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Thermodynamic Characteristics of Underground Thermal Energy Storage System

Wu, X. B.[1] and Ouyang, X. N.

1 CEEC Geothermal CO., LTD, Floor 18, No.63, Xidawan RD, Beijing 100022, China

wuxiaobo@126.com

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ABSTRACT

The difference between underground thermal energy storage (UTES) and ground source heat pump (GSHP) system has been analyzed from fundamental laws of thermodynamics and heat transfer theory. The main feature of UTES system is the passive cooling or/ heating system with high energy performance, which require high grade of thermal energy to be stored, and suitable terminal system for high temperature cooling or/ low temperature heating. The storage system with thermal stratification design could maintain thermal energy quality and enhance heat transfer during storage process at large extent. As the results, UTES shows its large potential for energy efficiency.

1. INTRODUCTION

In summer, there is a large amount of natural heat and industrial waste heat, while in winter, there is a large amount of natural cold and discharge cold, which has great potential for renewable heating and cooling. However, the supply and demand of heat and cold are not synchronized, the seasonal thermal energy storage can make up for the thermal energy imbalance with season. For large-scale seasonal thermal energy storage, underground thermal storage (UTES) is undoubtedly the most suitable.

UTES originated from of aquifer thermal energy storage (ATES) in Shanghai during 1960s [1][2]. Subsequently, borehole thermal energy storage (BTES) and cavern thermal energy storage (CTES) have been developed [3]. Due to the high construction cost of BTES, most applications are limited to small scale pilot projects, especially for solar thermal applications [4][5][6]。 CTES application is not often due to its special geological condition, with only few projects in Sweden [5]. Most ATES projects are from the Netherlands where good aquifer resources, sophisticated well construction technology and suitable climatic conditions are favorable for ATES application, mainly on low-temperature ATES (LT-ATES) whose temperature level is less than 25°C, with nearly 2,500 projects so far, accounting for 85% of the world [7].

Similar technology, known as ground source heat pump (GSHP) system, has been developed in North America and EU countries. Most common application is the borehole heat exchanger (BHE) with heat pumps for small buildings, which sometimes is called soil source heat pumps (SSHP) system. Of course, there are also groundwater source heat pumps (GWSHP) system. These technologies were introduced into China in the early 1990s, and ever since, China has been the largest market for GSHP in the world [8].

The two technologies are so similar and both might use heat pumps, aquifers or borehole heat exchanger, or even caves, even experienced practitioners cannot distinguish UTES from GSHP. The main international cooperation framework, IEA-ECES which UTES once was main subject of research, has now included GSHP content, and publications of UTES sometimes appear in GSHP conferences and journals. However, in EU countries, especially the Netherlands, advocate UTES application, including program of Europe-Wide Use of Sustainable Energy from Aquifers E-USE(aq) [9], European Technology Platform on Renewable Heating and Cooling [10], HEATSTORE [11] and IEA SHC Task 45 of solar thermal utilization [12]. Japan, the Unite State and other countries [13][14][15] also develop UTES as an upgrade version of GSHP or next generation of shallow geothermal. Usually UTES system have higher energy efficiency, while the energy efficiency of GSHP systems vary at different level [16][17]。

Obviously, there is the difference between UTES and GSHP, and some scholars have also tried to distinguish, but phenomenally[18]. This paper will analyze the difference from the fundamental of thermal science, for purpose of high energy efficiency and sustainable use of underground space.

2. THERMAL STRATIFICATION AND MIXING OF GROUND HEAT EXCHANGE

a. ATES and GWSHP

Aquifer is a water-bearing sand or gravel formation, usually with low permeability top and bottom layers, such as clay, or bedrock. Aquifer is a natural resource, and wells must be constructed for ATES or GWSHP application.

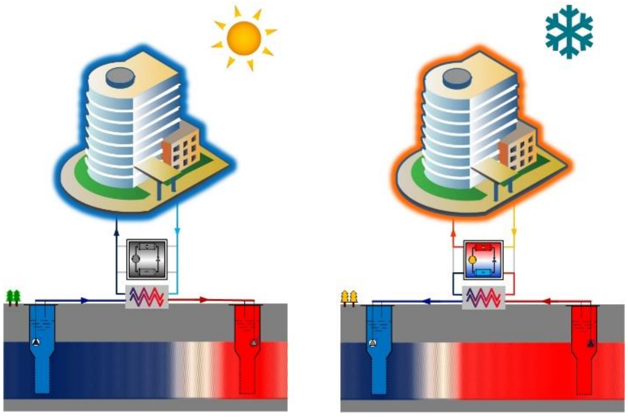


Figure 1: Aquifer Thermal Energy Storage System

The typical ATES system consists of a doublet, one cold well and one warm well, as shown in Figure1. Both wells are equipped with submersible pumps and groundwater injection lines. The flow direction of groundwater loop bi-directional. During summer, the groundwater extracted from the cold well to the warm well for cooling, and vice versa in winter, while the exchange of cold and heat with the above ground system is hydraulically separated with the plate heat exchanger. The aquifer around the cold well, the cold zone is formed to store cold, and aquifer around warm well, the warm zone is used to store heat. To maintain thermal stratification, a certain distance is kept between the cold and warm wells. To scale up ATES system, more doublet systems could be added, with cold and warm wells group.

Typical ATES system provides passive cooling in summer and active heating with the heat pump in winter. In most cases, natural groundwater flow has negative impact on energy storage, due to either natural hydraulic gradients or artificial disturbances (pumping and irrigation), which can be overcome by proper well group configuration.

The flow direction of GWSHP ground water loop is usually one-directional, and the groundwater is always pumped from the extraction well and re-injected into the injection well throughout the year, shown in Figure 2. In such case, the re-injected heat of summer and cold of winter are mixed with no distinct cold zone and warm zone, i.e., thermal mixing process. If the temperature of extraction well is suitable, passive cooling is also possible, while heating is with a heat pump in most case.

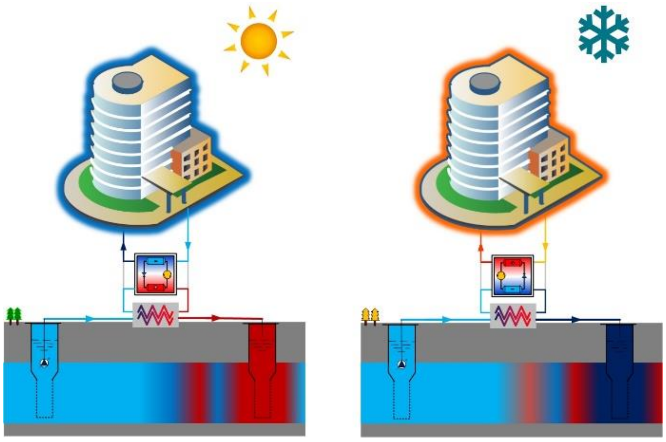


Figure 2: Groundwater Heat Pump System

It should be noted that both ATES and GWSHP face the problem of well clogging, which is main bottleneck for such applications [19]. These problems have been solved, at large extent, with well quality improvement and more sophisticated groundwater loop systems [20][21].

b. BTES and SSHP

For BTES, the heat transfer between the recirculation fluid and the soil is in the form of heat conduction. The borehole heat exchanger (BHE) usually consists of single or double U-shape pipes (PE or PEx pipe).

Like ATES, with serial routing of BHEs, see Figure 3, the borehole field could be divided into cold zone on one side and warm zone on the other side. During summer, the cold water is extracted from the BHEs in the cold zone, after releases the cold for the cooling of above ground system, the warm water is re-injected into the BHEs in the warm zone. In winter, the situation is vice versa, with reverse recirculation water flow. In such way, our BTES concept has been established with thermal stratification. So far, the main application of BTES is for high-temperature heat storage, with large temperature difference between supply and return of heat storage system. The series routing of BHEs could reduce thermal short cut within borehole, thus increase the heat transfer efficiency of BHEs.

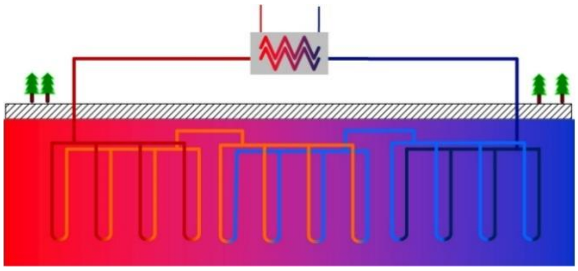
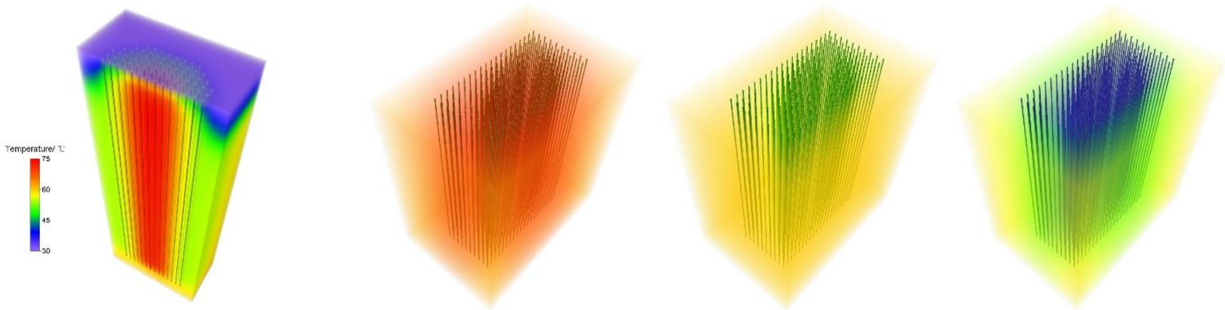


Figure 3: BTES Concept

Two types of BTES configurations have been classified, cylindrical and modular. Figure 4 and 5(a) is the typical BTES cylindrical configuration for small scale storage, especially for solar thermal passive heating [22]. For large-scale BTES projects, we propose modular configuration. The BHEs in the same temperature levels within one thermal zone are in the parallel connection as one module. These modules with different temperature zone are in serial routing with main pipe lines, as shown in Figure 5. The advantage of module BTES design could reduce heat loss among BHEs, which could increase storage heat transfer efficiency. The modular BTES system is scalable, more flexible for large projects.

Figure 4: BTES for Solar Thermal Application Established in 1985, Groningen, the Netherlands



(a) Cylindrical (b) Modular

Figure 5: BTES Configuration with Thermal Stratification

Usually, SSHP systems use the parallel routing BHEs configuration, as shown in Figure 6. In most case, the heating and cooling of SSHP system is always supplied with heat pumps. So, the injection of cold and heat from the ground system is mixed in the soil, i.e., thermal mixing process. If the ground temperature is suitable, the BHEs could also be used for passive cooling. Some EU countries, such as the Netherlands and Nordic countries, SSHP system is also referred as BTES system in practice.

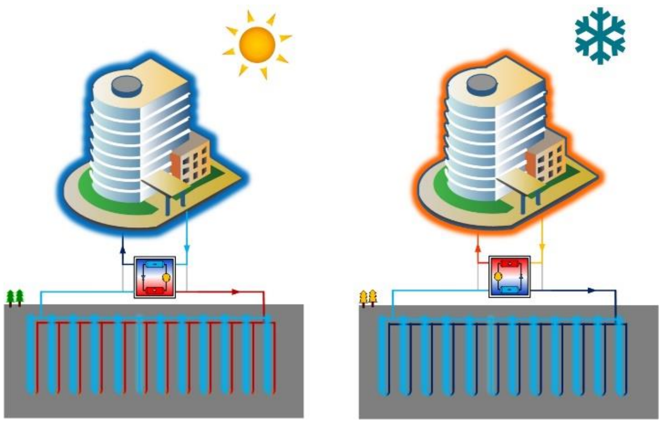


Figure 6: SSHP System

BTES and SSHP have different theoretic background. The design of SSHP is based on line source assumption of heat conduction, which ground is treated as heat source or sink, which might be suitable for small project or with sufficient spacing between boreholes, generally 4-5 meters. As for BTES, in order to reuse the stored heat or cold, the spacing between boreholes is much less than SSHP system, with typical spacing of 1.5 to 2.5 meters.

Due to high investment, most BTES applications are still on small scale pilot projects. However, BTES shows good market prospects in China, as the engineering cost of BHEs is only 1/8 to 1/5 of EU countries.

C. CTES

The main heat transfer in CTES is convection, and the heat is stored in a large cavern, as shown in Figure 7. During heat charge process, the hot recirculation water is injected into warm zone, on the upper part top of the cavern, and the cold water is extracted from the cold zone, on the lower part of the cavern, and vice versa for heat discharge with reverse flow direction. The vertical thermal stratification could maintain the temperature difference of thermal storage in the cave. With proper design, the transition area between hot and cold water is quite thin and moves up and down with charge or release of the heat storage. However, with one-directional flow of recirculation water, the cold and warm water is mixed. Like water tank thermal storage, thermal mixing results in low storage efficiency.

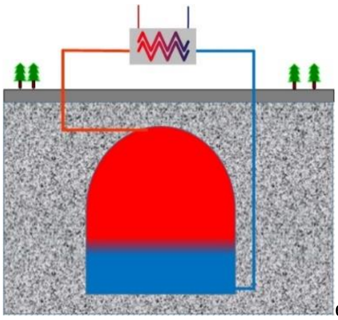


Figure 7: CTES System

The advantage of CTES system is the large recirculation water flow rate, and it is suitable for both short-term and long term storage. Its limitation is that it is difficult to find such caverns with high construction cost. Most of CTES projects are located in Sweden, such as Lyckebo and Avesta projects [5].

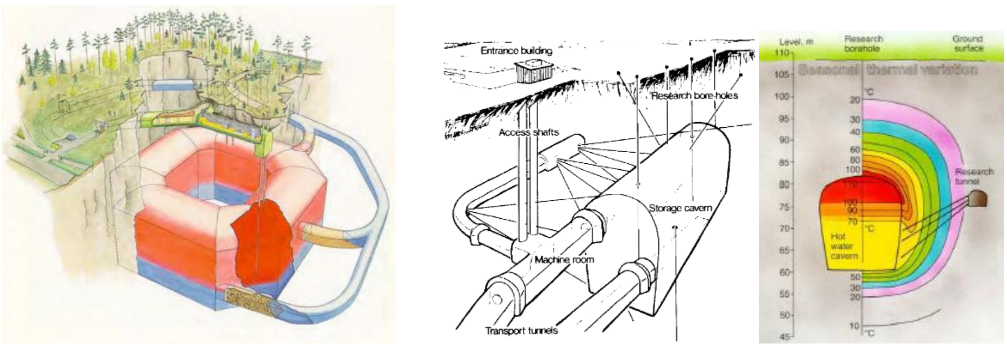


Figure 8: CTES of Lyckebo (left) and Avesta (right) Project in Swenden

To summarize, the concept GSHP design is to dissipate heat or cold to the ground, avoiding ground thermal buildup. While UTES is aimed at the accumulation and reuse of thermal energy, usually with the thermal stratification configuration. GSHP usually occupies large underground space, and UTES is relatively low. The large flow of groundwater has positive impact for GSHP application, but not for UTES. Small projects are easy for thermal dissipation, while large projects can reduce edge thermal loess and accumulate thermal energy for reuse. Similar topics has been mentioned in VDI-4640, the guidelines for underground thermal energy storage [18], as shown in table 1. However, the description of UTES and GSHP is limited to phenomenal level. This article will analyze those system from the thermodynamic point of view.

Table 1: Different Requirements which Subsurface Zone and System Layout
Between Thermal Energy Storage, and Direct Thermal Use (e.g. for Heat Pump Operation).

	thermal energy storage	direct thermal use
Heat exchanger at ground surface	minimize	maximize
Ratio boundary surface to volume	minimize	maximize
Geometry	compact	expanded
Presence groundwater flow	unfavorable	favorable

3. UTES THERMODYNAMICS

a. Energy Conservation

GSHP usually uses the ground as unlimited heat source or sink. It is believed that geothermal heat conducts through the crust to the earth surface, that is, terrestrial heat flow. Some scholars also believe that the ground heat source or sink could be replenished by solar radiation and atmospheric convection on the surface. Now more and more evidence indicates the limit of sources assumption [23][24], especially for large-scale projects, the thermal balance of ground will be used as a design criterion.

Though the terrestrial heat flow is also the most important feature of the geothermal field [25], which includes oceanic heat flow and continental heat flow. The latest global terrestrial heat flow compilation data is 51,621, and ocean heat flow compilation data is 12,333 [26]. The average global continental heat flow is 67mW/m^2. These heat flow data indicate the contribution of "shallow geothermal" is almost negligible in comparison with heating and cooling load of the buildings.

While the thermal energy of the surface is affected by many factors, and its balance depends on the net solar radiation, the convection with the air, and the evapotranspiration. The energy balance is constrained by the water balance, including precipitation, evapotranspiration, infiltration and runoff, as shown in figure 9. However, the surface heat flow or soil heat flux, which is also influenced by the continental heat flow, is smaller than other terms in the surface energy balance equation in the magnitude analysis [27][28] and could be set to zero on daily base. For further research, it can be estimated from the formula in the literature [29]:

$$G = 0.07\frac{10^6}{24 \times 60 \times 60}(T_{i+1} - T_{i-1})$$

T_{i+1} and T_{i-1} are the average temperature of the next month and the previous month respectively. The difference between these two temperatures is usually not more than 15℃. Therefore, the surface heat flux density is less than 12w/m^2, which is still small, and the annual average ground heat flux is zero.

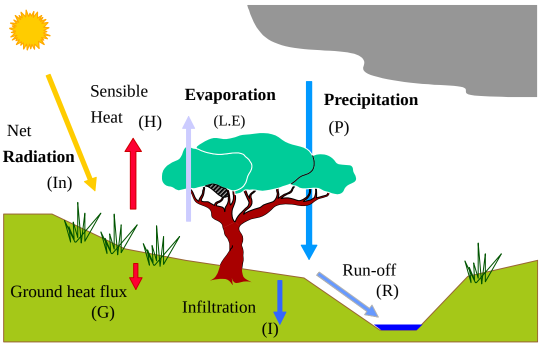


Figure 9 Energy and Water Balance of the Surface

As the enthalpy value of the shallow layer is low, the transportation of its geothermal from the distance is neither cost effective due to high construction cost, nor energy efficiency due to its high pumping power. The ground space for thermal use is rather limited. Therefore, from the energy conservation point of view, the role of the shallow layer for ground energy system is thermal energy storage with its soil heat capacity. Under natural conditions, ground temperature is relatively stable, generally the average value of the local annual temperature, which is warm in winter and cool in summer. Of course, the establishment of the ground energy system will alter the natural temperature. More precise temperature and thermal balance could be obtained by hydrological thermal simulation, which is always the requirement for large project design and evaluation, especially for UTES, see the following section.

The design of UTES requires data of heating and cooling demand of the above ground system, based on energy "banking" concept, to maintain the ground thermal balance to ensure the sustainability of system. For design of GSHP, the ground thermal balance is not required. Since the natural ground temperature is at level of local annual average temperature, the energy efficiency of the new system is high in the first several years. However, the ground thermal unbalance due to long term accumulation of cold or heat, especially for large systems, will results in a decrease or increase in the overall ground temperature [30][31], which results in low energy efficiency, or even failure of the system. To keep ground thermal balance, artificial heat or cold replenishment is needed, complying with the first law of thermodynamics, even for GSHP design. For example, for projects with capacity larger than 70kW, the ground thermal balance should be maintained as a legal requirement [32].

b. Energy Efficiency

As mentioned before, UTES usually refers to seasonal energy storage, because it is easy to access low temperature cold in winter, or high temperature heat in summer. The heat pumps or chillers are not always adopted in the UTES systems, such as early ATES system of Shanghai and then Netherlands, where main applications are for seasonal cold storage, with energy efficiency 10 to 20. As for BTES system of solar thermal and industrial waste heat application, the typical energy efficiency is 20 to 40. The main UTES difference from GSHP is passive cooling or heating.

Since UTES is a passive cooling or heating systems, which has the quality requirement for the stored energy. For cold storage the recharge temperature should be lower than a certain valve, known as cut-off temperature, and vice versa for heat storage.

The terminal or so-called climate system has the requirements for its supply temperature of cooling or/ heating. The terminal with high temperature cooling or/ low temperature heating could be beneficial to increase the cut-off temperature during cold charge, and reduce the cut-off temperature of during heat charge, thus increasing renewable cold or/ heat utilization and improving the efficiency of energy storage. The typical terminal systems are radiation terminals, such as floor heating and cooling system, capillary tub mats, metal cold ceilings, etc., and convection terminals, include dry FCU, AHU and chilled beams.

To maintain the quality of the energy during storage process, thermal stratification configuration is adopted, like that of the countercurrent heat exchanger, which follows with the "temperature difference uniformity principle of heat transfer" [33]. In such way, the charge and release of cold is carried out in the cold zone with less temperature rise, and the heat in the warm zone with less temperature drop in comparison with thermal mixing process, maintaining thermal energy quality and maximizing heat transfer efficiency of the storage process at large extent. Compared with thermal mixing process, thermal stratification configuration is idea from thermodynamic point of view, especially for passive cooling /or heating.

While GSHP system is active heating/or cooling system, which introduce more thermodynamic process of the heat pump, to extract heat from low temperature source to high temperature source, with the evaporator, compressor, condenser, and expansion throttle valve. It brings more temperature difference of heat transfer processes, reduce the thermodynamic perfection of the system, resulting in low energy efficiency. On the other hand, with the application of the heat pump, the requirement of the temperature level of the source is not always restricted, which could improve the system resilience.

Therefore, from the perspective of the second law of thermodynamics, the application of UTES, whether in terms of the storage process or overall energy system, both have the best thermodynamic perfection. The results will be further demonstrated by the entransy theory [34].

Nevertheless, as long as the temperature is suitable, thermal mixing configuration could also be used as for UTES. However, in most case, the temperature level from the thermal mixing storage fails to meet the requirements of passive heating /or cooling system, due to loss of energy quality and low heat transfer efficiency. On the other hand, thermal stratification configuration could also be used for GSHP systems, however its contribution to the overall thermodynamic perfection is still small due to the introduction of heat pumps in overall energy system.

Concerning the thermodynamic perfection of the energy system, passive heating /or cooling should be used as much as possible, and heat pump /or chillers are only used when the supply temperature level could not meet the meet the requirements. Therefore, most UTES systems are tailor made, of which most common application is passive cooling with active heating of heat pumps. For carbon neutral target and energy transition, high temperature UTES with passive heating become popular topic among academic research [35].

4. THERMAL SIMULATION AND STORAGE DESIGN

Local hydrogeology condition and ground heat transfer are important factors for the design, optimization, operation, and diagnosis of UTES systems, such as natural groundwater flow, configuration of the wells or the boreholes. This is not much concerned for GSHP system, as the ground is just simply regarded as the "source", at most to maintain thermal balance, and supply temperature could be modulated by the heat pumps. UTES systems are focus on realization of passive cooling /or heating, with strict requirement of supply temperature level from the storage so as to reach high energy efficiency. Thermal simulation is a requisite tool for the design of the storage.

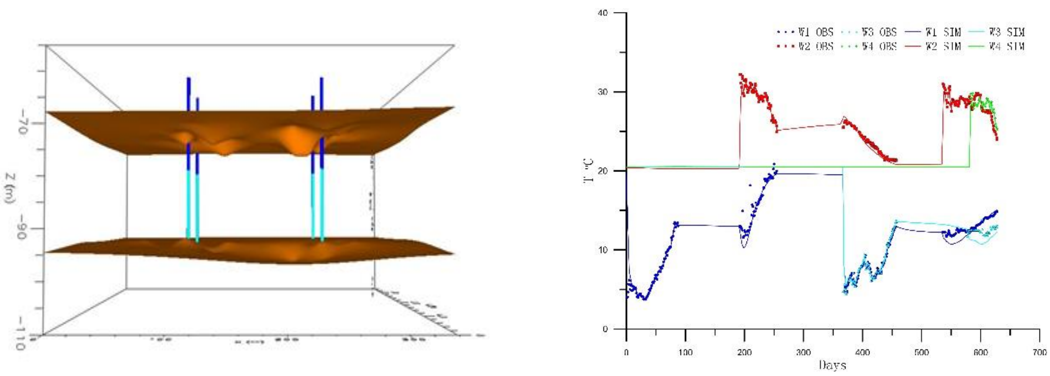


Figure 10: Validation of ATES Model with Field Observation Data

The open source program, MODFLOW of USGS [36], has been adapted for three-dimensional thermal and flow simulation of ATES. The accuracy of the modelling has be validated by the data from ATES test field in Shanghai during year of 1984 and 1985 [21], as shown in Figure 10.

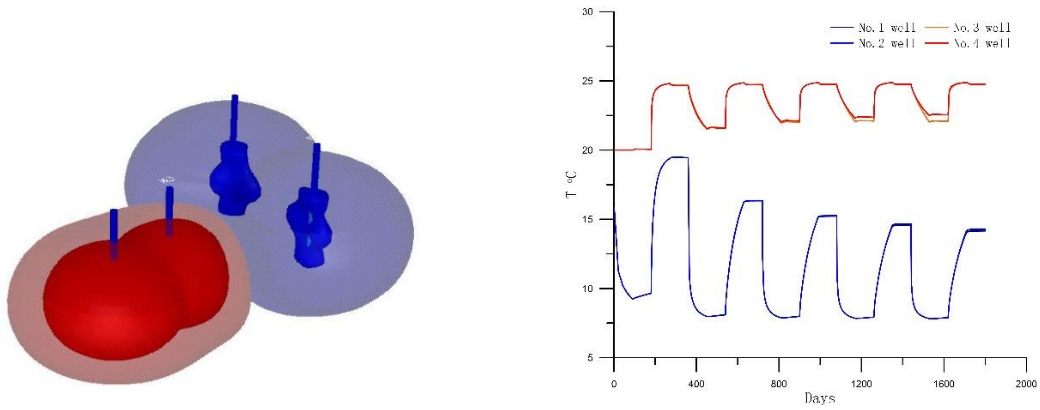


Figure 11: Thermal Simulation (left), Extraction and Reinjection Temperature Responses (right) of ATES

Figure 11 shows the application of ATES for the greenhouse [37]. During winter, the heat pump extracts heat from groundwater of the warm wells, providing heating for greenhouse. The groundwater is reinjected into the cold wells at 7.5 °C for summer cooling. During summer, the plants need cooling and dehumidification for optimal growth, which usually the passive cooling is used with high energy efficiency. The reinjection temperature of groundwater is about 25°C for this case. Though the natural groundwater with temperature of 18°C could also be possible for passive cooling, but its dehumidification effect is limited due to high cooling temperature. Other disadvantage is that bulky climate system should be matched with high investment.

For BTES design, a similar thermal simulation algorithm to ATES must be developed. So far, the thermal simulation of the ground heat exchangers is mainly based on the G-function algorithm of line source theory, and the main commercial software are EED, DST and TRANSYS [38]. However, these software are only for single-borehole heat transfer, or for the ground heat exchanger in parallel pipe routing, mainly for SSHP application. Our BTES model adopts multi-scales numerical method, the heat transfer within the pipe, the boreholes, and the field. With iteration, the heat transfer of coupling ground heat exchanger with thermal stratification (serial pipe or zone routing), typical BTES configuration, or thermal mixing (parallel pipe routing) for typical SSHP configuration, could be simulated. The output of field and pipes temperature of BTES is as shown in figure 6.

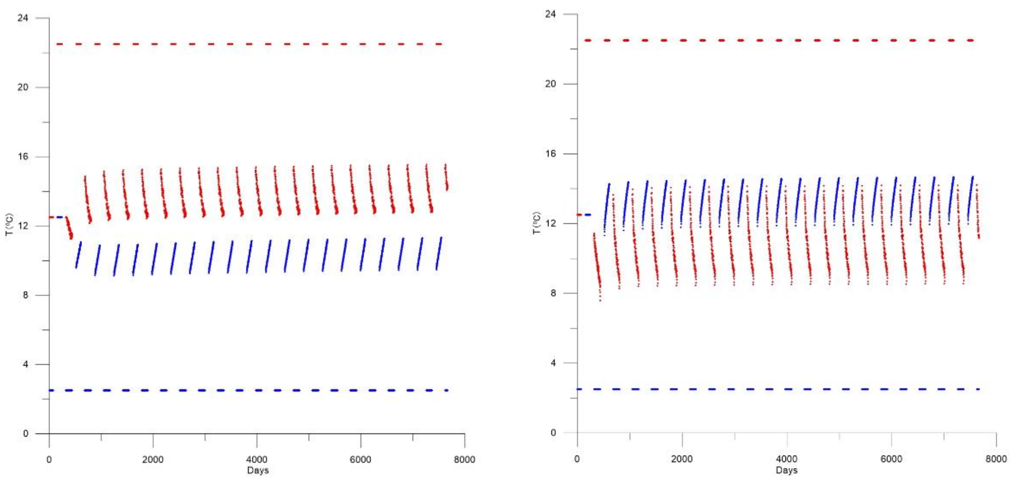


Figure 12: Temperature Response of Borehole Heat Exchanger
with Thermal Stratification (left) and with Thermal mixing Design

Figure 12 is the response curve of the outlet water temperature of the ground heat exchanger of different routing. Like ATES, in winter, the recirculation water flowing into the ground heat exchanger is 2.5°C after heating, and in summer, it is 22.5 °C after cooling. The annual and cooling and heating demands are the same, so as to keep thermal balance of the ground. It has been found out that, compared with the thermal mixing configuration, the thermal stratification design has lower temperature cooling in summer, and high temperature heating in winter, showing the similar temperature response curve of ATES, which is in favor of passive cooling in summer. With comparison of the temperature difference between the supply and the return of the ground heat exchanger, the enhancement of heat transfer with thermal stratification is obvious, which is equivalent to an increase of 20-25% of the heat exchange area.

The heat transfer mechanism of CTES is the same as the water tank thermal energy storage. With the thermal stratification, it has high thermal energy storage efficiency, which is another example that thermal stratification configuration of storage process has better thermodynamic perfection.

5. CONCLUSION

The thermodynamic analysis has been made for characteristic of UTES and GSHP. The advantages of energy efficiency of UTES are obvious. In-depth thermodynamic analysis of UTES could optimize its system configure, sustainability and efficient energy:

- The continental heat flow and surface heat flux into the shallow layer is small in comparison with the magnitude of heating and cooling load of HVAC system. According to the first law of thermodynamics of energy conservation, the role of shallow layer is thermal energy storage, and not always suitable as the heat source/sink for large and medium size of GSHP projects. To maintain the ground thermal balance, heat /or cold replenishment is required.
- UTES system is aimed at realization of passive cooling /or heating with the seasonal storage of accessible high quality cold and heat, resulting in high energy efficiency.
- Thermal stratification configuration has been adopted for the storage design, which the quality of cold /or heat in UTES can be maintained at large extent during storage process, which make the passive cooling /or heating possible;
- High temperature cooling /or low temperature heating terminal system, could increase thermal energy utilization rate and UTES storage efficiency;
- For the design of UTES system, geological exploration and thermal simulation are always required.

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