe diameter of 20 mm, as shown in Fig. 18. With the increase of pipe diameter and/or the number of pipes in each borehole (e.g., double U-tube), the borehole size needs to be enlarged accordingly. For example, a 40 mm single U-tube typically requires the borehole diameter to be at least 125 mm or 150 mm.

The length of a borehole is an important factor in the design of a VCS, which is usually half of the inserted pipe length for a single U-tube configuration. For a VCS, at least about 13 m length of borehole is typically needed for each HVAC kW capacity. Egg et al. [20] suggested the length of borehole to be 22 m/kW for an efficient vertical closed-loop heat pump system.

The two following equations (Eqs. 2 and 3) [2, 10, 29] are commonly used to determine a total bore length (L_{cooling} or L_{heating}) for a VCS:

Fig. 18 Minimum borehole size



$$L_{\text{cooling}} = \frac{q_n R_{ga} + (q_{cb} - W_c)\left(R_b + PLF_m R_{gm} + R_{gst} F_{sc}\right)}{T_{\text{ground}} - T_{\text{penalty}} - \left(\dfrac{T_{il} + T_{ol}}{2}\right)} \tag{2}$$

$$L_{\text{heating}} = \frac{q_n R_{ga} + (q_{hb} - W_h)\left(R_b + PLF_m R_{gm} + R_{gst} F_{sc}\right)}{T_{\text{ground}} - T_{\text{penalty}} - \left(\dfrac{T_{il} + T_{ol}}{2}\right)} \tag{3}$$

where

L_{cooling} [m] = bore length for cooling
L_{heating} [m] = bore length for heating
q_n [W] = net annual average heat transfer to ground ("+" for heating and "–" for cooling)
R_{ga} [m·°C/W] = effective thermal resistance of ground (annual pulse)
R_b [m·°C/W] = thermal resistance of bore
R_{gm} [m·°C/W] = effective thermal resistance of ground (monthly pulse)
R_{gst} [m·°C/W] = effective thermal resistance of ground (short term pulse)
PLF_m [–] = part-load factor during design month

F_{sc} [−] = short-circuit heat loss factor
T_{ground} [°C] = undisturbed ground temperature
T_{il} [°C] = inlet liquid temperature at heat pump
T_{ol} [°C] = outlet liquid temperature at heat pump
T_{penalty} [°C] = temperature penalty indicating the long-term thermal impact of using underground heat exchangers on local geologic formations ("+" for heating and "–" for cooling)
q_{cb} [W] = design cooling block load of building ("–" for cooling)
q_{hb} [W] = design heating block load of building ("+" for heating)
W_c [W] = system power input at design cooling load
W_h [W] = system power input at design heating load

Deeper boreholes are being attempted due to their access to higher ground temperatures, as well as fewer boreholes and the use of smaller land areas. For example, the boreholes of the GSHP system used in the project of SOK Logistic Center in Sibbo, Finland, have a depth of 300 m underground [30].

Borehole separation means the horizontal distance between each borehole, as shown in Fig. 17. Making boreholes too close to each other will increase the thermal interference between boreholes and may cause thermal saturation that could decrease the efficiency of a VCS. A minimum suggested separation for a VCS is 4.5 meters if annual heat flow is nearly balanced underground [2]. An ideal separation distance is typically 6 m or more in order to minimize the interaction between boreholes.

At the design stage, the borehole depth and separation are usually adjusted and optimized to minimize the ground temperature penalty (T_{penalty}) that represents the change of the ground temperature after a long period (usually 10 or 20 years), indicating the long-term thermal impact of using underground heat exchangers on local geologic formations. Ground temperature penalty is mainly caused by the unbalanced heat extraction and injection from/to the ground by a GSHP system. Therefore, when building heating and cooling loads are extremely unbalanced, a hybrid system (see section "Hybrid System") is often used, which may combine the ground loops with a cooling tower/fluid cooler (if for cooling-dominated buildings) or a boiler/solar thermal collectors (if for heating-dominated buildings) in order to offset the impact of excess heat either added or extracted to/from the ground.

Pump Power

In a VCS, a ground loop pump is used to circulate the working fluid through the underground pipes inserted in boreholes. The pipe size and length have a direct impact on the pump power. The use of shorter pipelines may reduce the associated pump power and ground loop cost; however a shorter ground loop may not have the capacity to handle the necessary cooling and heating loads. Series piping layouts usually consume higher pump power than parallel. A pump power between 1.1 and 2.1 kW per 100 HVAC kW is suggested by Egg et al. [20] for an efficient VCS. The use of a variable speed drive (VSD) motor contributes to the reduction of pump power.

Computer-Aided Design Tools

The working intensity of designing a VCS can be significantly reduced with the assistance of computer programs. The currently available programs for designing and/or simulating a VCS include, but are not limited to, GLHEPRO, OptGSHP, Gaia Ground Loop Design (GLD), GS2000™, Right-Loop™, Earth Energy Designer (EED), LoopLink®, GeoDesigner, GCHPCalc, TRNSYS, eQuest®, and EnergyPlus™. For example, the long-term impact of installing a VCS on the local underground temperature may be determined by using programs such as GLHEPRO, TRNSYS, etc., in which borehole length, separation, etc. may be optimized in order to minimize the ground temperature penalty. Some of these tools are able to be applied not only for a VCS but also for other types of GSHP systems.

Detailed mathematical (analytical and numerical models) descriptions about underground heat and mass transfer of vertical boreholes may be found in Rafid [31] and Sarbu and Sebarchievici [32].

System Installation

To install a VCS, drilling is a must. A test and evaluation of the local ground formation are usually necessary before drilling, in order to have an accurate knowledge of the site characteristics to select the proper drilling method. The most commonly used drilling methods for the installation of a VCS include hammer drilling and/or rotary drilling [10]. The mud rotary drilling method (Fig. 19) is suitable for the installation of a VCS in soft ground formation, consisting of clay, sands, etc. The use of drilling mud is to avoid the collapse of the borehole, which is usually not a problem for a hard (consolidated) formation, where the air rotary or air hammer drilling method (Fig. 19) is typically utilized. An experienced and licensed local drilling company is suggested, whose experience and knowledge contribute to the successful installation of a VCS.

The inserted high-density polyethylene (HDPE) pipes are typically connected using heat fusion techniques, such as socket, saddle, or butt fusion methods.

After the drilling and insertion of a ground loop in each borehole, the gap between pipes and borehole walls are filled with grout to enhance the heat transfer performance as well as to seal the borehole in order to avoid contamination of groundwater. The grout material should have a high thermal conductivity. The common grout material types are bentonite, thermally enhanced grouts with quartz, water-saturated sand, and bentonite with graphite, whose thermal performances are shown in Table 3. For a VCS, grout is typically backfilled from the bottom in each hole, as shown in Fig. 20.

The sites for installing a VCS may be an open field, a parking lot, or the backyard of a residential house. In addition to these typical installations, a VCS could be incorporated into a building foundation and installed underneath (energy piles), as shown in Fig. 21, in order to further reduce the required land areas. This is a special benefit for buildings located in the center of a city where available land resources for VCS are scarce.

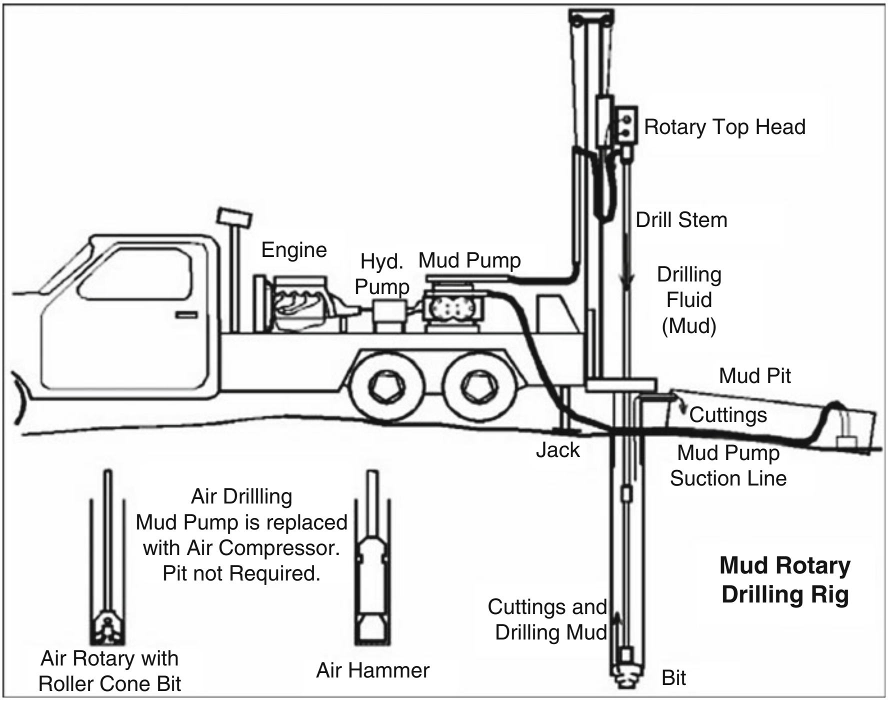


Fig. 19 Drilling methods for a VCS [10] (©ASHRAE, www.ashrae.org. *Geothermal Heating and Cooling – Design of Ground-Source Heat Pump Systems*, Appendix D, 2014)

Table 3 Grout material thermal performance [33]

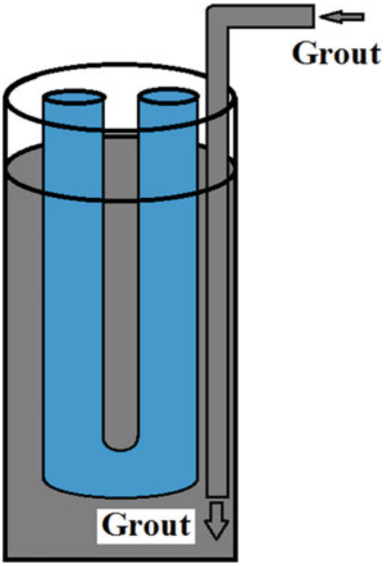
Grout material	Thermal conductivity^a [W/m-K]
Bentonite	0.80–1.00
Thermally enhanced grouts with quartz	1.00–1.51
Water saturated sand	1.51–2.01
Bentonite with graphite	3.00

[a] Source: Hellström [34]

System Control and/or Operation

The major energy consumption of a vertical closed-loop heat pump system comes from heat pump units (compressors and fans) as well as circulation pumps for ground loops. Regardless of indoor heat pump units, the energy use associated with circulation pumps of a VCS is expected to be less than 10% of the total energy consumption of the system [10], which may be accomplished by using VSD motors. An example of a control strategy of a VCS (Fig. 22) used in cold regions is given in Table 4, which has backup boilers to provide additional heating when the return water is below a certain temperature, such as 1.0 °C. One of the operating pumps

Fig. 20 Grout backfilling



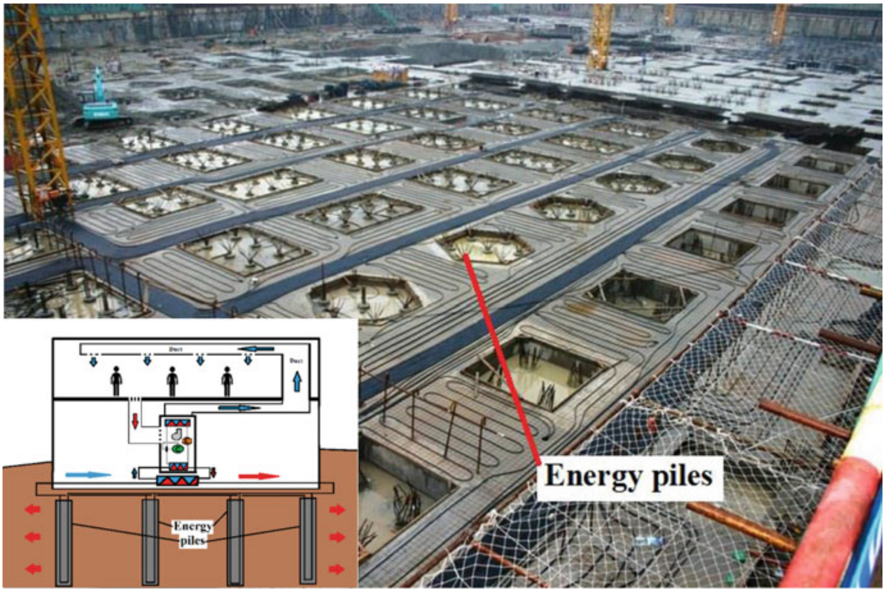


Fig. 21 Underground heat exchangers (energy piles) under concrete foundations (Printed with permission of Enercret)

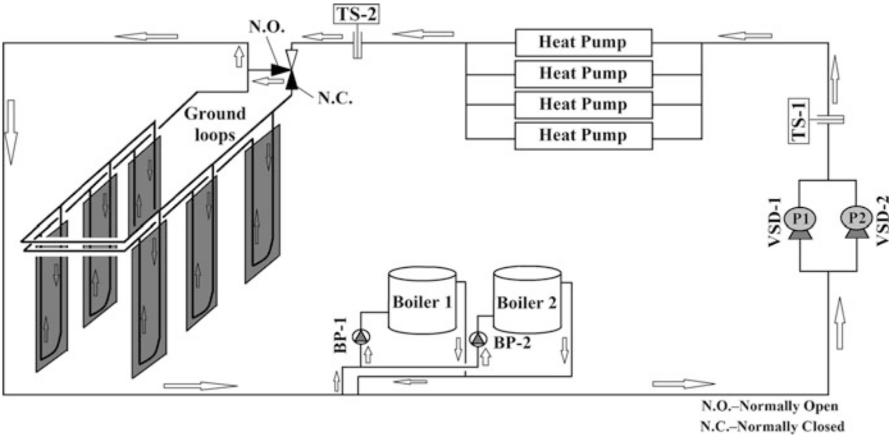


Fig. 22 Control diagram for a VCS

Table 4 Control strategy for a VCS

Return water temperature (TS-2)	Three-way valve (control the N.C. side to ground loops)	Boiler(s)	VSD pump
Less than 1 °C	Open to ground loops	On	Modulate to maintain ΔT = 6 °C between TS-1 and TS-2
1 ~ 5 °C	Open to ground loops	Off	Modulate to maintain ΔT = 6 °C between TS-1 and TS-2
5 ~ 15 °C	Modulate to maintain ΔT = 6 °C between TS-1 and TS-2	Off	Operate at minimum speed
15 ~ 25 °C	Closed to ground loops	Off	Operate at minimum speed
25 ~ 35 °C	Modulate to maintain ΔT = 6 °C between TS-1 and TS-2	Off	Operate at minimum speed
More than 35 °C	Open to ground loops	Off	Modulate to maintain ΔT = 6 °C between TS-1 and TS-2

(lead pump – P1) shall run when the system is enabled with the other pump (P2) to be standby until failure of the lead pump. The lead and standby pumps shall frequently be rotated.

As shown in Table 4, the three-way valve and VSD pumps are operating according to the different return water temperatures, in order to maintain an appropriate temperature differential between the supply and return water for heat pump units. The whole system may be controlled by a building automation system (BAS), which will also provide monitoring and diagnostic information for the purposes of management.

System Trouble Shooting

The common issues that need to be avoided in the design and operation of a VCS, include, but are not limited to, the following:

- A low velocity of the working fluid in ground loops, resulting in a lower Reynolds number than its critical value of 2500, which is probably caused by the oversizing of the pipes (the low Reynolds number indicates the formation of laminar flow in pipes, which reduces the heat transfer between the fluid and the ground and thus results in lower capacities of heat pump units)
- Undersized ground heat exchangers, such as a short borehole separation distance, an insufficient borehole length, etc., which may cause a higher or lower loop temperature in a cooling or heating mode, respectively, thus reducing the system efficiency and even resulting in the failure of the entire system
- An oversized VCS, aiming to overcome the uncertainties in building construction and system installation, which may require a higher capital cost and lead to a lower efficiency because of more frequent part-load operations
- Unbalanced heating and cooling loads that may result in a temperature change of the ground over a long period (ground temperature penalty) and negatively influence the capacity and efficiency of a VCS
- The occurrence of leaks (even though it is not common for heat-fused pipes) with the actions to be taken right after, including:
    1. The system should be shut down automatically when it measures a pressure loss of the underground heat exchangers, indicating that leaking is likely happening.
    2. The section of leaking pipes should be isolated, waiting for the repair or replacement with new pipes, and the detection and repair of leaking pipes may be time-consuming and expensive due to the needs of tests and excavations.

Other problems that a vertical closed-loop heat pump system may have include a poor system design and/or control strategy, compressor failure caused by low suction/high discharge temperature, as well as the lack of regular system maintenance.

Horizontal Loop

In a horizontal closed-loop system (HCS), the heat exchanger pipes (usually HDPE) are buried horizontally in the shallow ground, below the local region frost line but not as deep as a VCS. The depth of horizontal pipes is expected to be at least 0.9 m below the ground surface, regardless of frost line consideration. This type of closed-loop system typically requires more land area than a VCS, but is less expensive for installation due to the avoidance of vertical drilling. Therefore, an HCS is usually suggested as long as the available land area is large enough for its installation. A conservative approximation of $26 \sim 40\ \mathrm{m}^2$ per kilowatt was made by Egg et al. [20] for estimating the average land area needed for an HCS. Like a VCS, the working fluid in an HCS is circulated throughout horizontal ground loops to accomplish its heat transfer with the ground. In cold-climate regions, an antifreeze solution is a must to prevent freezing of the working fluid.

The piping layouts of HCS are various and may often be categorized into four types, including single pipe, multiple pipes, slinky pipes, and horizontally bored pipes, as shown in Fig. 4b.

The single-pipe configuration shown in Fig. 23 is easy to design and install. Multiple-pipe systems usually involve the use of more than one pipe in each trench. In a two-pipe system, as shown in Fig. 23, pipes (one for supply and one for return) are buried one over the other or side by side in the same trench. The four-pipe system typically consists of a header connected with two loops (four pipes) buried in the same trench in two ways, as shown in Fig. 23. Although the use of multiple pipes in one trench may reduce the total length of trench needed for a given capacity, the actual pipe length will be increased in order to offset the thermal interference between pipes. A slinky-pipe system allows the maximization of the effectiveness of land resources in an HCS. The slinky pipes that are overlapped with each other and buried underground may be configured in a series or parallel circuit. This slinky layout is typically used when the land resources are too limited to allow the installation of single or multiple pipes. The slinky-pipe layout may stand vertically in a trench or be put flat on the bottom of a trench (Fig. 24). Another variant of an HCS involves the installation of pipes in deeper horizontal boreholes (usually 9 ~ 15 m) (Fig. 24), thanks to new types of horizontal drilling machines. An HCS with horizontally bored pipes may meet higher building cooling and heating requirements (for large commercial projects) than a conventional HCS, since the pipes may be placed beneath the building.

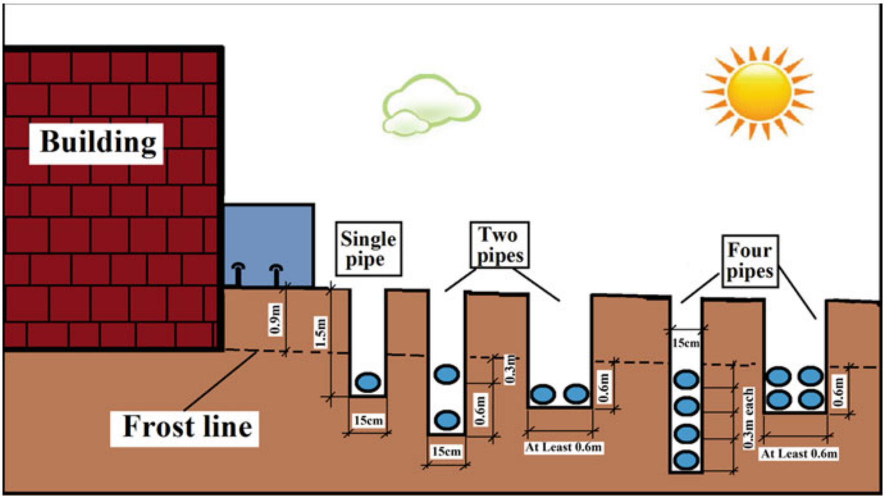


Fig. 23 Single- and multiple-pipe systems

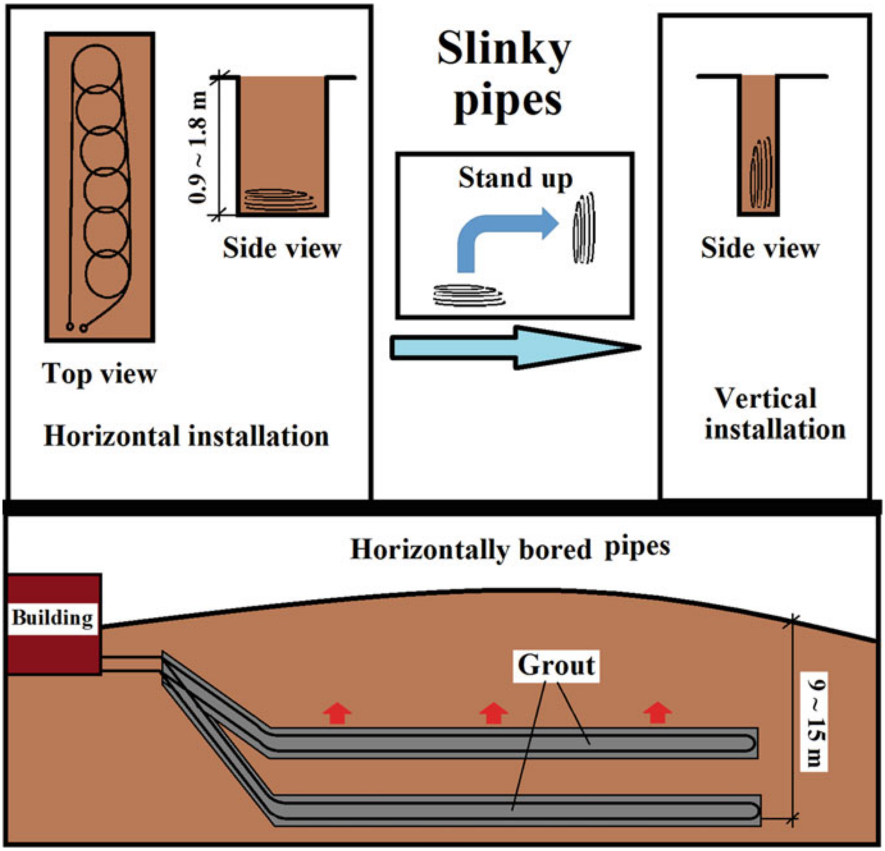


Fig. 24 Slinky and horizontally bored pipes

The advantages of an HCS may include the following:

- Easier to install than other ground loop systems
- Less cost for installation than vertical-loop systems, due to the avoidance of vertical drilling
- Fewer threats to the surrounding environment than other ground loop systems, because of its pipeline position in the near-surface ground
- Fewer restrictions to the field, such as water quality, bedrock, etc., than open-loop systems

One of the largest obstacles that may limit the application of HCS is the requirement of relatively large land areas compared to other ground loop systems. Hence, an HCS is not commonly used for urban commercial buildings, unless deeper horizontally bored pipes are considered in the design.

Other disadvantages include that:

- An HCS is more likely to be influenced by the outdoor environment, because the underground loops are near the ground surface.
- Buried pipes of an HCS in the shallow ground are more easily disturbed and damaged by other excavation activities.
- An HCS may require higher pump power than a VCS owing to its longer pipe length and therefore have a lower system efficiency.

System Design

Single-Pipe System

A single-pipe system can be considered as the simplest HCS. It only consists of a single pipe that is buried underground in a narrow trench (usually in series), as shown in Fig. 25. A circulation pump pushes the working fluid throughout the piping loop to carry out heat transfer with the ground. Plastic (usually HDPE) is typically used as the pipe material. The depth of the pipe is suggested to have a minimum of 1.5 m below the ground surface if the frost line has a depth of around 0.9 m (Fig. 23). The deeper the frost line, the more depth of the pipe. A minimum of 0.6 m below the frost line is suggested.

The nominal pipe diameter typically varies from 32 to 50 mm, and its (pipe or trench) length is usually between 30 and 43 m/kW with an average of around 36.5 m/kW. This type of system is usually applied in a small residential building or single house with a capacity of up to 17.6 kW.

Two-Pipe System

The layout of two-pipe systems may be designed in series or parallel, as shown in Fig. 25. Two pipes are typically buried in one trench, which may result in a reduction of the total trench length. As shown in Fig. 23, the two pipes may be positioned in the trench one over the other (up and down) or side by side. For the up-and-down position, a minimum of 0.3 or 0.6 m below the frost line is suggested for the upper and lower pipes, respectively, and for the side-by-side installation, a minimum of 0.6 m below the frost line is suggested. The separation distance between these two pipes in each trench is typically 0.6 m, in order to minimize their thermal interference between each other.

The parallel design is suggested in pursuit of lower pumping power and less pipeline cost (caused by the smaller pipe size). The nominal pipe diameter for two-pipe systems is typically between 32 and 50 mm. The trench length is usually smaller than single-pipe systems and typically between 17 and 35 m/kW. Compared to single-pipe systems, a longer pipe length is typically required for multiple-pipe underground loops (e.g., 35 ~ 70 m/kW for two-pipe systems).

Four- or Six-Pipe System

It is possible to arrange more pipes in each trench, such as four pipes (Fig. 23) or even six pipes. As shown in these figures, for these piping configurations, the

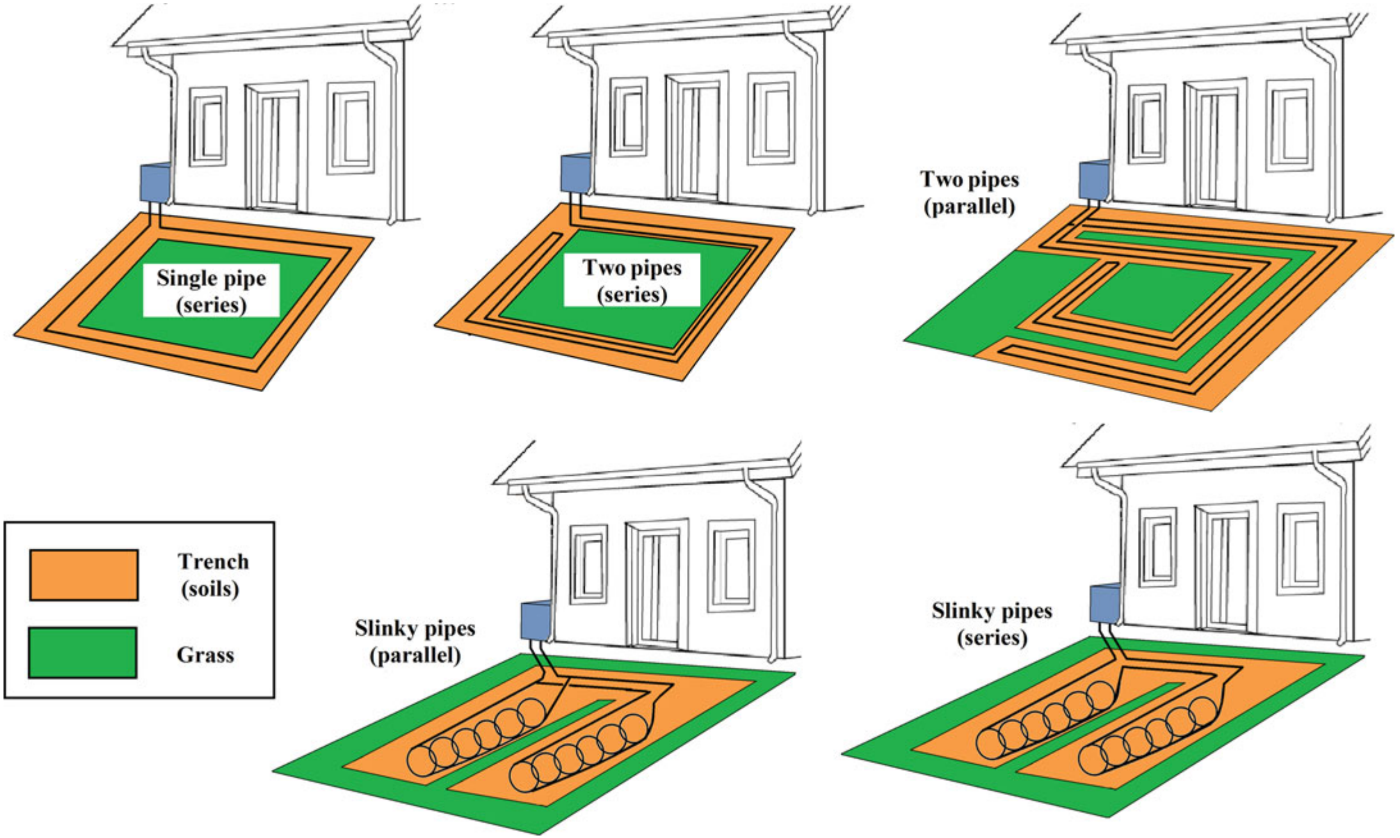


Fig. 25 Single-, two-, and slinky-pipe layouts

spacing between pipes could be lower, and thus the use of more pipes may reduce the trench length further. For example, the length of a trench per kilowatt is usually between 10 and 26 meters per kilowatt for a four-pipe system. Since the thermal interference reduces the heat transfer performance of each pipe, a longer pipeline (40 ~ 100 m/kW for four-pipe systems) is typically required to cancel out this thermal impact between pipes.

Slinky-Pipe System

In an HCS, arranging pipes to form circles that closely overlap each other, as shown in Fig. 24, may maximize the utilization of land areas. This type of system is reported to be able to further reduce the land use, because of its higher pipe density, but usually needs longer pipes than other piping configurations. The maximum pipe density is typically limited to 10 m of pipe for each linear meter of trench [2]. Theoretically, slinky pipes can be arranged in series or parallel (Fig. 25) and positioned vertically or horizontally in a trench (Fig. 24). The typical depth of a horizontally positioned slinky pipes is around 0.9 ~ 1.8 m below the ground surface, the minimum separation distance between trenches is usually 3 m, and the minimum trench width is usually 0.8 m with a maximum suggested trench length of 30 m [22].

Horizontally Bored System

A horizontally bored system is a variant of an HCS and can be considered as an intermediate underground heat exchange system between conventional HCS and VCS. The development of this type of system benefits from a horizontal drilling technique that allows the installation of horizontal heat exchangers in the deeper ground at different layers, as shown in Fig. 24. Like a VCS, the horizontal boreholes are typically grouted in order to improve the heat transfer performance. This type of system is less disturbed by outdoor weather and thus may have higher cooling and heating capacities for larger building applications. Because of the deeper positions of horizontally bored loops underground, the design of this underground system is very similar to that of a VCS, including pipe size and length, etc.

Soil characteristics play a key role in the design of underground heat exchangers. These characteristics determine the heat transfer performance of soils and thus significantly influence the design of pipes, including size and length. In a field with a low soil thermal conductivity, longer horizontal pipes (greater meters of pipe per kilowatt) are usually required to enhance their heat transfer with the ground. An accurate knowledge of the local soil condition is important for a successful design of ground source heat exchangers. If data about the soil condition on the field is not available, on-site test and evaluation may be necessary to determine the thermal characteristics of geologic formations. For an HCS, this task is relatively easy compared to a VCS, because it is easier to obtain a soil sample for an HCS from the shallow ground than a VCS whose pipe depth is typically more than 15 m underground. More descriptions regarding the test and evaluation of soil characteristics can be found in section "Low-Temperature Geothermal Resources."

Detailed design information of an HCS is described in Chap. 34 of *2015 ASHRAE Handbook – HVAC Applications* [2] as well as the GSHP design and installation guide by Remund and Carda (2009) [17].

System Installation

The installation of an HCS involves the excavation, placement of underground heat exchangers, and backfilling.

Excavation

The working intensity of excavating trenches is dependent on the dimension of trenches, including length, width, and depth. Designs with shorter and shallower trenches may result in a reduction of the total excavated volume. Narrow trenches, as shown in Fig. 23, are usually 15 cm width and dug with trenching equipment, such as a chain trencher. Wider trenches can be dug with a backhoe, which usually have a width of at least 0.6 m, allowing the placement of more pipes (or slinky pipes), as shown in Fig. 23. Horizontal bores (Fig. 24) are made using horizontal boring devices and are typically deeper than conventional trenches for an HCS. Cautions should be given during excavation to avoid damage to existing pipelines or cables buried underground.

Heat Exchanger Placement

Buried pipes, which are usually made of HDPE, are joined using heat fusion methods. If multiple pipes are placed in a single trench with several layers, backfill lower pipe(s) partially before the placement of upper pipes on the top, as shown in Fig. 26. In addition, make sure the return pipe(s) from heat pumps are positioned on the upper level, which allows the supply pipe(s) to be placed in deeper ground to maximize system efficiency. When placing U-bends, special cautions should be taken to prevent kinking of the bends, especially for the installation of slinky pipes.

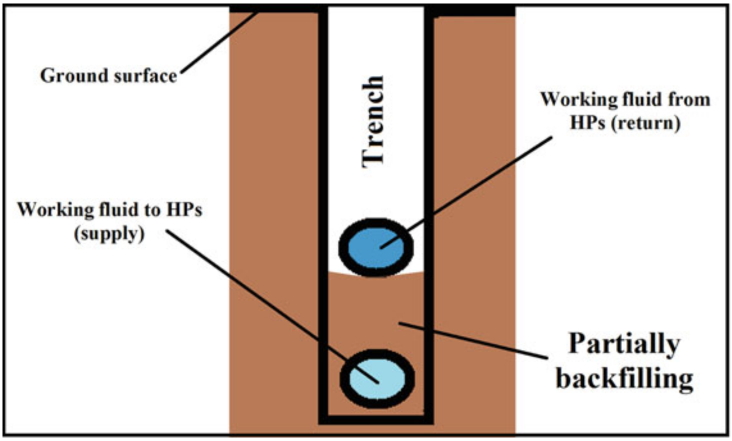


Fig. 26 Two pipes at two layers in a trench

Backfilling

Care should be taken in backfilling trenches, and sometimes more hands are needed to avoid installation issues, such as pipe kinking. When backfilling slinky pipes, ensure that the gaps between circles are filled with fine soil, and avoid using rocky soil and the presence of air space between pipes which may reduce the heat transfer performance.

System Control and/or Operation

As closed-loop underground systems, the control and operation of an HCS are not much different from that of a VCS. Pump power for an HCS is typically higher than a VCS, because of its longer pipe length and greater head losses, especially for slinky-pipe systems. An HCS may have a lower efficiency than a VCS since it is more likely to be influenced by outdoor weather conditions.

System Trouble Shooting

Most of the issues a VCS has are also common to an HCS. Other concerns should be taken into account when designing, installing, and operating an HCS, such as the protection of pipes from freezing, pipe kinking, ground surface coverings, etc.

Freezing protection is needed for an HCS applied in cold climates with the use of antifreeze solutions. The solutions used should be nontoxic to avoid the pollution in case of leaking. In addition, in the design of underground heat exchangers in cold regions, it is important to avoid the proximity of GSHP pipes with any other waterlines in order to reduce the threat of ice formation around any other pipes.

Kinked pipes may occur if underground heat exchanger loops are not installed properly. This may limit the normal flow of water, thus reducing the heat transfer effectiveness and system efficiency, and eventually require a system repair.

It is important to be aware that an HCS is like an indirect solar collector and the heat going into an HCS from the shallow ground is mainly derived from solar radiation that hits on the ground surface and is absorbed by the soil. Therefore, for heating-only applications, the ground surface where an HCS is buried underneath should be kept clear without any coverings in order for an HCS to gain enough solar energy [32].

Lake or Pond Loop

Lakes, rivers, ponds, etc. are alternatives as heat sources or sinks for heat pump systems. The use of these surface water bodies to provide heating or cooling effects to buildings can be carried out through either open- or closed-loop heat pump systems. This section only covers the general concepts about a surface water closed-loop system (SWCS) and more detailed descriptions with respect to SWCS, including design, installation, operation, etc., as well as the topics regarding surface water open-loop system (SWOS) are discussed in chapter ▶ "Introduction of Water Source Heat Pump System."

Unlike a VCS or HCS whose heat exchange loops are buried underground, the heat transfer loops (pipes) of a SWCS are typically submerged underwater (lakes, rivers, ponds, or even oceans). As a closed-loop system, the working fluid (usually water or a mixture of water and antifreeze) of a SWCS in pipes (usually HDPE) is not exposed to the water bodies. Like other closed-loop systems, the heat transfer of a SWCS between inner fluid and outer natural water takes place through the walls of the underwater pipes. Circulation pumps are typically used to push the enclosed working fluid throughout the system, including the underwater pipes and water-to-refrigerant heat exchangers embedded in heat pump units, as shown in Fig. 4c. The performance of a SWCS could be similar to that of other closed-loop systems, as long as it is designed and utilized properly. Temperatures of open water bodies, however, may not be as stable as ground bodies. The thermal behavior of water bodies will be influenced by these surrounding environments. Therefore, the performance of a SWCS is determined by many factors, such as the body size of water, the position and depth of heat exchangers in the water, etc. For example, water temperatures of a small and shallow lake will be more dependent on outdoor weather conditions. Therefore, the performance and efficiency of a SWCS located in it is more likely to be influenced by seasons, rainfalls, winds, solar radiation, etc. An accurate knowledge regarding the thermal characteristics of proposed water bodies will lead to a more successful design.

The advantages of a SWCS may include the following:

- Less cost for installation than vertical or horizontal underground loop systems, due to the avoidance of drilling and excavation
- Less pumping power and less chance of pipe fouling than SWOS, thus resulting in lower maintenance and operation cost
- Fewer restrictions to the field, such as water quality, bedrock, etc., than open-loop systems

The disadvantages of a SWCS may include the following:

- The greater impact of outdoor conditions on the performance of a SWCS than underground loop systems, which may result in lower system efficiency and capacity.
- Damage of underwater pipes could occur, for example, caused by boat anchors/propellers or by floating/drifting objects in case of flood if locating heat exchangers in a river or stream.

Open-Loop System

As its name implies, an open-loop system refers to a system that is “open” to the surrounding environment. The difference between open- and closed-loop systems depends on whether the working fluid is directly exposed to the ambient medium or not. In open-loop systems, as shown in Fig. 27, ground or surface water is pumped directly from water sources (aquifers, lakes, etc.) and circulated through terminal units (water source heat pumps or water-to-water heat exchangers) before discharging it back to ground or surface water bodies. In general, compared to

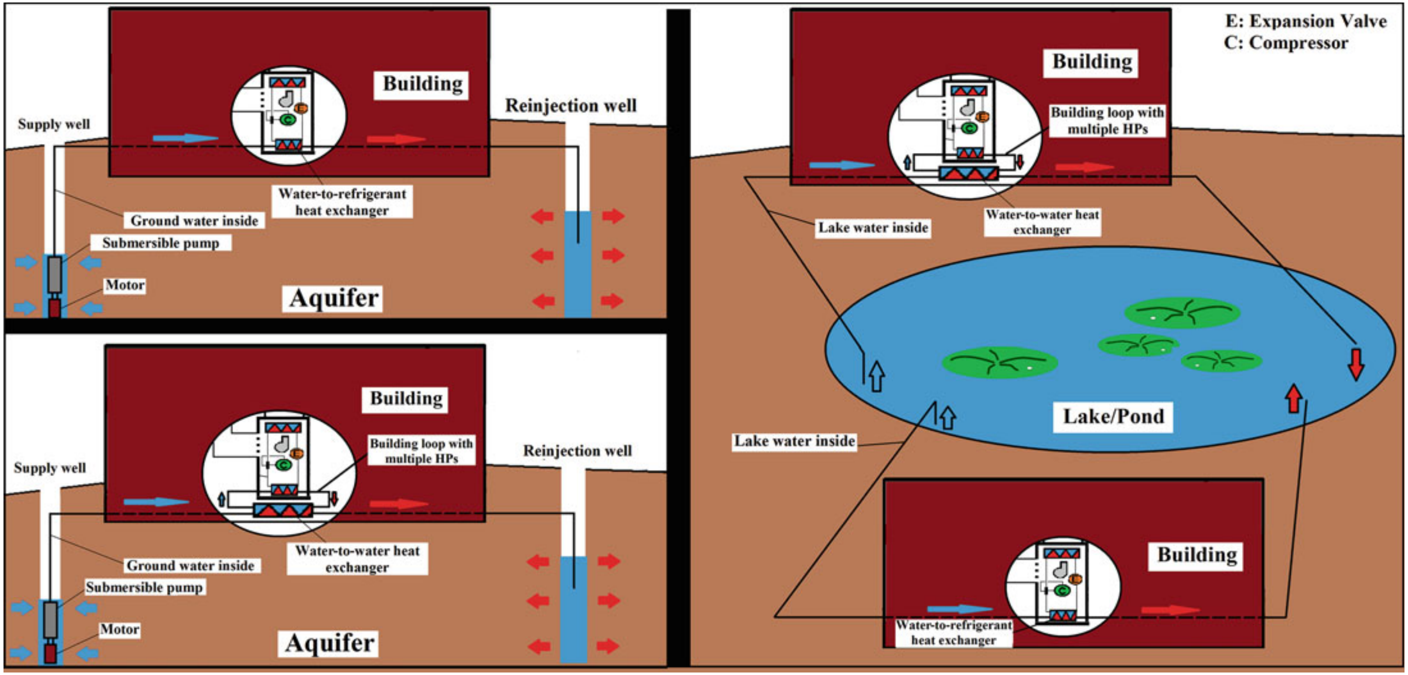


Fig. 27 Ground and surface water open-loop systems

other ground source systems, the advantages of open-loop systems may include the following:

- A lower capital cost than closed-loop systems
- A higher operational efficiency than closed-loop systems
- A more mature technology and support

A lower capital cost is one of the most attractive features possessed by open-loop systems, in contrast to conventional closed-loop systems, like vertical borehole systems. A ground loop capital cost comparison was done by Rafferty in 2008 [28], in which commercial open-loop systems demonstrate a 30% lower cost than closed-loop systems with the same capacity of around 176 kW, and greater ground loop cost savings (75%) may be achieved when using open-loop systems with a higher system capacity (1760 kW).

In open-loop systems, pumping the water from local water bodies and using it directly avoids the heat transfer loss through pipe walls of closed-loop heat exchangers and thus contributes to the improvement of system efficiency. In addition, this type of system allows a direct cooling effect (free cooling) to buildings by bypassing mechanical refrigeration systems, as long as the water extracted from surrounding water bodies is cold enough (usually below 15 °C).

Due to the direct use of ground or surface water, well-trained and experienced designers, contractors, and engineers are needed for the design, installation, and operation of open-loop systems. Fortunately, open-loop systems, especially groundwater heat pump systems, have been widely used for decades, and thus many lessons learned from the accumulation of experience with time are extremely conducive to the formation of a more mature technology as well as its wide application and dissemination. According to past experience and lessons, the major disadvantages of open-loop systems involve the following:

- Potential threats to mechanical equipment because of the direct contact with groundwater or surface water, including corrosion, scaling, and/or fouling
- Environmental issues due to the direct extraction and discharge of water from and into water bodies
- Higher pump power and maintenance cost, especially for groundwater open-loop systems, compared with closed-loop systems

Potential threats exist to mechanical equipment when water from nature is used directly and circulated through either one side of a water-to-water heat exchanger for commercial use or through a heat pump unit for residential use, as shown in Fig. 27. If the water quality does not meet a certain standard, corrosion, scaling, and/or fouling may occur, which could damage the system, cause leaks, and significantly decrease the effective heat transfer owing to the formation of limescale. Therefore, additional maintenance is typically required for open-loop systems in order to clean the system, remove the fouling, etc., which may result in a higher maintenance cost than closed-loop systems.

In addition to the negative impacts on mechanical equipment when using open-loop systems, emphasis should also be placed on potential environmental threats. Unlike DX systems that may cause environmental issues because of the leak of refrigerant, the potential threat of open-loop systems involves the depletion of aquifers. Typically, aquifers are the source of groundwater for groundwater open-loop systems, and the extraction and injection of groundwater from/to aquifers would cause a net-zero water use. However, the reduction of groundwater injected back to aquifers may occur if the groundwater is pumped up to the surface not only for heat pump systems (nonconsumptive use) but also for consumptive use (surface disposal). The continuous consumption of the groundwater over time could eventually result in a drop of the aquifer water level that may negatively impact the natural ecosystems. Therefore, open-loop systems are restricted per local environmental regulations in some regions.

Unlike closed-loop systems, a pump (submerged) in a groundwater open-loop system has to overcome an additional elevation difference between the water levels in the supply and reinjection wells, such as the vertical lift as shown in Fig. 32, in order to lift the groundwater from the bottom to the top surface. Therefore, pumps in open-loop systems would consume higher power than the circulation pumps used in closed-loop systems. A proper and careful design of an open-loop system may reduce the pump power. For example, based on the pump affinity laws, the use of VSD motors may lower the required average power. However, VSD systems have to be designed and controlled carefully in order to avoid the failure of the motors/pumps [10].

Technically, in open-loop systems, both ground and surface water bodies may be used as water sources in conjunction with heat pumps. Therefore, in the category of open-loop systems, there exist two types of heat pump systems, i.e., groundwater heat pump (GWHP) and surface water heat pump (SWHP) systems, depending on the source of the circulated water. In this section, only GWHP open-loop systems are discussed; while more descriptions with respect to SWHP open-loop systems may be found in chapter ► "Introduction of Water Source Heat Pump System."

System Design

In GWHP open-loop systems, groundwater may be extracted from one well and dumped to the other, which is known as pump and reinjection system (PRS) [20], as shown in Fig. 28, or groundwater may be extracted from and dumped to the same well, which is known as standing column well system (SCWS), as shown in Fig. 29.

Pump and Reinjection System (PRS)

In a PRS, two wells are typically drilled with one for groundwater supply and the other one for water discharge or injection back to aquifers. The discharged groundwater from heat exchangers or heat pumps may be used as service water or drained to surface water bodies, such as a lake or river, as long as the water quality meets the requirement of local environmental regulations, and it is allowed by responsible authorities. The consumptive use (surface disposal) of the discharged groundwater, however, is not suggested due to the potential issue of the depletion of aquifers,

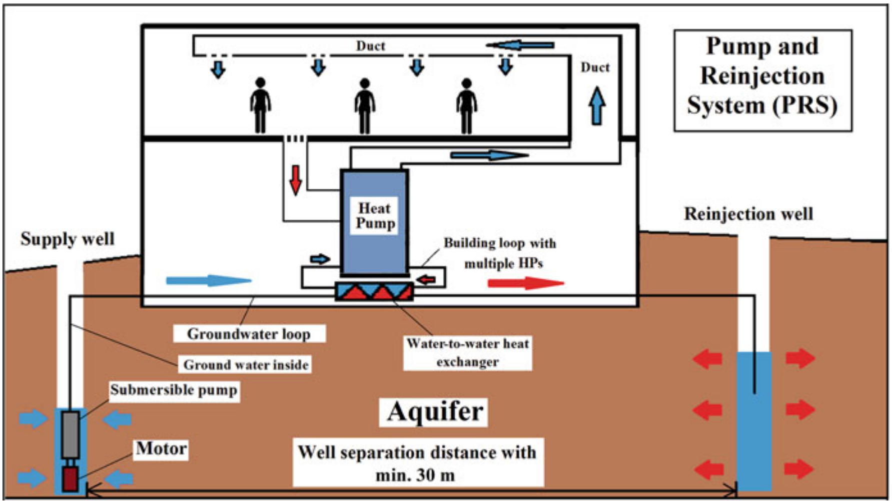


Fig. 28 Pump and reinjection system (PRS)

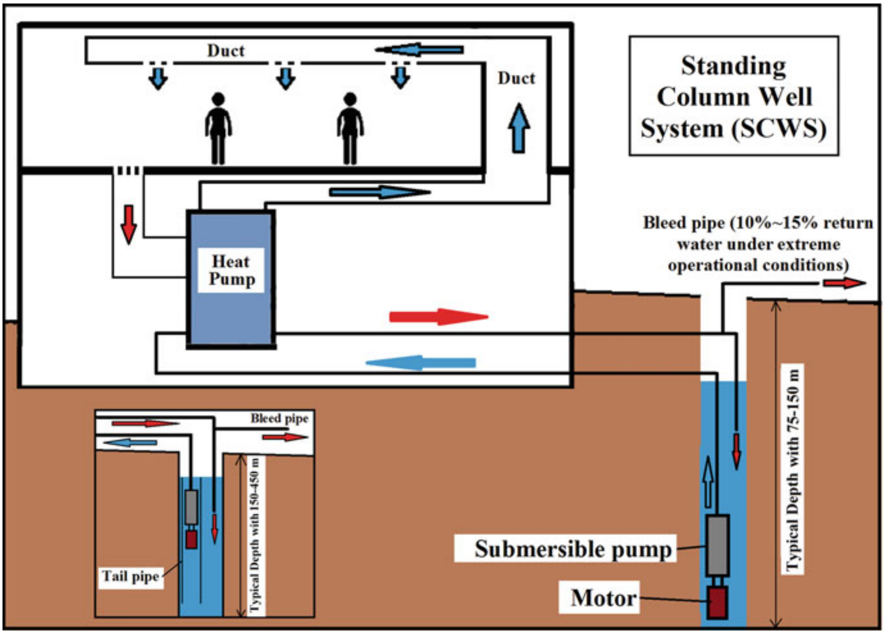


Fig. 29 Standing column well system (SCWS)

as described in the previous section. The two drilled wells should be located in the same locality, not far from each other, but should maintain a separation distance of at least 30 m with the reinjection well located in the downstream direction of the groundwater flow in order to minimize the thermal interference between them. Suggested minimum well separation distances are shown in Fig. 30 with the variations of average groundwater flow rate and aquifer thickness. The groundwater from a PRS may be circulated directly to each heat pump, usually located inside of buildings, to transfer heat through a water-to-refrigerant heat exchanger in each heat pump unit, as shown in Fig. 27. This design may cause the risk of corrosion and fouling of some of the indoor distribution system (including heat pumps). This type of system is usually applied in residential or small commercial buildings with a typical groundwater flow rate of 2.2 L/min/kW or more.

Another alternative is to isolate the heat pumps from the groundwater, as shown in Fig. 27, by using a water-to-water heat exchanger, where the heat transfer takes place between the indoor circulation water and the groundwater without the direct contact with each other, thus avoiding the contamination by the untreated water to the heat pump units. In this design alternative, the well pump power is typically optimized with the groundwater flow rate that varies between 1.1 and 2.2 L/min/kW. A detailed description regarding the design of PRS can be found in Kavanaugh and Rafferty [10].

Standing Column Well System (SCWS)

In an SCWS, only one well is needed to extract and inject well water that is circulated through each heat pump, as shown in Fig. 29. An SCWS may be regarded as an intermediate system that reaches a compromise between PRS open-loop and closed-loop systems. SCWSs are characterized by lower capital cost and higher efficiency than closed-loop systems. In an SCWS, a bleed circuit is typically required to control the temperature of the circulation well water under extreme operational conditions by dumping a portion of return well water to the outside

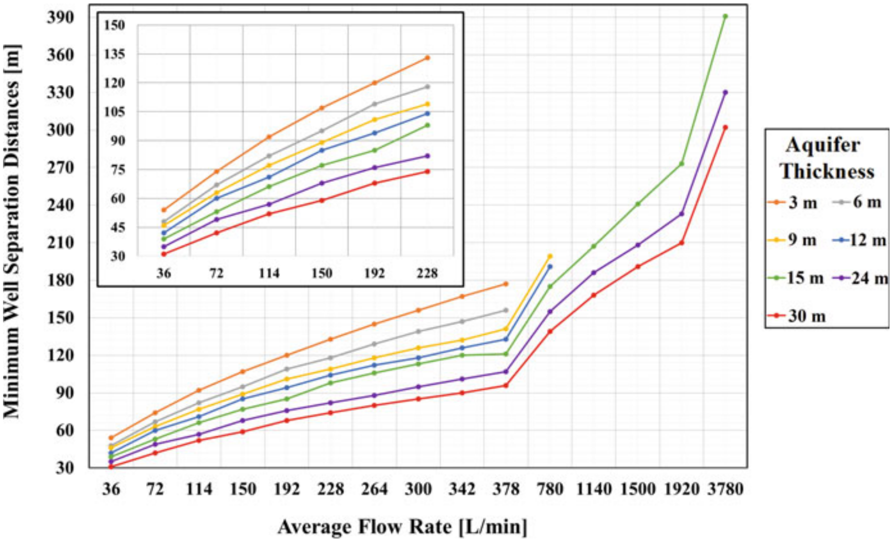


Fig. 30 Minimum well separation distances [meters] (Source: Kavanaugh and Rafferty [10])

(Fig. 29). Although a high bleed rate is able to reduce the design well depth and thus the associated cost, it may also result in a reduction of groundwater considering the accumulation of the bleed flow for many years.

In the design of an SCWS, a thermal response test is typically needed to evaluate the ground condition of the field. For larger commercial projects, more than one test bore may be required. The best geologic formation for an SCWS is near-surface bedrock (less than 60 m in depth) with a modest amount of water in fractures [20]. Ground that consists of clay or sand is typically not suitable for the use of an SCWS. The design of an SCWS involves the determination of the well depth, the bleed rate, and the circulation groundwater flow rate.

Unlike a PRS, the well, used in SCWS, can be either a heat source or sink. Well water is extracted from the bottom of the well by using a submersible pump and then returned to the top of the same well, as shown in Fig. 29. Due to the use of one single well and the short-circuiting between the bottom and top of the well, the well of an SCWS is typically deeper than a PRS with a greater design water flow rate (around 3.2 L/min/kW), in order to ensure that the heat transfer between the return water and the ground is fully developed and to minimize thermal interference between the top and bottom water. The well depth below the ground surface of an SCWS may be up to 450 m. With larger building loads, the diameter of the well and/or its depth needs to be increased accordingly. For larger commercial buildings, a tail pipe (or called porter shroud) (Fig. 29) may be utilized with multiple standing column wells that have the well separation between 15 and 23 m [20].

At the design stage, once the building cooling and heating loads are known, the heat pump units may be selected, and the circulated water flow rate from well(s) may also be established. In an open-loop system (PRS or SCWS), the performance of heat pump units is typically determined by the amount of well water flow provided. A greater well water flow rate means a better performance of the system. Therefore, designers should pay attention to the determination of an appropriate well water flow rate for the sake of maximizing the system performance. A detailed description regarding the design of SCWS was given by Egg et al. [20].

Well Pumps

In a GWHP open-loop system, a submersible pump is most commonly used to lift groundwater from aquifers to the surface. Its motor is typically submerged under the water table (at the bottom of the well), which thus is able to be cooled by the groundwater, as shown in Figs. 28 and 29. Motors with nominal 3600 rpm are typically used with submersible pumps, whose power is provided through a cable from the surface. Usually, if the vertical distance between the water table and the ground surface exceeds 60 m, a GWHP open-loop system is not a wise selection for residential projects, since it does not operate as efficiently as a high-performance air source heat pump system [35]. Large submersible pumps usually used in large commercial buildings with greater design water flow rates have higher efficiencies (around 80%) than small well pumps (around 60% or lower) that exist in small residential projects [12], as shown in Fig. 31. As a result, the percentage of the pump energy in the overall building energy consumption of a typical residential building is

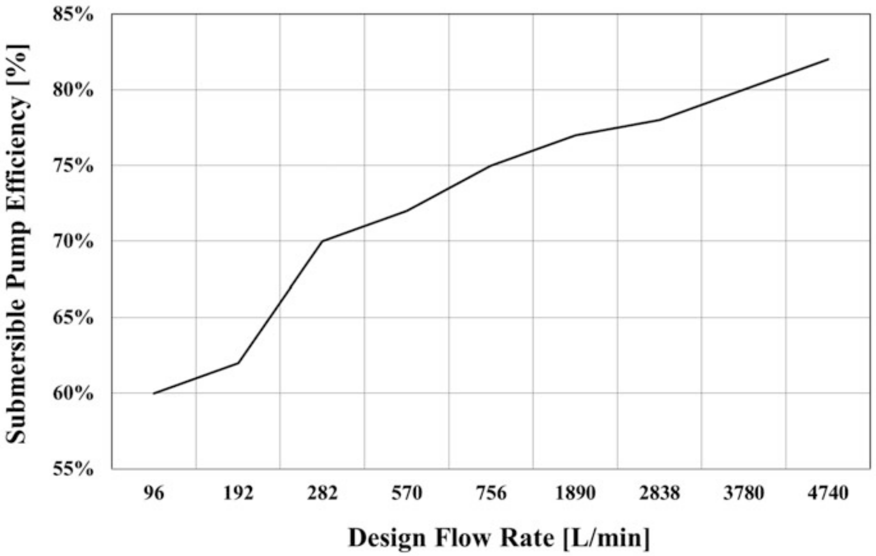


Fig. 31 Submersible well pump efficiency (nominal 3600 rpm) (Source: Kavanaugh and Rafferty [10])

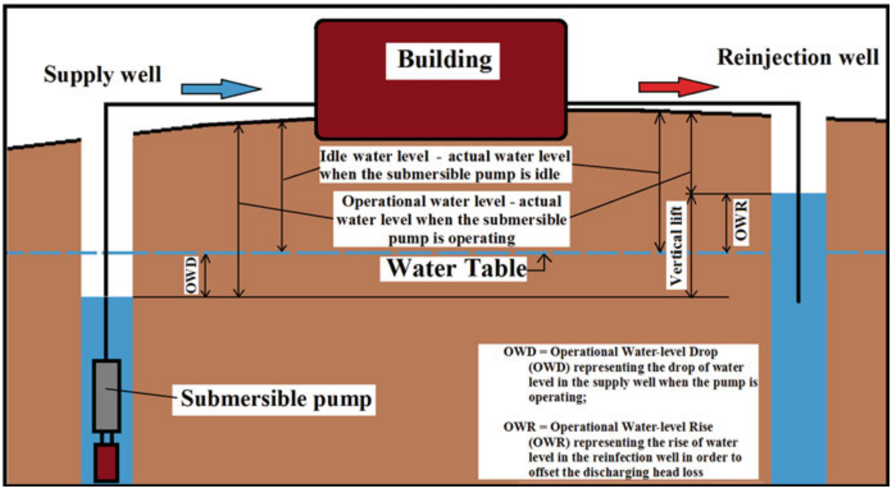


Fig. 32 Water levels in a PRS

more significant than that of a large commercial building [2]. Therefore, the use of GWHP open-loop systems in large commercial projects may be more cost-effective and attractive than using them in small residential buildings. As shown in Fig. 32, the total head (TOT) of a submersible pump in a PRS consists of the difference of the water levels in supply and injection wells (OWD + OWR), the head loss in heat pump units (HPL), the head loss caused by piping friction (PFL), and the head loss (CPL) associated with fittings (valves, etc.), i.e.,

$$\mathrm{TOT} = \mathrm{OWD} + \mathrm{OWR} + \mathrm{HPL} + \mathrm{PFL} + \mathrm{CHL} \tag{4}$$

where

TOT [m] = the total required head for the system
OWD [m] = operational water-level drop representing the drop of water level in the supply well when the pump is operating
OWR [m] = operational water-level rise representing the rise of water level in the reinjection well in order to offset the discharging head loss
HPL [m] = heat pump loss (HPL) representing the head loss in heat pump units (or water-to-water heat exchangers)
PFL [m] = piping friction loss representing the head loss due to piping friction
CHL [m] = component head loss representing the head loss due to fittings (valves, etc.)

Another alterative type of well pump for a GWHP open-loop system is known as a lineshaft pump, whose motor is located at the ground surface with a rotating shaft extended down into a well for groundwater extraction. The typical operating speed of the motor for this type of well pump does not exceed 1800 rpm, which is one of the reasons that lineshaft well pumps are not widely applied compared to submersible pumps that have the capacity to produce more groundwater due to their higher operational speed [10].

System Installation

One of the most important tasks for the installation of a GWHP open-loop system is drilling. The drilling methods that may be suitable for GWHP are cable tool drilling, mud rotary drilling, air rotary drilling, and air hammer drilling, whose detailed descriptions can be found in Kavanaugh and Rafferty [10]. The selection of an experienced local driller is suggested, whose experience and knowledge contribute to the successful completion of the installation task. Valuable recommendations or precautions could be given by drillers to designers/owners in order to avoid unwise decisions that may cause failure or schedule delay in the construction process. Commissioning can be done by qualified commissioning authorities/agents to ensure the installation quality.

Due to the fact that open-loop systems are restricted per local environmental regulations in some regions, obtaining the necessary permits is a must before any construction.

System Control and/or Operation

As described, the performance of an open-loop system is mainly determined by the amount of the groundwater delivered. Therefore, the optimization of the system operation to maximize its performance could be accomplished by adjusting the supplied groundwater flow rate through the control of well pumps. The simplest pump control strategy, i.e., a constant pump operation, is not suggested, due to its unnecessary waste of pump power. An on-off control is another option, which is suitable for a single-well pump system. For example, in an isolated system where indoor building distribution and groundwater loops are separated using a water-to-water heat exchanger, as shown in Fig. 28, the water temperature in the building distribution loop may be controlled by turning the well (submersible) pump on and off. When this temperature is off the set point, the well pump will start to circulate groundwater through the heat exchanger, transfer heat to/from the building loop, and eventually carry out the water temperature control of the building loop. A staging control is an updated version of an on-off control strategy, in which multiple well pumps would be started and operated one after another to provide the staged control to the water temperature of the building loop. The use of VSD motors in open-loop systems may significantly reduce the power consumption of well pumps, especially when multiple well pumps and/or heat pumps are involved. However, in order to avoid the failure of the motor/pump, more emphasis should be given to the cautions that are usually included in manuals for application, installation, and maintenance from motor/pump suppliers when using VSD submersible motors in GWHP open-loop systems [2, 12].

System Trouble Shooting

Since a sufficient groundwater supply is a key to maintain normal operation of an open-loop system, the shortage of groundwater in the field may restrict the application of open-loop systems, especially for a PRS, where closed-loop systems may be more suitable. Instead, an SCWS could be another alternative, whose well length is required to be not less than 8.7 m/kW [36], and a bleed flow may or may not be required depending on whether the well is deep enough.

Other concerns that are important and should be taken into account when using a groundwater open-loop system include, but are not limited to, the following:

- Regular maintenance of the system is required, and cleaning the pipes (the groundwater side of a heat exchanger) with a solution of an inhibited acid is acceptable in case of scaling or fouling.
- A submersible pump is suggested for use in a well in order to avoid the threat of air going into the system.
- A minimum well diameter of 200 mm is suggested for a system using a submersible pump, in order to avoid the introduction of sand in the flow [22].
- The outlet of the injection pipe should be submerged under the water table in order to avoid the entry of air/oxygen.

Hybrid System

The hybrid (multisource) version of a GSHP system can be defined as a heat pump with other source/sink element(s) of thermal energy in addition to the ground. Common elements besides the ground are solar, air, generated heat (from natural gas, oil, or electricity), or waste heat, and these are often coupled with thermal energy storage tanks or devices.

The terms hybrid and multisource are considered herein to be synonymous. Other terms in use are:

- Dual source heat pump with the assumption that there are only two elements of thermal energy
- Solar combisystem (also called geosolar) in which the additional thermal energy source is the sun (solar thermal collection).

One of the main purposes in the use of a hybrid GSHP system is to neutralize the underground temperature penalty by using supplemental source(s)/sink(s) in addition to the ground. Underground temperature penalty is caused by redundant heat dumped into or extracted from the ground for a long period (e.g., more than 10 years) as a result of unbalanced cooling and heating loads of buildings. For example, in a commercial building, cooling may be needed all the year around because of the large amount of internal heat generated by equipment (computer, printers, etc.), lighting systems, and occupancies, even during winter seasons in some cold regions. Therefore, in this cooling-dominated building, if the ground is the only source/sink element in the GSHP system (Fig. 33), more heat from the building would be rejected into the ground in the cooling mode than that extracted from the ground and used by the building in the heating mode. This unbalanced heat transfer between cooling and heating modes in the ground would be accumulated year after year and eventually cause a change of the local ground temperature. This change of local

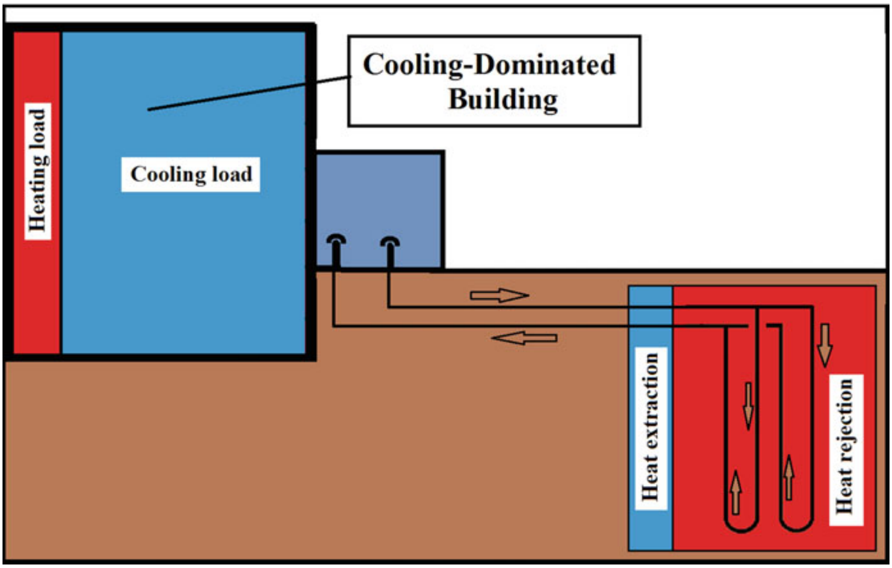


Fig. 33 A GSHP system used in a cooling-dominated building

ground temperatures will have a negative impact on the performance and efficiency of the GSHP system.

A solution to this problem is to use a hybrid GSHP system by adding an additional sink element of thermal energy (e.g., a cooling tower) to deal with the unbalanced heat rejection, as shown in Fig. 34.

Hybrid GSHP systems have multiple significant advantages, but also have some disadvantages.

The advantages include:

- Lower initial cost due to the reduced ground heat exchanger size and/or length
- Lower operating cost due to an increased efficiency of cooling and/or heating if the best temperature fluid, such as underground water or antifreeze solution (sometimes called brine), solar heated water, or ambient air, can be chosen appropriately at any time
- Longer useful life considering that a conventional borehole system with only one source/sink element (the ground) may be undersized and unbalanced in heating and cooling

The disadvantages are shown below:

- A hybrid system is more complex, with possibly more pumps, valves, controls, and heat exchange or generation elements.
- The probability of failure is increased with more moving parts and components.

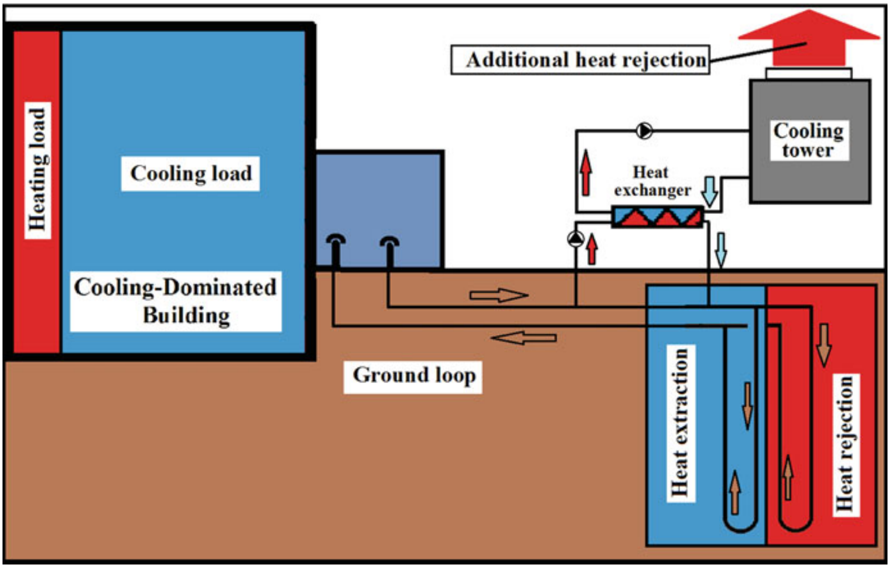


Fig. 34 A simple hybrid system (ground loop and cooling tower)

- It would be more difficult in simulating and guaranteeing performance of a more complex design.
- Fans and pumps make some noise, which could be objectionable.
- Cooling towers, boilers, and solar collectors take up extra space either inside or outside of a building.

In spite of the list of disadvantages above, the fundamental benefits of hybrid systems may be the deciding factor in many cases. This appears to be a trend and will likely be good for the bottom line profit of building owners and also a benefit for the environment of our planet in future years.

System Design and/or Installation

Most commonly, the designs to be considered here will use any combination of these six source element locations and forms: underground, surface water, solar thermal collector, air-to-liquid heat exchanger, evaporative cooling tower, and boiler or other similar heat source.

Hybrid heat pump systems can range from being very simple and easy to understand to being highly complex with many sources and variables.

One simple design that is in current use is the series connection of a ground heat exchanger with an evaporative cooling tower, as shown in Fig. 34. The cooling tower may be optionally connected in parallel with the ground loop and located either upstream (as shown in Fig. 34) or downstream depending on local outdoor weather and ground conditions, as well as the allocation of building cooling and heating loads. Typically, the device(s) or component(s) with relatively larger cooling/heating capabilities would be placed downstream. For example, in a heating-dominated building in a very cold region, the cooling tower shown in Fig. 34 may be replaced with a boiler and located downstream of the ground loops (a boiler has larger heat output than the ground loops) to provide supplemental heating whenever it is necessary. This kind of system has been shown in Fig. 22.

It should be noted that there are multiple types of cooling devices that can be considered for use in hybrid heat pump systems. Although evaporative cooling towers are mentioned above, consideration should also be given to dry cooling towers or sometimes called simply dry coolers. In terms of functionality, a dry cooler is equivalent to an air-to-liquid heat exchanger (Fig. 35). The difference to be considered is that although an evaporative cooling tower may be highly advantageous in the summer for cooling-dominated systems, a dry cooler might be useful both summer and winter. As an example for this, consider a cooling-dominated climate zone, where there is a danger that the earth around the underground heat exchanger can become too hot to be useful (temperature penalty). If a dry cooler could be part of a hybrid system, this cooler might be used to precondition the ground temperature during the coldest winter nights. Also, this same type of cooler can be used for heating-dominated applications (cold climates). In this case, the dry cooler would be used to precondition the ground to a higher temperature during the warmest months of the year.

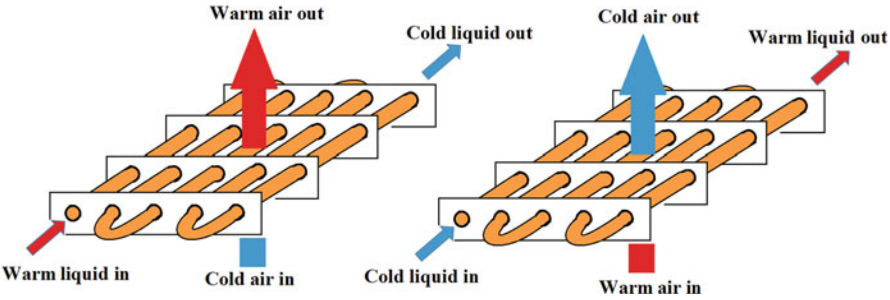


Fig. 35 Air-to-liquid heat exchanger

A solar thermal collector array could also be used for this preconditioning function. With regard to the preconditioning mentioned here, it is important to recognize that the underground portion of a hybrid heat pump system is both a heat exchange element and a heat storage element. For some types of systems, the heat storage function is of greater importance than the heat exchange function. This is often the case for aquifer systems and open-loop systems with multiple wells.

There are three or four solar thermal collector types that have been used or might be considered to be used as part of a hybrid heat pump system:

- Unglazed flat plate collector
- Glazed flat plate collector
- Evacuated tube collector
- Concentrating collector

The arrangement in the list above goes from least expensive and lowest thermal performance at the top to most expensive and highest thermal performance at the bottom.

There are many examples of the use of the first three collector types above as part of hybrid heat pump systems. The unglazed collector type has considerable extra benefit due to its use as a cooling element. Although this type of collector is usually used for swimming pool heating, it can also allow the transfer of the coldness of winter or cool summer nights into antifreeze solution, which in turn allows for preconditioning of underground thermal exchange regions. To say it in another way, it transfers undesired underground heat through antifreeze solution into the cold outdoor environment. This will generally be done through convection from the wind, radiation into the cold night sky, or even conduction into a snowbank. No other solar collector type or dry cooler has this capability. Radiation cooling from an unglazed collector can be used on either a diurnal or a seasonal basis. A custom design rooftop cooler coupled with underground heat exchangers is shown in Fig. 36. In this system, the nocturnal cooling radiator located on the roof would be used during the night to reject the accumulated heat from the ground heat exchangers (GHE) to the outside mainly through radiation and convection. This system was

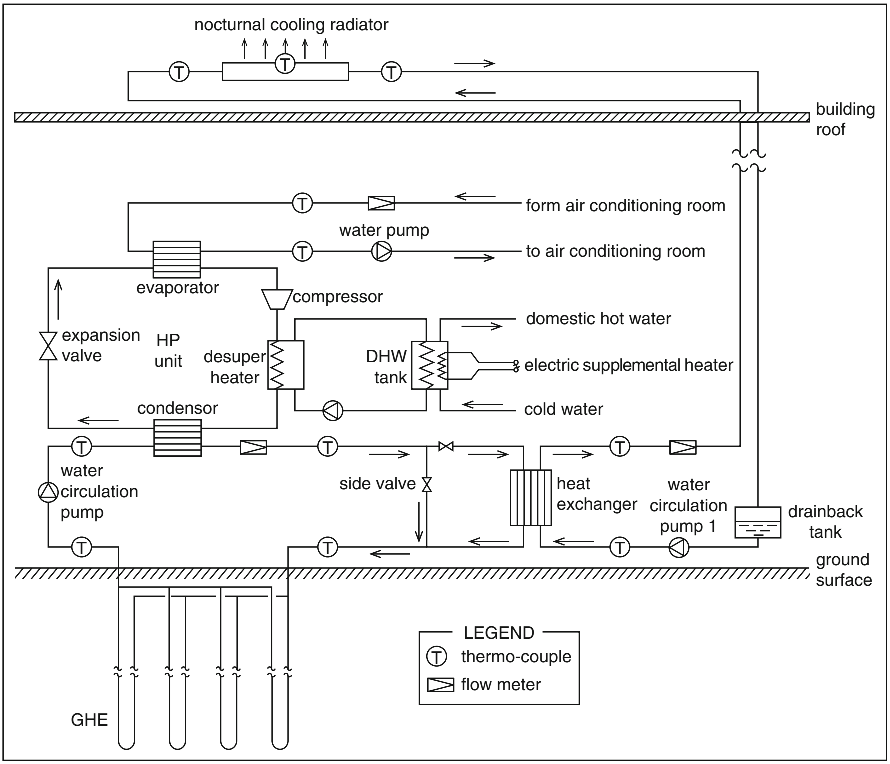


Fig. 36 Hybrid GSHP system with nocturnal cooling radiator [37] (Reprinted from Applied Energy [37] with permission from Elsevier)

designed by Man et al. in 2011 [37], and the feasibility of the design was proved by them through computer simulations.

Software tools, such as HyGCHP, TRNSYS, GLHEPRO, EnergyPlus™, etc., may be used in the design and simulation of hybrid GSHP systems in order to realize system optimization.

As might be apparent, there is significant overlap in performance and functionality of dry coolers (Fig. 35) using a fin-and-tube with a fan and unglazed solar thermal collectors. Both of these provide convection transfer of thermal energy between the atmosphere and a flowing liquid. The dry cooler might be best for maximizing the use of space, whereas the solar collector will allow for solar thermal collection as well as convection transfer. The solar collectors also provide radiation thermal transfer whereas the dry cooler does not. Both of these product types have been designed for long-term outdoor use and are in reasonably large-scale production. In regions of the world with a possibility of severe hailstorms, a dry cooler might be a better choice than a plastic unglazed collector; however, it is possible to obtain more durable unglazed collectors made of metal rather than plastic but at an added cost.

A comprehensive study of the use of unglazed solar collectors for a heating-dominated application is described in Helpin et al. [38], whose conclusion is that the use of unglazed collectors as part of a hybrid GSHP design provides a 23 percent lower capital cost than a non-hybrid ground source system. This is for a moderate-size three-floor office building with total of 3750 m^2 floor space and a climate zone similar to northern France.

Another way the system could be designed is to allow the heat pump(s) to be bypassed in some situations. For example, when hydronic floor heating and evacuated tube solar thermal collectors are utilized along with GSHPs, the fluid temperature conditions might be such that the temperature boost from heat pumps is not needed, so a valve design could allow for the option of bypassing and the direct feed of hot water from solar thermal collectors to the hydronic floor heating system. For this same system, there would be other situations where the ground alone would be used, or the solar and ground heat could be combined at the input of the heat pump.

System Control and/or Operation

There are many ways for the different thermal elements to be combined, usually utilizing a specific arrangement of valves, dampers, pumps, fans, and heat exchangers. In recent years the system will also likely use a variety of sensors for temperature, flow rate, and perhaps pressure to allow for computer control and optimization. For example, the use of BAS provides an automatic control of the various systems to achieve the optimal system integration and operation.

It may be noted that the design shown in Fig. 34 has only two modes of operation:

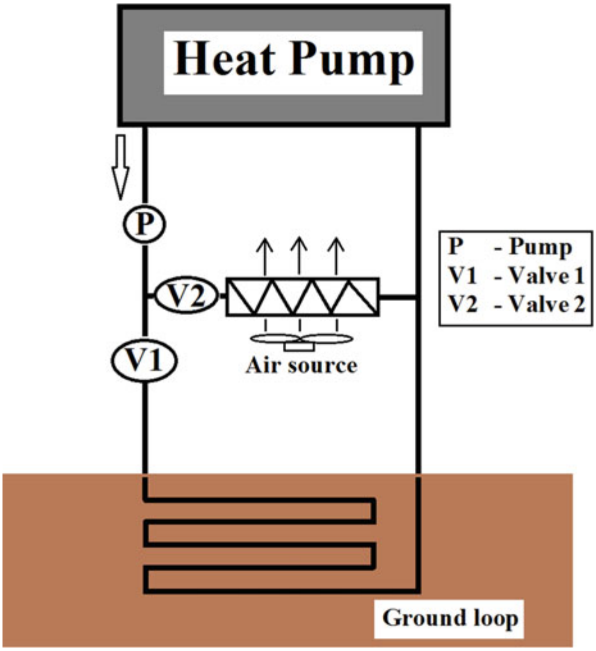
1. The ground exchanger is used as the single heat exchange element.
2. The ground exchanger is placed in series with a second heat exchange element (cooling tower or boiler).

It may also be noted that this design has some fundamental limitations such as:

- Not being able to exchange the series sequence depending on season of the year (cooling tower first or cooling tower second in the flow path)
- No provision for the cooling tower to be used alone in the system
- No provision for parallel operation
- No provision for the cooling tower to be connected directly to the ground exchanger alone (bypassing the heat pump)

Each of the items above could be advantageous in some situations, but they would require additional valves or pumps and will add complexity in operation and optimization. The system diagram illustrated in Fig. 37 demonstrates an improved control and operation [39], in which the ground exchanger is placed in parallel with an air-to-liquid heat exchanger. As shown in this figure, the two valves (V1 and V2) allow for three modes of operation:

Fig. 37 Parallel mode hybrid GSHP with air-to-liquid heat exchanger



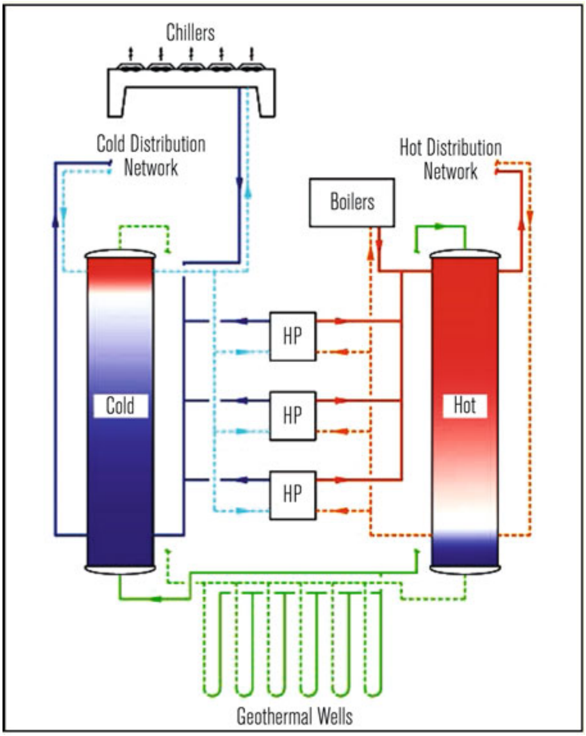
1. Air source mode with Valve 2 open and Valve 1 closed.
2. Ground source mode with Valve 1 open and Valve 2 closed.
3. Parallel mode with both valves open.

It may be noted that with the addition of a second pump in the ground loop path of Fig. 37, a fourth operating mode is possible, i.e., preconditioning of the ground exchange region based on the outdoor air temperature (bypassing the heat pump).

An example, where a GSHP system is combined with boilers, has been given in the section "Closed-Loop System," and the detailed control diagram and strategy can be found in Fig. 22 and Table 4, respectively.

A recent project (the Anne-Marie Edward Science Building (AMESB) at John Abbott College, Montreal, Canada) [40], where a GSHP system is combined with boilers and air-cooled chillers as well as hot and cold thermal storage tanks, shows a significant benefit of the hybrid approach for a college building. This building has a total area of 11,300 m^2 and is used for education purposes, such as laboratories, classrooms, offices, etc. In this hybrid system, the ground heat exchangers (45 wells with the depth of 122 m for each) and five water-to-water heat pump units account for 50 ~ 70% of the total heating and cooling loads, and the rest are taken care of by two air-cooled chillers (528 kW for each) and two electric boilers (288 kW for each), as shown in Fig. 38. The two thermal storage tanks (one for cold storage and the other one for hot storage) are used to simultaneously provide cold and hot water to the building system. The heat pumps are controlled to continuously transfer heat from the cold tank to the hot tank with the underground loops to gain and reject heat from/to the ground.

Fig. 38 Hybrid GSHP system [40] (©ASHRAE www.ashrae.org. *ASHRAE Journal*, March, 2016)



All the systems are controlled through a BAS to allow their optimal integration and operation. As a LEED (Leadership in Energy and Environmental Design) Gold building, with initial occupancy in 2012, the AMESB demonstrates a superior performance with 45% lower energy use than the baseline case where a standard HVAC system is typically used, such as a variable air volume (VAV) system. Other features of this building include VSD fans and water pumps, a solar heating system for domestic hot water preheating, radiant slab systems, dedicated outdoor air system (DOAS) with energy recovery, demand controlled ventilation (DCV) with CO_2 sensors, natural ventilation control, daylighting, no CFCs, reduced CO_2 emissions, rainwater collection and reuse, low-flow fixtures, etc. For this building, it is expected that the higher initial cost due to the nonstandard HVAC system will be fully paid back after about 6 years.

Applications of Ground Source Heat Pump Systems in Buildings

Indoor Distribution Systems

The two major parts of GSHP systems are outdoor ground source heat exchangers and indoor distribution systems. An indoor distribution system consists of indoor heat pump units, ductwork, pipelines, heat exchangers, pumps, etc. The role of

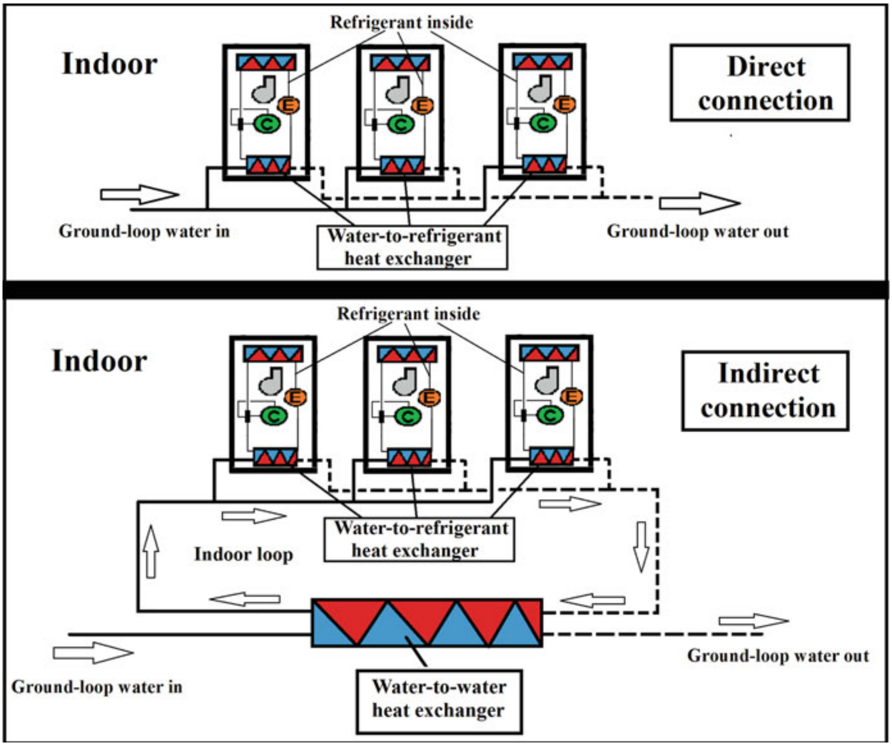


Fig. 39 Direct or indirect connection of indoor systems with ground heat exchangers

indoor distribution systems is to handle building cooling and heating loads by absorbing room heat gains or compensating for room heat losses through indoor heat pump units, which are directly or indirectly connected with ground source heat exchangers to carry out either heat extraction or injection from/to the ground (or groundwater). The direct connection typically involves the direct circulation of water in ground heat exchangers through water-to-refrigerant heat exchangers installed in heat pump units (Fig. 39) to transfer heat between the ground-loop water and the refrigerant that is the working fluid in heat pumps. Nevertheless, when the ground-loop water is not safe to use directly because of potential issues, such as fouling, corrosion, etc. (e.g., the groundwater open-loop system), water-to-water heat exchangers are typically used to isolate the indoor and outdoor (ground) loops, as shown in Fig. 39. The heat transfer between the indoor and outdoor (ground) loops takes place at the heat exchangers. Sometimes, the water in ground loops may be used directly without the need of the refrigeration cycles in heat pumps, if it is cold enough to sufficiently provide cooling to buildings, for example, in groundwater or surface water heat pump systems.

The GSHPs usually used inside of buildings are either water-to-water or water-to-air heat pump units that may be located in cabinets, ceiling plenums, or mechanical

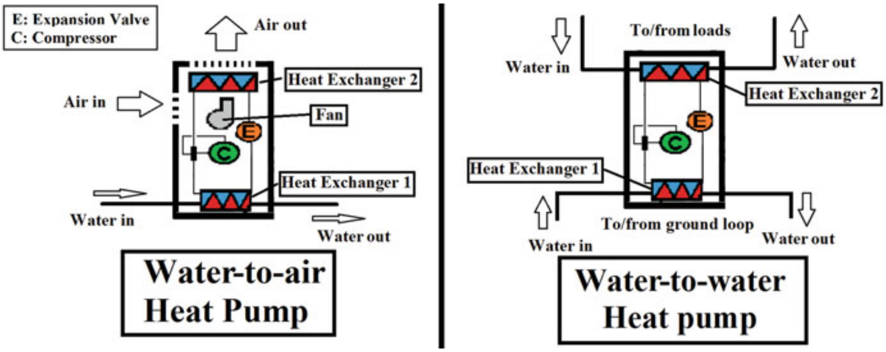


Fig. 40 Water-to-air/water-to-water heat pumps

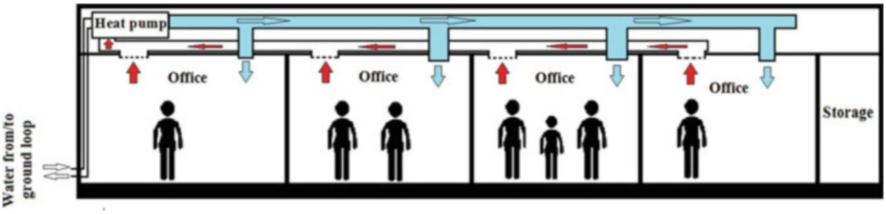


Fig. 41 Water-to-air heat pump used in a building

rooms. In a water-to-air heat pump unit, as shown in Fig. 40, water (or a mixture of water and antifreeze) is used on one side at Heat Exchanger 1 for heat rejection during cooling (or for heat extraction during heating), while, on the other side, air is cooled at Heat Exchanger 2 during cooling (or heated during heating) before it is supplied to rooms. Heat Exchanger 1 is typically called condenser in cooling mode or evaporator in heating mode, and, on the contrary, Heat Exchanger 2 represents condenser and evaporator in heating and cooling modes, respectively. Therefore, water is typically used at both Heat Exchangers 1 and 2 (a mixture of water and antifreeze may be used in ground loops at Heat Exchanger 1 instead of water) in a water-to-water heat pump unit (Fig. 40).

Water-to-air heat pumps are usually located near target rooms where heating or cooling are needed. Conditioned air from the heat pumps may be supplied to these rooms with ductworks, as shown in Fig. 41. These GSHP units usually have capacities of up to 176 kW with a relatively high efficiency (around 6 COP for cooling and 4.0 COP for heating) compared to a conventional direct-expansion cooling device with a gas-fired furnace. Acoustic issues should be considered in the design and use of water-to-air heat pumps that are in the vicinity of living or working areas of people.

Like central chillers or boilers, water-to-water heat pump units may provide hot or cold water to buildings. The conditioned water may be pumped into different terminal devices that use cold or hot water to accomplish the control of indoor temperature. For example, the conditioned water can be conveyed to the heating and cooling coils of an

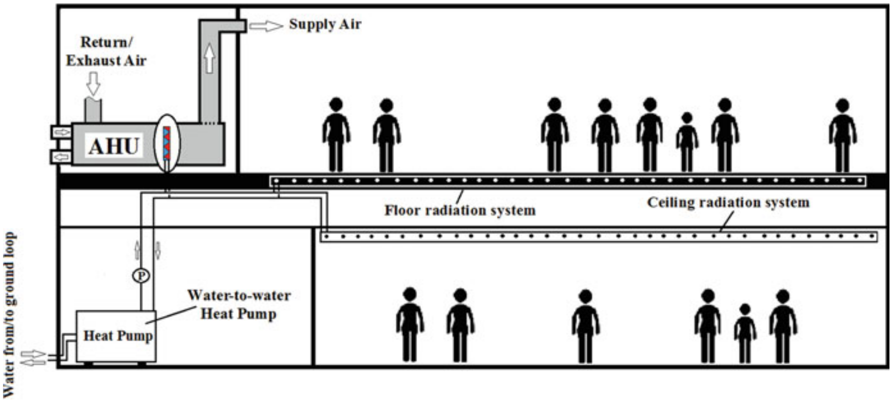


Fig. 42 Water-to-water heat pump used in a building

air handling unit (AHU) (Fig. 42) for outdoor air preconditioning or to floor radiation loops or ceiling radiation panels (Fig. 42). Higher performance and efficiency may be achieved by using modular packaged heat pump units that are connected together and designed to provide heating and cooling simultaneously (with several packaged units to provide cooling and the rest for heating), which allows heat recovery between these two modes (cooling and heating) before going to ground-loops. For example, as shown in Fig. 43, the heat rejected by Unit 1 that is in cooling mode may be neutralized by the cold rejected by Unit 2 that is in heating mode, which may balance the requirements for both heating and cooling and reduce the need of using ground loops.

Coefficient of Performance

The coefficient of performance or COP of a heat pump is determined by the ratio of thermal energy (heating or cooling) provided from a heat pump to the work consumed by it. A higher COP means a higher efficiency and lower operating costs. The energy efficiency ratio or EER is another measure of the cooling or air-conditioning efficiency of a heat pump or air conditioner, calculated by dividing the cooling output in British thermal units per hour (BTU/hr) by the power input in watts. Equivalently, in terms of energy rather than power, the EER is the ratio of BTU of cooling to watt hours of electrical energy consumed. The conversion from COP to EER is:

$$\mathrm{EER} = 3.412 \times \mathrm{COP} \tag{5}$$

In the industry of North America, the cooling and heating efficiencies of a GSHP unit are typically represented differently, i.e., the cooling efficiency uses EER and the heating efficiency uses COP. For example, Table 5 specifies the minimum performance of GSHPs with cooling capacities less than 40 kW, per the most current ANSI/ASHRAE/IES Standard 90.1-2013 [41].

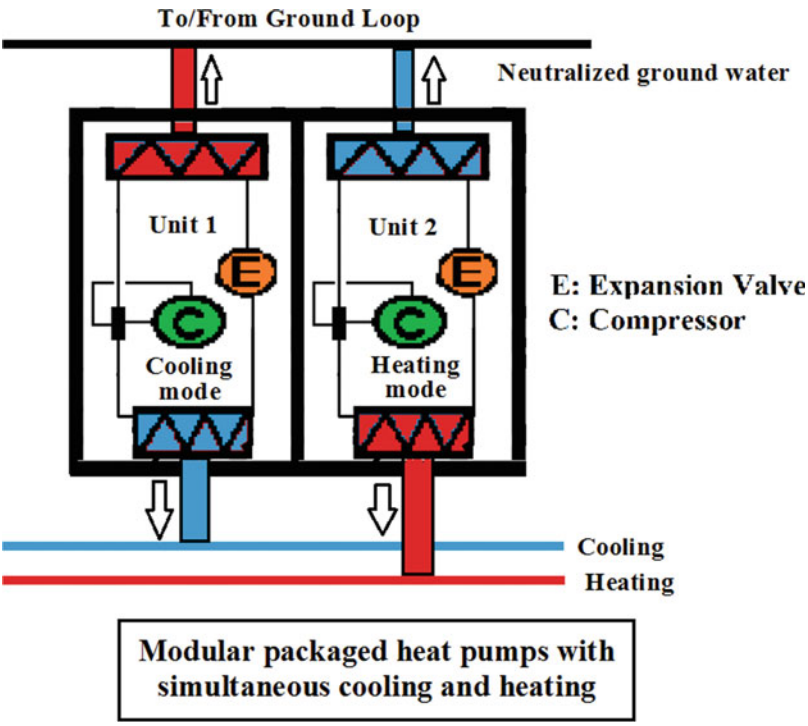


Fig. 43 Modular packaged heat pump units with simultaneous cooling and heating (Source: ClimaCool Corp.)

Similarly, the key product criteria for Energy Star certified geothermal heat pumps are listed in Table 6. Models have to demonstrate an equal or higher performance compared to the efficiencies shown in this table in order to meet the requirement of Energy Star certified products (effective on January 1, 2012).

In order to fairly compare the performances of heat pumps to each other, the efficiencies shown in Tables 5 and 6 follow the standardized test procedures established by the ARI/AHRI as well as the International Organization for Standardization (ISO). For example, the water-to-air and water-to-water heat pump models (for either open- or closed-loop systems) mentioned in these two tables follow the test procedures of ISO 13256-1 [42] and ISO 13256-2 [43], respectively; while the DX GSHP systems follow the test procedure of AHRI 870 [25].

Two other widely used measures of heat pump cooling and heating efficiencies are called the Seasonal Energy Efficiency Ratio (SEER) and Heating Seasonal Performance Factor (HSPF). Although they are usually used for air source heat pumps, SEER and HSPF may be considered as important parameters for GSHPs and used to represent the seasonal cooling and heating performances, respectively.

A heat pump with high efficiency features is also likely to be more expensive and complex, so there might be a difficult trade-off to find the best compromise among

Table 5 Minimum performance of water source heat pumps

Heat pump type		Minimum efficiency[a]
Cooling mode	Water-to-air HP using groundwater	5.3 COP or 18.0 EER
	Antifreeze solution-to-air HP using ground loop	4.1 COP or 14.1 EER
	Water-to-water HP using groundwater	4.8 COP or 16.3 EER
	Antifreeze solution-to-water HP using ground loop	3.5 COP or 12.1 EER
Heating mode	Water-to-air HP using groundwater	3.7 COP
	Antifreeze solution-to-air HP using ground loop	3.2 COP
	Water-to-water HP using groundwater	3.1 COP
	Antifreeze solution-to-water HP using ground loop	2.5 COP

[a] Source: ANSI/ASHRAE/IES Standard 90.1–2013 [41]

Table 6 Energy efficiency requirements for geothermal heat pumps (Energy Star certified product criteria)

Type of heat pump	Cooling COP (EER)	Heating COP
Closed-loop water-to-air	5.0 (17.1)	3.6
Open-loop water-to air	6.2 (21.1)	4.1
Closed-loop water-to-water	4.7 (16.1)	3.1
Open-loop water-to-water	5.9 (20.1)	3.5
Direct geoexchange (DX)	4.7 (16)	3.6

Source: Energy Star geothermal heat pumps key product criteria. https://www.energystar.gov/products/heating_cooling/heat_pumps_geothermal/key_product_criteria

cost, efficiency, reliability, and perhaps other factors. All other factors being equal, a higher efficiency is better.

Heat Storage Technologies Applied in Ground Source Heat Pump Systems

Thermal storage can be used with GSHPs in many different configurations. A broad distinction can be made between storage on the building side of the heat pump versus storage on the outside and perhaps underground. If the storage is to be indoors, the storage would typically be by means of water/ice in tanks (e.g., those shown in Fig. 38). Because of size restrictions, the time duration for indoor tank storage is likely to be a few hours (or perhaps diurnal). On the other hand, outdoor or underground storage, with much larger storage volumes, could have a storage duration of many months. A storage duration of 6 months allows for summertime heat to be used in winter and wintertime cold to be used in summer.

Combining thermal storage with heat pumps may lead to a higher efficiency (COP or EER) compared to a conventional GSHP system, due to the more desirable temperature condition from the source for heat pump units. If the storage temperature is sufficiently high in winter and/or sufficiently cold in summer, the heat pump could be bypassed, at least for some of the time. Another consideration is the source of the heat or cold to be stored. A heat pump or chiller can be used at night to provide antifreeze fluid with a temperature below the freezing point of water. This cold fluid can be used to produce ice which is stored in a tank for use as a source of cooling the next day. In this way the electrical power for the heat pump or chiller can remain off during the hottest afternoons. If storage is to be outdoors or underground, three possible sources for heat and/or cold collection would be the heat pump itself, solar thermal collectors, or air-to-liquid heat exchangers. Note that unglazed solar thermal collectors will collect heat when the sun shines (on a warm calm day), but they will also collect cold (during a cold windy night). Air-to-liquid heat exchangers (also called dry coolers, as shown in Fig. 35) can also be used to collect either heat or cold and will take up much less space than unglazed solar panels. Heat and/or cold from these three possible sources may be seasonally stored underground (Fig. 44) and

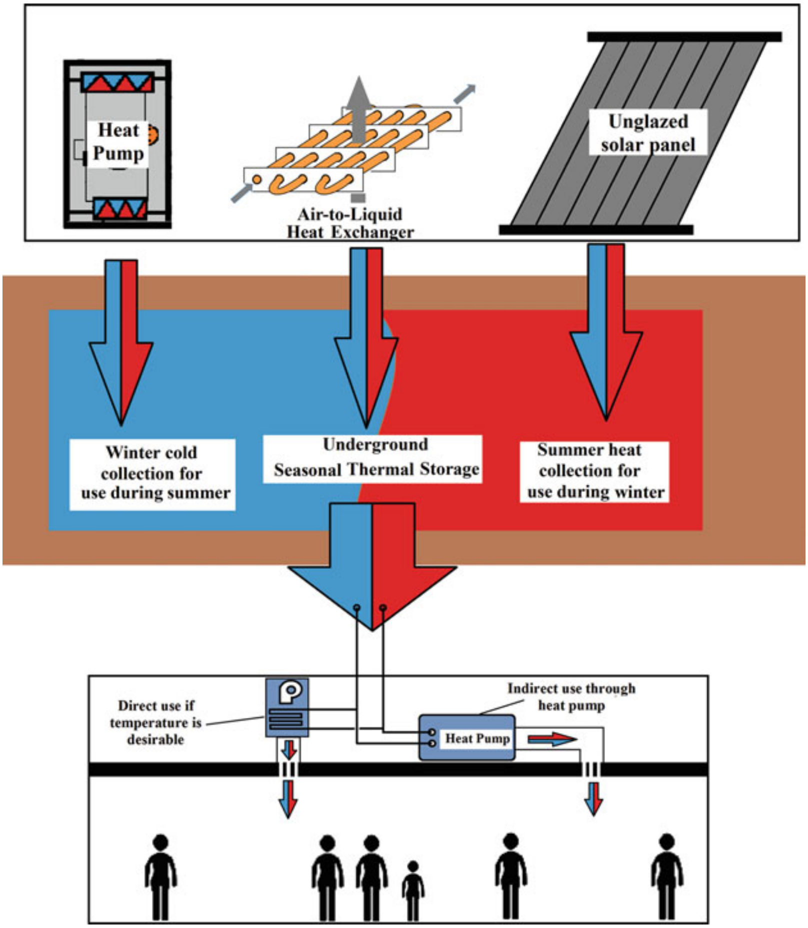


Fig. 44 Underground thermal energy storage and use

harvested directly or indirectly through GSHPs after a relatively long period (several months), as long as the storage volume is large enough.

Other than size, location, and source, there are other subdivisions of thermal storage that can be considered with regard to heat pumps. As described in Lee [44], there are three major categories of thermal storage:

- Sensible heat storage (no phase change involved)
- Latent heat storage (a phase change is used)
- Thermochemical heat storage

It appears that the use of ice in a storage system is one form of latent heat storage; however, there is very active research into other phase change materials for this purpose. As compared to ice/water transitions, there are many uncertainties and considerations in using any other phase change material for thermal storage. Some of these considerations are:

- Cost
- Stability over many cycles and many years
- Environmental dangers
- Suitability of transition temperature

Because of the difficulty in dealing with the multiple issues listed above, there seem to be no phase change materials for thermal storage in widespread use with heat pumps today other than ice/water. This is not to say that there will not be some good solution for this situation at some future time. The four considerations above for phase change materials also apply to thermochemical heat storage; however, the time duration for storage might be somewhat easier for the thermochemical concept.

Regarding outdoor or underground storage, there are five types in widespread use [44], including:

- Aquifer thermal energy storage (ATES)
- Borehole thermal energy storage (BTES)
- Cavern thermal energy storage (CTES)
- Pit thermal energy storage (PTES)
- Tank thermal energy storage (TTES)

Figure 45 shows these five thermal energy storage types. The first two methods (ATES and BTES) are also widely used for heat exchange with the earth rather than heat storage in the earth. There is no sharp distinction between heat exchange and heat storage with the aquifer and borehole concepts. There will always be some of both. There are many cases where an array of boreholes in a warm climate region has been found to work too well as a heat storage system. After many years of use for heat exchange, and with a heat pump (or pumps) putting hot water into the boreholes every summer, the earth around the boreholes can become too hot to be used. The

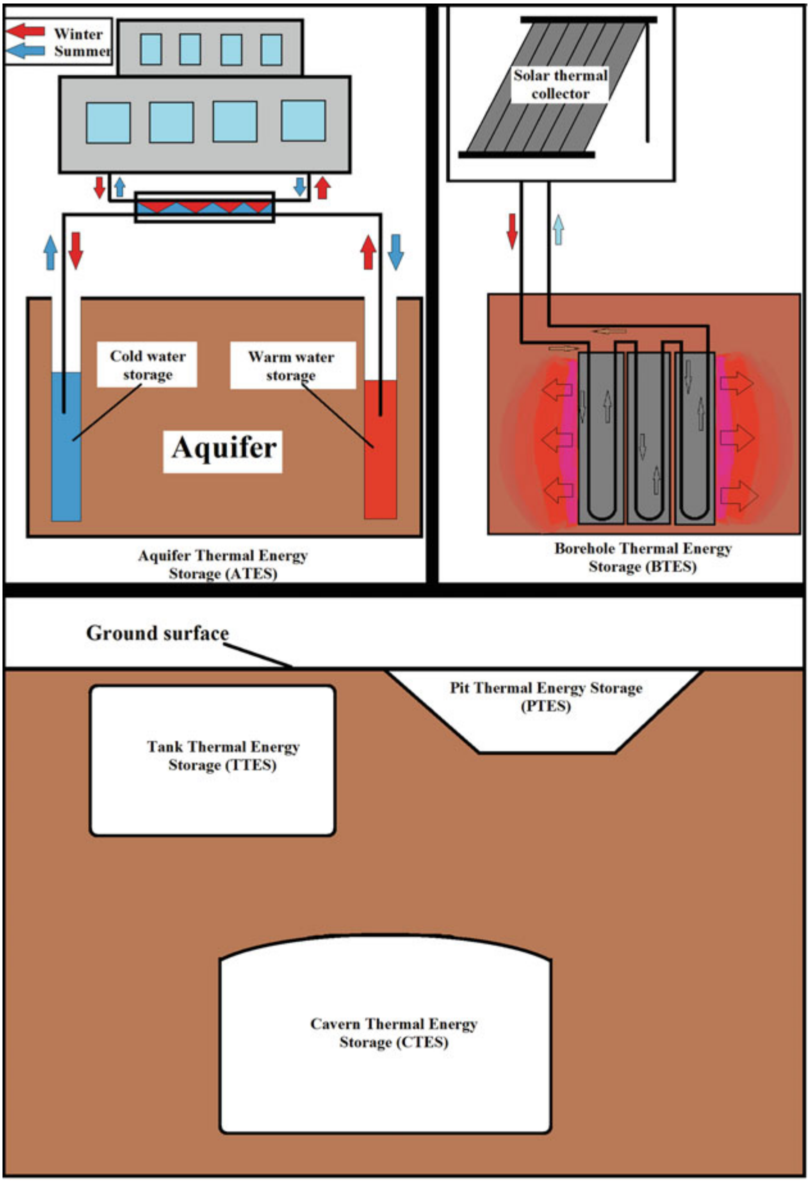


Fig. 45 Thermal energy storage types

reverse of this is also possible in very cold climates. The usual diagnosis for this problem is that the system is unbalanced and undersized.

An actual BTES project (Drake landing solar community in Alberta, Canada) [45] involves the seasonal storage of solar thermal heat collected through 800 solar thermal collectors during summer, which is transferred into the ground through

144 vertical boreholes with a depth of 47 m for use during winter. It is reported that the ground temperature can be up to 82 °C by the end of summer season, which is sufficiently high for the direct use of the underground heat during winter, and more than 85% of space heating (for 52 homes) can be covered by this solar and BTES system.

Another distinction to be considered is that of open- or closed-loop circulation of water. In these five thermal energy storage types, the BTES concept is the only one which is inherently closed loop; however, it is possible for tanks to be designed for either open- or closed-loop operation. The closed-loop design would include a water-to-water heat exchange coil installed inside the tank. Closed-loop systems have been found to be highly beneficial, or, to put it differently, open-loop systems are often prone to early failure. Typical failure modes involve chemical or biologic changes in the water and/or damage to pumps due to contaminants such as fine sand or other solid particles in the water. With a closed-loop system, these degrading factors are avoided.

In recent years, it has been found that there is yet another storage method to be added to the list of five storage methods. This sixth method is the use of a near-surface horizontal array of pipes placed in the earth (or embedded in concrete) just below a horizontal thermal insulator [46] (Fig. 46). This method may be called HTES (horizontal thermal energy storage) and has been in use for heat exchange and/or heat storage by at least these three organizations:

- ICAX™ Limited in London, England
- Enercret GmbH in Röthis, Austria
- Building Tech Services in Naples, Maine

Note that this method of heat storage is not the same as a horizontal slinky system that is placed in a trench (Fig. 24). The slinky system works well for heat exchange but is less well suited for thermal storage. The projects completed by ICAX™ show storage of both heat and cold and generally use a GSHP as part of the system. Since ICAX™ provides thermal storage over a 6-month time, they use the trademarked phrase “Interseasonal Heat Transfer” to describe their capability. Regarding cost-effectiveness, Building Tech Services provides information about the cost

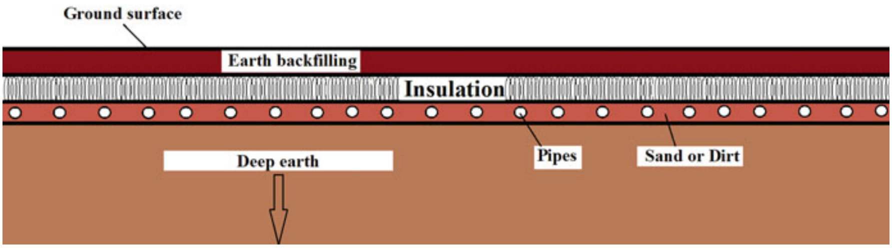


Fig. 46 Horizontal thermal energy storage (HTES)

comparison between a borehole heat exchange system and a horizontal pipe array system for a 21 kW capacity design. This comparison shows the horizontal system to be approximately 1/3 the cost of the borehole system. It is reasonable to expect that this comparison would also apply to larger systems that would be used for long-term (seasonal) thermal storage [47].

Regarding the effects of size on storage effectiveness, as any of these systems grows in size, the quantity of heat or cold to be stored goes up as the third power of the dimension (approximately). The rate of heat loss, however, is proportional to the area surrounding the storage region. This heat loss rate is proportional to the second power of the dimension. These facts show why size matters for storage duration and minimization of loss to the surroundings even without any insulation around the sides and the bottom, as is the case for borehole storage.

Case Study

The Gorecki Alumni Center (GAC) (Fig. 47) is located at the University of North Dakota (UND) in Grand Forks, North Dakota of the United States. This building has an area of about 3530 m^2 with administration areas, a ballroom, conference rooms, etc. for development and alumni services. It was built in late 2012 and is the first LEED Platinum building (LEED BD + C: New Construction v3) in the State of North Dakota. Other features include a GSHP system for space cooling and heating,

Fig. 47 Front view of Gorecki Alumni Center (Printed with permission of Obermiller Nelson Engineering, Inc.)

207 solar photovoltaic (PV) panels for electricity production, VSD fans and water pumps, AHUs with energy recovery, DCV with CO_2 sensors, etc. The simulated energy cost savings is more than 34% compared with an ASHRAE baseline where a standard HVAC is typically used, such as a packaged VAV system with reheat (direct-expansion cooling units and hot water boilers) for this type of building.

Vertical Closed-loop System (VCS)

In the GAC, the space cooling and heating are provided by a GSHP system with 142 vertical boreholes under a nearby parking lot with a depth of 64 m (Fig. 48) and a separation distance of 4.5 m. At the beginning of the design stage, a thermal response test was performed on site during the summer of 2011, in which two test wells (wells 1 and 2) were drilled in order to obtain the accurate knowledge of the thermal characteristics of the local geologic formations (section "Low-Temperature Geothermal Resources"). The test results in terms of vertical ground temperature distribution are shown in Fig. 49. The depth of the test wells was 61 m with a test duration of 36 h. The results in terms of thermal conductivity for wells 1 and 2 were 1.6 and 1.7 W/ (m-K), respectively, which were used to design the VCS.

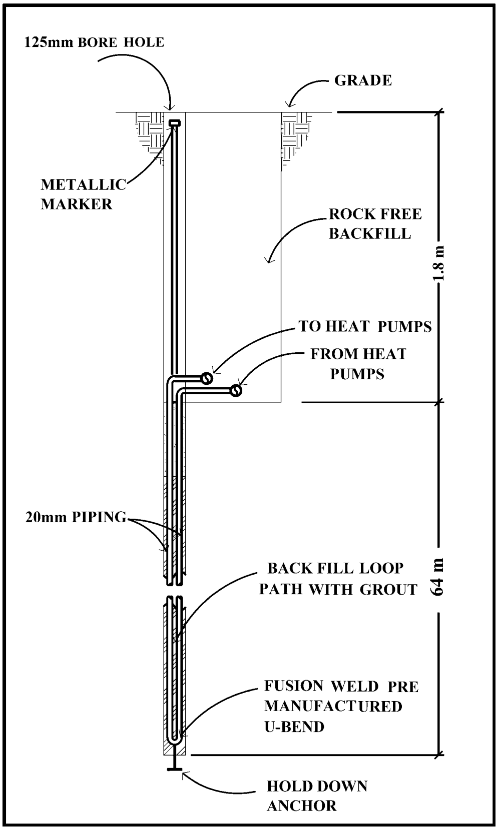


Fig. 48 Borehole section (Printed with permission of Obermiller Nelson Engineering, Inc.)

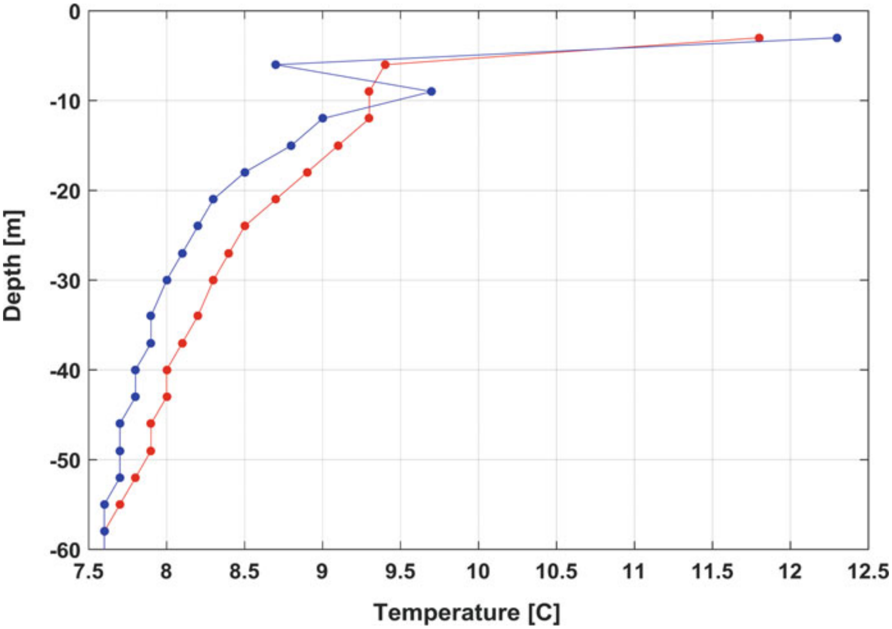


Fig. 49 Vertical underground temperatures of test wells 1 and 2 (Source: Braun Intertec Geothermal, LLC)

Indoor Distribution System

At the water side, simultaneous cold and hot water are provided to terminals by four modular packaged water-to-water heat pumps (similar to Fig. 43). This design is intended to achieve a high system performance, and it is reported by the manufacturer's catalog that, in summer, the cooling efficiency at full load is 5.9 COP (20.3 EER) with a heating mode efficiency (the use of reheat coils) of up to 6.93 COP. Figure 50 shows the detailed design piping schematics for both the outdoor and indoor loops. The water-to-water heat pumps are controlled to maintain 50 °C and 7 °C supply water temperatures in both heating and cooling modes, respectively, by cycling all module compressors as necessary.

At the air side, three AHUs are connected with multiple VAV boxes (with hot water reheat coils) through ductwork to deliver conditioned air to each space.

Energy Use and Savings

The monthly energy use of the GAC for the year of 2015 is shown in Fig. 51, and the corresponding actual site EUI (energy use intensity) of the building is 165 kWh/m^2/year, which is about 39% lower compared to a similar building with a site EUI of 271 kWh/m^2/year (the Energy Star Target Finder result for the median property). As shown in this figure, electricity is the major energy use, due to the heavy use of GSHPs for both space cooling and heating.

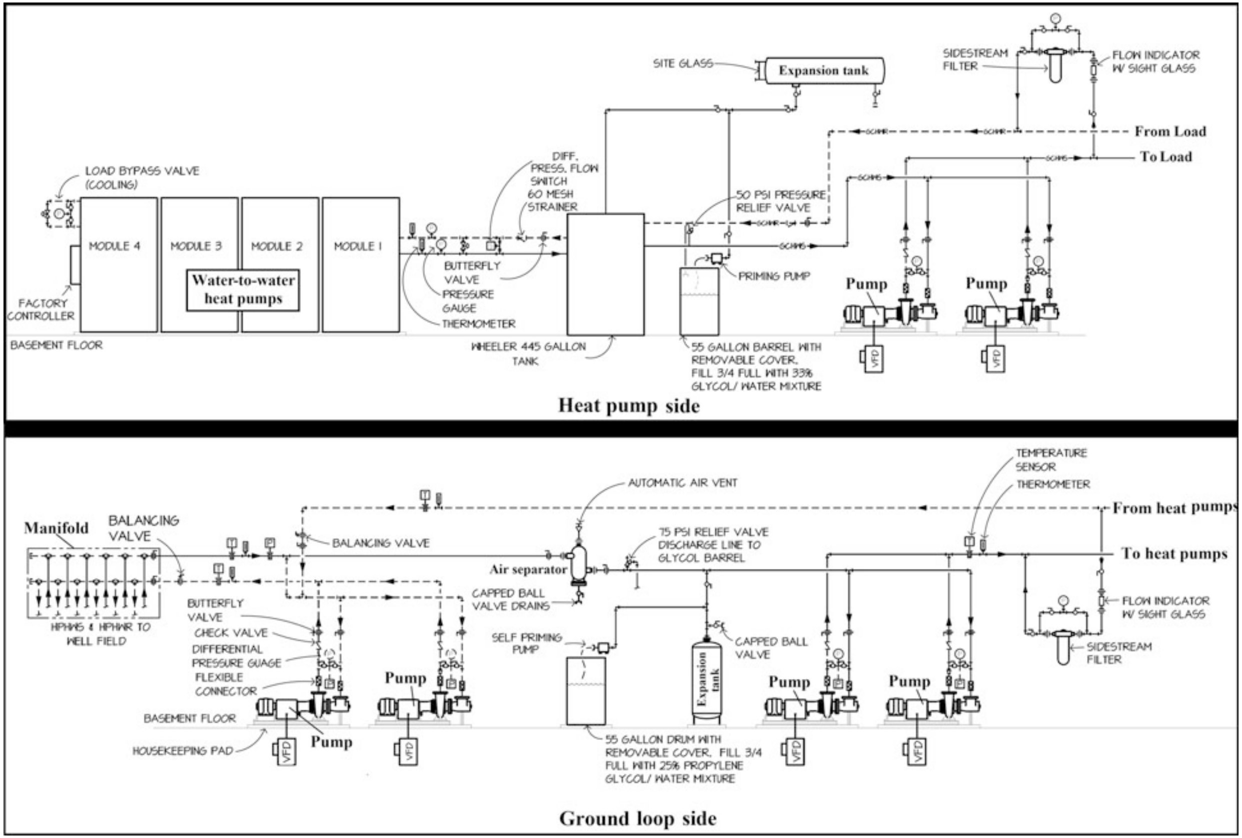


Fig. 50 Piping schematic of GAC (Printed with permission of Obermiller Nelson Engineering, Inc.)

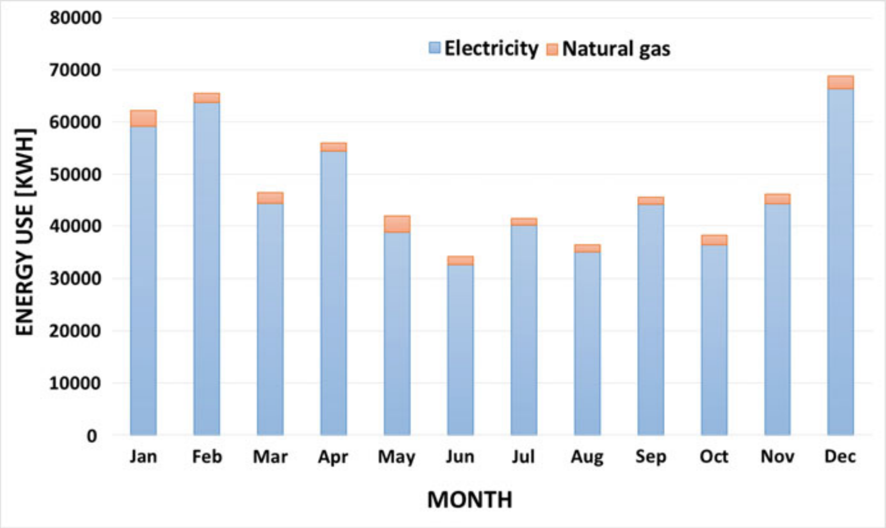


Fig. 51 Monthly energy use (Source: Obermiller Nelson Engineering, Inc.)

Economics and Environmental Impact

Economic Considerations

GSHP systems have proven to be very economical and cost-effective in many parts of the world; however, there are also examples of projects that are poorly designed or poorly maintained to the point of being bad investments and giving the GSHP industry a black eye. One way to avoid this problem is to do a very thorough design and simulation study before any work is started. It is also important to have a thorough knowledge of the local geology and hydrology at the project location. For commercial or large-scale projects, one or more thermal response tests are often done to be more certain of the thermal characteristics underground. All of this also assumes that the people doing the design have adequate knowledge and skill for the job and have access to well-proven simulation software.

As an example of a thorough study for a new GSHP system, Kavanaugh and Gray [48] have done an evaluation of three different designs for the HVAC portion of a 6690 m^2 school in Birmingham, Alabama, in the United States. The three designs are a conventional vertical borehole GSHP system and two different conventional four-pipe chilled water systems (one with constant air volume, fan coil units, and the other with variable air volume, fan-powered VAV boxes) using chillers, boilers, and cooling towers. All of these designs included all interior piping and controls. The result from this study is that the GSHP system has a lower installation cost than either of the conventional systems, and the design system demand was also significantly lower. Part of the explanation for this result is the experience, skill, and knowledge of the designers. In many other designs, the GSHP system has a higher initial cost; however, the operating cost for the GSHP system is much lower than conventional HVAC systems. In this case, there will be a "payback period," that is, the time at which the total of installation cost plus operating expenditure for both systems is equal. A significant consideration in this case is the type of fuel that is to be used for the different designs. Most GSHP systems will have electricity as the power source, and competitive fuel sources for heating will typically be fuel oil or natural gas. It has been found that with recent prices of fuel in the United States, the payback time for a single family residence GSHP system will be 6 years or less with heating oil as the conventional fuel but greater than 10 years with natural gas as the conventional fuel. Certainly, during the expected useful life of a GSHP system, there is a great uncertainty about any conventional fuel price. This being the case, it is not unreasonable for a property owner to choose a GSHP system over a natural gas system. An even stronger GSHP case can be made for a property owner who has an investment in non-fossil fuel electricity such as solar panels. In this case, the property owner is somewhat protected against the variability of both fossil fuel prices and electricity prices.

With regard to general economic viability, there are at least six different categories for GSHP application:

- New design campus system (campus being multiple buildings at one site)
- Retrofit campus system
- New design large building (commercial, residential, or industrial)
- Retrofit large buildings
- New design single family home
- Retrofit single family home

The chance for a GSHP system to be cost-effective decreases from top to bottom in the list above. For example, with multiple building types and uses on a campus, some buildings might be heating-dominated, and some might be cooling-dominated. A data center building will have excess heat all months of the year, and nearby a residence building may need heating much of the year. A well-designed GSHP system allows for transfer of heat or cold from one location to another without any underground transfer. The effective campus-wide COP can be as high as six or seven in these situations, which is about twice what is to be expected in a single family home, leading to higher cost-effectiveness for the campus system. A similar situation arises in systems for individual large buildings. With large windows, the southern exposure rooms will be solar heated, whereas the northern exposure rooms may experience significant convection heat loss. A well-designed GSHP system should allow for a north/south transfer similar to what was described above for the campus situation. With regard to new design versus retrofit, a new design large building might have an array of boreholes placed directly below the building. This is possible but very difficult with an already existing building. Other than boreholes, horizontal pipe arrays and energy piles (Fig. 21) can also be used in the foundation of a new building, but not for a retrofit.

From the standpoint of electric utility companies, heat pumps are generally viewed as financially beneficial. The danger of high peak use (or brownouts) on hot summer days is reduced since GSHP systems are much more efficient than conventional air conditioners. A second benefit is that during winter months and at night, some of the money that might have gone to pay for fossil fuel is now going to the electric utility instead. Some electric utilities have given lower rates to customers who have installed GSHP systems.

Governments also provide incentives and financial benefits to encourage use of GSHP systems. For the United States, a database to evaluate these incentives in the different states is DSIRE® (Database of State Incentives for Renewables & Efficiency® – www.dsireusa.org).

Regarding long-term use of GSHP systems, a closed-loop field of HDPE pipes may be guaranteed for 25–50 years. Expected life is generally much longer than 50 years. Open-loop systems are not so long lasting and may require periodic maintenance. The above ground portion of a GSHP system also requires periodic maintenance and will eventually have replacement costs; however, these costs are similar but usually lower than other HVAC hardware.

Environmental Impact

GSHP technology is certainly one of the most environmentally clean space conditioning methods available today. Environmental concerns can be subdivided into those which affect the underground environment and those which change the makeup of the atmosphere. There certainly have been some underground environmental concerns from GSHP use. For open-loop systems, some systems have used a "pump and dump" arrangement which has water extracted from an aquifer and then dumped on the earth or into a nearby stream rather than using a second well to reinject the water to the original aquifer. In the United States, there are local restrictions regarding wells and aquifer use to limit how these systems are designed and used. Another danger arises for closed-loop systems with a possible leak of antifreeze liquid/refrigerant either above ground or underground. Again, there are restrictions on the chemical makeup of these products. Since boreholes use grout for better heat conduction around the pipes in boreholes, the chemical makeup of the grout is also a concern. Some grout products are allowed in some regions but disallowed in others. All of the underground environmental issues are perhaps less significant than the worldwide effects on the atmosphere related to ozone depletion and greenhouse gas emission (GHG).

The phaseouts of CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons) are reducing the environmental impact of refrigerant in terms of ozone depletion. HFCs (hydrofluorocarbons) are alternatives to CFCs and HCFCs, and they have no effect on ozone depletion. However, they may cause global warming. Therefore, HFCs are restricted for use in some regions of the world and may be phased out eventually due to their high GWP. Natural refrigerant, such as R-744, is a promising alternative to the current types of refrigerant used in GSHP systems. The ODP and GWP of the commonly used refrigerants, such as R-22, R-134a, R-744, etc., are included in Table 2, and more types of refrigerant can be found in Chap. 29 of *2013 ASHRAE Handbook – Fundamentals* [19]. Without leakage of refrigerant, GSHPs produce no atmospheric gas emissions locally (at the point of use), and any environmental emission issue will be a function of the power sources for the electric grid that supplies any specific GSHP system. Although this is also true for electric resistance space heating, if the GSHP has a COP of three or more, the GSHP will cause less than 1/3 as much emission as the resistance heating system.

In the United States, if a GSHP replaces a system using either heating oil or electric heating in a detached residence, it would save about 2 or 10 tons of GHG emission per year, respectively [49, 50]. The only fuel that has a neutral impact on GHG emission due to GSHP replacements is natural gas. Of course, if a homeowner with a GSHP also has ownership of renewable electricity generation, either on a roof or elsewhere, which is equal to the homeowner’s consumption from the grid, there will be zero (or negligible) contribution to GHG emission from a use of GSHP.

The trade-off with the analysis outlined above is such that if the electric grid is supplied largely with green sources already such as hydroelectricity, wind farms, and solar electricity, there is a great environmental benefit from the use of a GSHP. On the other hand, if the local grid is supplied largely from coal, the displacement of a gas furnace with a GSHP may do more harm than good environmentally, even though the homeowner might gain financially (depending on specific prices of hardware and fuel).

Over the long term, there could be widespread use of GSHP systems for space conditioning without any fossil fuels. Electricity supply could be from a combination of at least six sources, including solar, wind, hydroelectricity, deep earth geothermal, biomass (grown sustainably), and nuclear. There is a good reason to be optimistic for a much better environment for all regions of the world and in which GSHP systems will play a major role.

Summary

More than 70 years have elapsed since the realization of the first GSHP in the 1940s. With the accumulation of these 70 years’ experience, people are not only able to foster a better understanding of the current GSHP systems from lessons but also to explore new technologies regarding the design, development, and application of GSHP systems. The potential for the reduction of CO_2 emissions and fossil fuel consumption is one of the main motivations of using GSHP systems. On the one hand, advancements in GSHP technologies contribute to maximizing the use of ground resources; and on the other hand, efforts are needed to improve the commercial acceptance among people in order to enlarge the positive impacts of GSHP systems on the economics and environments of the world. The financial support from governments and/or utility companies through incentives and/or tax credits encourages the use of GSHP systems. In the meantime, green building certification programs, such as LEED, provide a better environment for the further development of green buildings, in which high-performance systems are more likely to be selected and applied, such as GSHP, to achieve the purpose of saving energy.

Additionally, various associations and organizations have been formed all over the world to regulate the GSHP industry for the sake of its healthy and sustainable development, including, but not limited to, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the Air-Conditioning, Heating, and Refrigeration Institute (AHRI), the Earth Energy Society of Canada, the European Heat Pump Association (EHPA), the Geothermal Exchange Organization (GEO), the Ground Source Heat Pump Association (GSHPA), the Heat Pump Centre of the International Energy Agency, and the International Ground Source Heat Pump Association (IGSHPA).

References

1. Merriam-Webster (2008) Merriam-Webster's advanced learner's dictionary. Merriam-Webster, Inc. Made in the United States of America
2. ASHRAE Technical Committee 6.8 – Geothermal Energy Utilization (2015) Chapter 34: Geothermal energy. In: ASHRAE handbook – HVAC applications, SI edition. ASHRAE, Atlanta
3. Bloomquist RG (1999) Geothermal heat pumps, four plus decades of experience. Geo-Heat Center. Q Bull 20(4):13–18
4. Lund JW, Freeston DH, Boyd TL (2005) Direct application of geothermal energy: 2005 worldwide review. Geothermics 34(6):691–727
5. Goetzler W, Zogg R, Lisle H, et al (2009) Ground-source heat pumps: overview of market status, barriers to adoption, and options for overcoming barriers. Final report to U.S. Department of Energy, Energy Efficiency and Renewable Energy, Geothermal Technologies Program. Navigant Consulting, Inc.
6. Foren M, Nowak T (eds) (2008) European heat pump outlook 2008. Version 1.5. European Heat Pump Association (EHPA), Brussels
7. International Ground Source Heat Pump Association (IGSHPA) (2009) Ground source heat pump residential and light commercial – design and installation guide, Oklahoma State University
8. U.S. Energy Information Administration (US EIA) (2010) Geothermal heat pump manufacturing activities 2009. Office of Electricity, Renewable, and Uranium Statistics, U.S. Department of Energy, Washington, DC
9. Liu X, Lu S, Cai Z et al (2013) A comparative study on the status of GSHP applications in US and China. Lawrence Berkeley National Laboratory, Berkeley. http://cercbee.lbl.gov/sites/all/files/attachments/Comparison of GHP Applications in US and China %28Final%29.pdf. Accessed 9 May 2016
10. Kavanaugh S, Rafferty K (2014) Geothermal heating and cooling – design of ground-source heat pump systems. ASHRAE, Atlanta
11. Farouki OT (1982) Evaluation of methods for calculating soil thermal conductivity. U.S. Army Cold Regions Research and Engineering Laboratory report 82–8, Hanover
12. Toulokian YS, Judd WR, Roy RF (1981) Physical properties of rocks and minerals. McGraw-Hill/Cintas, New York
13. Robertson EC (1988) Thermal properties of rocks. U.S. Geological Survey open file report 88-411, Washington, DC

14. Carmichael RS (1989) Physical properties of rocks and minerals. CRC Press, Boca Raton
15. Kavanaugh S (2000) Field tests for ground thermal properties – methods and impact on GSHP system design. AHSRAE Transactions 106(1). Paper DA00-13-4
16. Kavanaugh S (2001) Investigation of methods for determining soil formation thermal characteristics from short term field tests. ASHRAE research project RP-1118, final report
17. Remund CP, Carda R (2009) Ground source heat pump residential and light commercial design and installation guide, International Ground Source Heat Pump Association, Stillwater
18. ASHRAE Technical Committee 4.2 – Climatic Information (2013) Chapter 14: Climatic design information. In: ASHRAE handbook – fundamentals, SI edition. Appended CD-ROM. ASHRAE, Atlanta
19. ASHRAE (2013) ASHRAE handbook – fundamentals, SI edition. ASHRAE, Atlanta
20. Egg J, Cunniff G, Orio CD (2013) Modern geothermal HVAC – engineering and control applications. McGraw-Hill Education. Printed in the United States of America
21. Omer AM (2013) Direct expansion ground source heat pumps for heating and cooling Int Res J Eng 1(2):027-048
22. Ochsner K (2008) Geothermal heat pumps – a guide for planning and installing. Earthscan, London/Sterling
23. Austin BT, Sumathy K (2011) Transcritical carbon dioxide heat pump systems: a review. Renew Sust Energ Rev 15:4013–4029
24. Hu H, Eikevik TM, Neksa P (2016) Performance analysis of an R744 ground source heat pump system with air-cooled and water-cooled gas coolers. Int J Refrig 63:72–86
25. Air-Conditioning, Heating, and Refrigeration Institute (AHRI) (2009) 2005 Standard for Performance Rating of Direct GeoExchange Heat Pumps. ANSI/AHRI Standard 870 – 2005 with addendum 1, Arlington
26. Mei V, Baxter VD (1991) Experimental analysis of direct-expansion ground-coupled heat pump systems. Oak Ridge National Laboratory, Oak Ridge
27. Wang H, Zhao Q, Wu J et al (2013) Experimental investigation on the operation performance of a direct expansion ground source heat pump system for space heating. Energ Buildings 61:349–355
28. Rafferty K (2008) Design issues in commercial open-loop heat pump systems. ASHRAE Trans 114(2)
29. Ingersoll LR, Zobel AC (1954) Heat conduction with engineering and geological application, 2nd edn. McGraw-Hill, New York
30. Gehlin SEA, Spitler JD, Hellstrom G (2016) Deep boreholes for ground source heat pump systems – scandinavian experience and future prospects. ASHRAE winter conference, Orlando, 23–27 Jan 2016
31. Rafid A-K (2012) Computational modeling of shallow geothermal systems. CRC Press/Taylor & Francis Group, LLC, Boca Raton
32. Sarbu I, Sebarchievici C (2016) Ground-source heat pumps fundamentals, experiments and application. Academic Press/2016 Elsevier Ltd., Amsterdam
33. EECA and GNS Science (2013) Geothermal heat pump in New Zealand – introductory technical guide. GNS Science miscellaneous series 54
34. Hellström G (1998) Thermal performance of borehole heat exchangers. In: Proceedings of the 2nd International Stockton Geothermal Conference. Galloway, NJ, 16 Mar 1998
35. Wang SK (1993) Handbook of air conditioning and refrigeration. McGraw-Hill, Inc. Printed in the United States of America
36. Lancley BC (1989) Heat pump technology – systems design, installation and troubleshooting, 2nd edn. Prentice Hall, Englewood Cliffs
37. Man Y, Yang H, Spitler JD et al (2011) Feasibility study on novel hybrid ground coupled heat pump system with nocturnal cooling radiator for cooling load dominated buildings. Appl Energy 88:4160–4171
38. Helpin V, Kummert M, Cauret O (2011) Experimental and simulation study of hybrid ground-source heat pump systems with unglazed solar collectors for French office buildings. Paper

presented at 12th conference of International Building Performance Simulation Association, Sydney, 14–16 Nov 2011
39. Margen PHE (1978) Heat pump system. US Patent 4,091,636, 30 May 1978
40. Lemire N, Baril P-L, Fredericks RO et al (2016) Dedicated to efficiency. ASHRAE J 58(3):54–60
41. ASHRAE (2013) Standard 90.1 – energy standard for buildings except low-rise residential buildings, SI edition, Atlanta
42. ISO 13256-1 (1998) Water-source heat pumps – testing and rating for performance – part 1: water-to-air and brine-to-air heat pumps, International Organization for Standardization
43. ISO 13256-2 (1998) Water-source heat pumps – testing and rating for performance – part 2: water-to-water and brine-to-water heat pumps, International Organization for Standardization
44. Lee KS (2013) Underground thermal energy storage. Springer, London
45. Drake Landing Solar Community (DLSC) brochures (2016) http://www.dlsc.ca/DLSC_Brochure_e.pdf. Accessed 24 May 2016
46. Carder DR, Barker KJ, Hewitt MG et al (2007) Performance of an interseasonal heat transfer facility for collection, storage and re-use of solar heat from the road surface. Project report PPR 302. TRL Limited, Nov 2007
47. Building Tech Services (2016) http://www.bts-hvac.com/residential/GEOEXCHANGE.html. Accessed 24 May 2016
48. Kavanaugh S, Gray C (2016) A simple approach to affordable GSHPs. ASHRAE J 58(4):14–24
49. Widipedia (2016) Geothermal heat pump – environmental impact https://en.wikipedia.org/wiki/Geothermal_heat_pump#cite_note-strategic-4. Accessed 24 May 2016
50. Hanova J, Dowlatabadi H (2007) Strategic GHG reduction through the use of ground source heat pump technology. Environ Res Lett. https://doi.org/10.1088/1748-9326/2/4/044001