Overview and outlook of thermal processes in geothermal energy extraction

Biao Shu[a,*], Yating Bao[a], Christos N. Markides[b], Giorgio Besagni[c], Joseph Moore[d]

[a] *School of Geosciences and Info-Physics, Central South University, 932 South Lushan Rd., Changsha, Hunan 410083, PR China*
[b] *Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK*
[c] *Politecnico di Milano, Dipartimento di Energia, Via Lambruschini 4, 20156 Milano, Italy*
[d] *Energy & Geoscience Institute, University of Utah, 423 Wakara Way, Suite 300, Salt Lake City, UT, 84108, USA*
** E-mail: biaoshu@csu.edu.cn*

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Abstract

This vision article accompanies a Special Issue of *Applied Thermal Engineering* dedicated to Heat Transfer in Geothermal Energy Extraction. This issue contains original research articles selected for publication in *Applied Thermal Engineering*, all connected by a focus on processes, technologies and systems for the exploitation of geothermal energy. Geothermal resources, which can be found at depths ranging from a few m to several km below the earth's surface, are amongst the most promising renewable, zero carbon, and clean energy sources. Geothermal energy utilization technologies can be classed into four categories: ground source heat pumps, energy geo-structures, enhanced geothermal systems, and closed-loop geothermal systems. Ground source heat pumps are the most well-developed geothermal technology for shallow depths, and have been widely used for building cooling and heating applications. Current and future heat pump research is focused on the coupling and hybridization of different heat pump configurations, using supplementary energy sources and phase change materials as storage media to overcome the thermal imbalance of the ground. Energy geo-structures, including energy piles, energy walls and energy tunnels, are an emerging and promising geothermal technology, with current research mainly focusing on simulating the effects of influencing factors on heat extraction effectiveness. Enhanced geothermal systems are a technology that can be used to extract deep geothermal energy for power generation and direct use. This technology has attracted significant renewed attention in the last decade. Future research should focus on the heat transfer mechanisms in high temperature rock fractures, and how the layout of inlet and outlet wells and different heat transfer fluids – such as CO_2 – affect performance. Closed-loop geothermal systems, including coaxial and U-shaped systems, have no direct physical contact between working fluid and the reservoir, and may overcome some shortcomings of enhanced geothermal systems, such as leakage of the working fluid and water-rock interactions; however, further research is urgently needed on understanding the thermal recovery performance of these systems.

Key words: closed-loop geothermal system, energy geo-structures, enhancing geothermal systems, geothermal energy, ground source heat pump, heat transfer

Nomenclature and abbreviations

CLGSs	Closed-loop geothermal systems
DCM	Dual-continuum model
DFM	Discrete fracture-matrix model
ECM	Equivalent continuous model
EDFM	Embedded discrete fracture model
EGSs	Enhanced geothermal systems
GHE	Ground heat exchanger
GSHPs	Ground source heat pumps
HGSHPs	Hybrid ground source heat pumps
PCMs	Phase change materials
s-CO_2	Supercritical carbon dioxide

1. Introduction

Geothermal energy is the thermal energy stored underground at depths that range from a few m to several km, and can be classed as either low-temperature (<90 ℃), moderate-temperature (90 to 150 ℃) or high-temperature (>150 ℃) [1]. The total geothermal energy reserves in the world are estimated to be 15×1025 J, which is equivalent to almost 5000 trillion tons of standard coal [2]. Based on the depth and temperature of a geothermal reservoir, and the application scenarios, the most popular geothermal energy technologies include: ground source heat pumps (GSHPs), energy geo-structures, enhanced geothermal systems (EGSs), and closed-loop geothermal systems (CLGSs).

Amongst these, the GSHP is the most commonly used technology for extracting geothermal energy from shallow depths. They use the constant temperature in underground soil and rocks as a heat source or sink to provide space heating or cooling for residential and commercial buildings [3]. These systems consist of a conventional heat pump coupled to a ground heat exchanger (GHE), which can extract heat from or inject heat into the ground. When the GSHP is in cooling mode, heat extracted from the building is transferred to the ground; when the GSHP is in heating mode, heat energy extracted from the ground is transferred to the building [4]. Energy geo-structures are a type of relatively new geothermal energy system, and mainly include energy piles, energy walls and energy tunnels. This technology relies on burying heat exchange devices underground and can provide heating and/or cooling for specific buildings or utilities. Similar to GSHPs, energy geo-structures are also a shallow and low-temperature geothermal energy technology.

High temperature geothermal resources mainly exist in the form of hot dry rock, located at depths of 3-10 km, with a temperature of 150-650 ℃, and the rocks have low porosity and permeability [5]. The extraction of heat from hot dry rock requires a highly connected fracture network created by hydraulic fracturing between the injection and production wells, and to establish an enhanced geothermal system (EGS) for which accurate reservoir stimulations are required [6]. Water or other working is injected into the reservoir where it migrates through the hot rock to the production well. The spent water is reinjected into the reservoir [7]. An EGS is used to extract high temperature energy from deep hot dry rock reservoirs, with the heat transfer fluid, fracture connectivity, injection and production parameters all affecting the performance of the system.

Closed-loop geothermal systems (CLGSs), which do not need direct contact between the heat transfer fluid and the geothermal reservoir rocks, are being tested in recent years. In CLGSs, the heat transfer fluid does not flow through the soil or rocks, and heat transfer is achieved only through the deep downhole heat exchange pipeline.

In general, the four aforementioned geothermal technologies and systems are suitable for different reservoir conditions and applications, and require appropriate heat recovery methods and heat exchange equipment. The energy recovery effectiveness of all these geothermal systems depends on the heat transfer between fluid and heat source or heat exchanger, as well the heat transfer in the geothermal boreholes and pipelines.

This vision article accompanies a Special Issue of *Applied Thermal Engineering* titled "Heat Transfer in Geothermal Energy Extraction", which contains original research articles selected for publication that are connected by a focus on processes, technologies and systems for the exploitation of geothermal energy. This article considers the different technological options, the relevant heat transfer mechanisms, system operation and performance. Both established and emerging technologies are covered, and key challenges are identified along with promising directions for future research and the further development of geothermal energy extraction.

2. Heat transfer in ground source heat pumps

A schematic diagram of a GSHP is shown in Fig. 1 [8]. At present, research in the field of heat transfer in GSHP systems mainly focuses on the following aspects: (1) the influence of the thermal properties of the soil and of groundwater seepage on heat transfer; (2) the design of heat transfer equipment; and (3) use of supplementary energy and phase change materials (PCMs) to reduce thermal imbalances in the system(s).

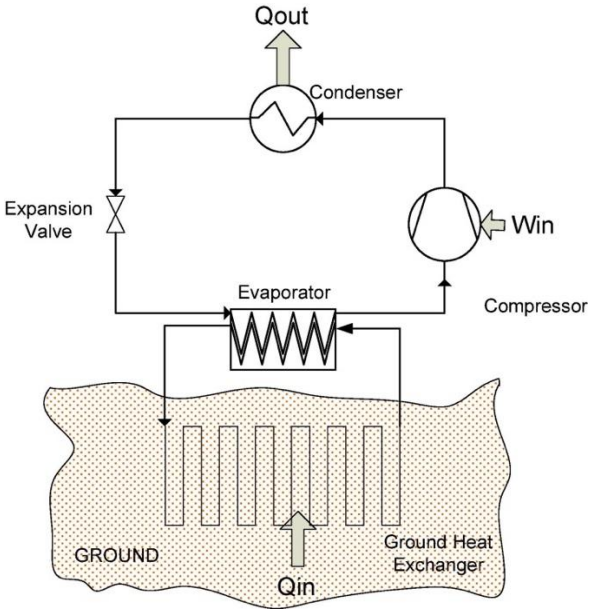


Figure 1. Illustration of the working principle of ground source heat pump [8].

2.1 Influence of soil thermal properties and groundwater seepage

The heat transfer mechanism between soil and groundwater system is complex,

involving the initial ground temperature, groundwater seepage, thermal physical properties of rock and soil, and the cooling and heating load of the system. Temperatures of water in the heat exchanger and air at the heat pump are found to be the most influential parameters for cooling and heating load of the system [9]. In addition to that, the heat transfer performance of GSHP depends mainly on the soil thermal properties and groundwater seepage.

Soil thermal properties may affect the heat transfer of GSHP. Li et al. [10] described a mathematical model of GSHP, which considers the influence of depth and varying unsaturated soil thermal properties, and found that neglecting variations in moisture content in unsaturated soil could lead to underestimating the heat transfer capacity of the soil.

Groundwater flow can improve the heat exchange performance of soils. Chen et al. [11] analysed the evolution of ground temperature field, and the system performance in winter and summer, under different groundwater seepage conditions. The results showed that groundwater seepage can effectively alleviate the heat accumulation and improve the heat transfer effectiveness of GSHP. A building with GSHP under groundwater seepage is shown in Fig. 2 [11]. Groundwater flows in the soil close to the ground surface, which can reach a quick thermal balance during the switching off period of GSHP. Shao et al. [12] measured the groundwater seepage velocity, simulated the heat accumulation, and concluded that with increased seepage velocity, the temperature of the rock and soil mass would more easily recover to the initial state. The accurate prediction of relative permeability is one of the most important issues in the study of multiphase flow in porous media of geothermal energy development. In order to accurately study multiphase flow in soil, Cheng et al. [13] proposed a generalized theoretical model for calculating relative permeability of GSHP, based on the fluid distribution characteristics and the fractal capillary bundle model.

Based on the previous discussion, the prevailing challenges are the accurate representation of depth-dependent variations in unsaturated soil thermal properties, as oversimplification can lead to underestimations of heat transfer capacity. Different soil types, such as compact clay, lightweight sand, and dry shale, also exhibit distinct heat transfer behaviours that require precise characterization. Additionally, groundwater seepage significantly impacts thermal effectiveness, but modelling its effects on heat accumulation and dissipation, influenced by seepage velocity, remains complex. Predicting relative permeability in multiphase flow within porous media is another critical issue, as current models require refinement to capture complex fluid distribution and capillary effects [14]. Integrating these factors into a unified framework for reliable GSHP performance prediction continues to be a major challenge.

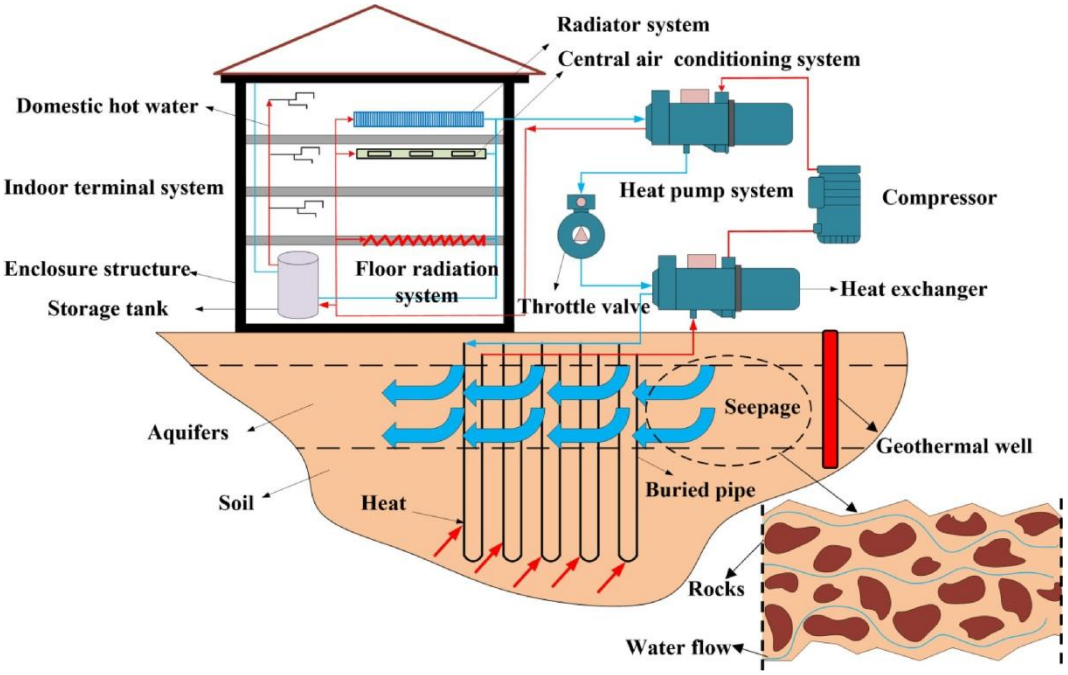


Figure 2. Schematic illustration of ground source heat pump with underground drop seepage effectively alleviates the problem of cold (or heat) accumulation [11].

2.2 Influence of heat exchange equipment

The ground heat exchanger is one of the key components of GSHP system. The heat exchanger is divided into borehole heat exchanger and horizontal ground heat exchanger, according to their direction of placement. The borehole heat exchanger is usually installed in a deep vertical borehole with a depth of tens of meters to more than one hundred meters; while the horizontal ground heat exchanger is generally placed horizontally at a depth of several meters underground. The horizontal trenches require much lower excavation costs than vertical boreholes, so they are more economical. However, the performance of a horizontal heat exchanger is more responsive to the local oscillations of the ground temperature and to the soil heterogeneity [15].

The horizontal ground heat exchanger can be mainly classified into three types: slinky, spiral, and linear-type [16]. Luo and Gan [17] demonstrated that the thermal performance of a slinky ground heat exchanger and the thermal interference between parallel heat exchanger pipes vary with trench spacing, installation depth, soil properties and daily operation duration. Zhou et al. [16] and Yu et al. [18] found that under the same working conditions, a spiral horizontal ground heat exchanger has a larger heat exchange volume and higher thermal performance than the other heat exchange configurations.

Gravity heat pipe is a new type of heat transfer equipment, and has been applied to geothermal energy extraction because of its excellent thermal conductivity, low maintenance cost and high heat transfer effectiveness. The gravity heat pipe is a sealed and evacuated vessel

partially filled with a refrigerant (such as ammonia), which comprises an evaporator section, a condenser section, and an insulated section in between, called the adiabatic section [19]. During the operation of a gravity heat pipe, the liquid mass in the evaporation section absorbs heat from the ground and vaporizes. The vapour then flows along the adiabatic section of the heat pipe to the condensation section on the ground surface and condenses to liquid, while releasing heat [20]. Since the evaporation section of the gravity heat pipe is located below the condensation section, the condensate will flow back to the evaporator spontaneously under gravity. With the phase change and flow cycle of the working fluid, the thermal siphon has very high heat transfer effectiveness and can effectively transfer heat over long distances at relatively small temperature differences. Zolfagharroshan et al. [21] proposed an efficient computational framework for geothermal utilization using a gravity heat pipe, which facilitates the optimization of the design and operational parameters for gravity heat pipe. The environmental problem of using synthetic refrigerants in GSHPs has led to the adoption of harmless working fluids such as CO_2 [22]. Deng et al. [23] designed a new hybrid gravity heat pipe composed of metallic copper and polypropylene random copolymer materials. It was found that the average soil temperature around the condensation section during the experimental period increased by 3.1 ℃, compared to the soil temperature of the control group without the heat pipe.

The concept of a thermal response test on a borehole was introduced by Mogensen [24] to determine the ground thermal conductivity and borehole thermal resistance. At present, in situ thermal response tests have been a major approach to determining key design parameters of ground/geothermal heat exchanger, including the thermal conductivities and diffusivities of the soil and the backfilling material. Under continuous test conditions, in order to reduce the errors caused by changes in electric power and heat capacity of materials in the well, advanced optimization algorithms [25], improved heat transfer models [26], revised object functions [27] and improved uncertainty estimation [28] were introduced. Under interrupted test conditions, Beier [29] developed a robust deconvolution algorithm for generating transient temperature curves and applied this technique to interrupted thermal response tests. Li et al. [30] developed a new parameter estimation algorithm by integrating three key elements: a short-time model, a derivative-enhanced objective function, and the zero-order Tikhonov regularization strategy. The algorithm is validated to be reliable by a reference sandbox dataset. It increases the independence of the sensitivity coefficients, thus resulting in high identifiability.

Based on the previous discussion, the prevailing challenges are related to optimizing the ground heat exchanger. Different configurations, such as borehole and horizontal heat exchangers, have varying efficiencies influenced by placement depth and soil conditions. Horizontal exchangers, while economical, are sensitive to ground temperature fluctuations and soil heterogeneity, making their performance less consistent. Understanding the impact of

factors like trench spacing, installation depth, and soil properties on the effectiveness of horizontal configurations, particularly slinky and spiral types, remains a challenge. Gravity heat pipes offer promising heat transfer effectiveness, but their design and operational optimization require advanced frameworks and material innovations. Challenges include improving thermal conductivity, minimizing maintenance costs, and enhancing the heat transfer cycle through phase change mechanisms. Additionally, determining key parameters such as ground thermal conductivity and borehole thermal resistance through thermal response tests poses significant challenges. Developing ad-hoc parameter estimation methods and enhancing the reliability of in situ tests are essential to advancing heat exchanger design and GSHP performance.

2.3 Complementary energy and phase change materials

When GSHP is in the heating mode, the soil loses heat and the temperature of the soil decreases; whereas in the cooling mode, the soil absorbs heat and its temperature increases. There are very few cases where thermal loads are balanced throughout the year, so thermal imbalance of the soil, known as “thermal drift”, commonly occurs. This results in the decrease of the GSHP effectiveness in its long-term service life [31].

One of the solutions for the thermal imbalance is hybrid ground source heat pump, which is to add supplementary heat sources to overcome the heat imbalance and improve the system performance [32]. According to the requirements of the heating/cooling loads, supplementary energy sources can be divided into auxiliary heating or cooling source devices. Auxiliary heating injection can be accomplished with boilers, solar collectors, waste heat and so on. Auxiliary cooling sources could include cooling towers, ice storage tanks, fluid coolers and so on [33]. In terms of the control mechanism, the borehole heat exchanger is usually temporarily stopped during the operation of the hybrid system [34], or the working fluid is circulated in the borehole heat exchanger loop to accelerate the recovery of the ground temperature by releasing accumulated heat energy to the ground [35].

A number of scholars have studied the hybrid ground source heat pump system. Langevin et al. [36] evaluated the effectiveness, heating costs and relevance of solar-assisted geothermal systems in a subarctic climate. Results showed that a conventional configuration of borehole heat exchangers effectively meet low heating demands, while borehole thermal energy storage enables the annual balancing of ground loads and meets the high unbalanced heating demands. Cirillo et al. [37] analysed and identified the energy saving and the economic return derived from the investment of placing an earth to air heat exchanger as a pre-treatment unit of a heating, ventilating and air conditioning system serving buildings of a company in Italy. This hybrid system takes advantage of the heat capacity of the soil surrounding buried pipes for passively preheating and/or precooling the air before it is

ventilated into the building. The buried pipes can provide preheated and/or precooled air to improve the energy performance of the heating ventilating and air conditioning system. Naranjo-Mendoza et al. [7] described a study of an experimental solar assisted ground source heat pump system for domestic heating applications. Similarly, it was shown that the solar energy injected in the ground is useful not only to recover the soil from the thermal imbalance but also to store heat. Park and Kim [38] proposed a series-connected hybrid ground source heat pump system. The results showed that although the total required length of the borehole heat exchanger is reduced by half, the proposed serial-connected hybrid ground source heat pump cases effectively fulfil the building load demand, similar to the conventional GSHP cases, but with even better performance in certain cases. Sarbu and Dorca [39] verified through experiments that the average temperature of the working liquid was increased by 2.4% after the hot injection technology was adopted.

Phase change materials (PCMs) are another solution used to overcome thermal imbalance in GSHP systems and to moderate average ground temperature variations. PCMs are substances that store and release heat during phase change [40]. PCMs, in general, can be classified based on how they store latent heat through various phase change processes, as seen in Fig. 3 [41]. These phase change processes include liquid-gas, solid-gas, solid-solid and solid-liquid transitions [42]. PCMs can effectively reduce soil thermal imbalances [43], and improve overall system performance. According to the study of Alavy et al. [41], PCMs can be effective at enhancing performance for conventional GSHP and foundation-based geothermal energy systems by, on average, 17% and 36%, respectively. PCM can be used as decoupling from demand side and supply side and based on the operational temperature different PCM can be selected.

At present, studies on the impact of PCMs on the performance of geothermal or ground-based energy systems can be divided into three categories: (1) studies on the use of PCMs as working fluids in heat pump systems [44,45]; (2) research on using PCMs as filling materials in geothermal boreholes [46]; and (3) research on the use of PCMs in structural foundations.

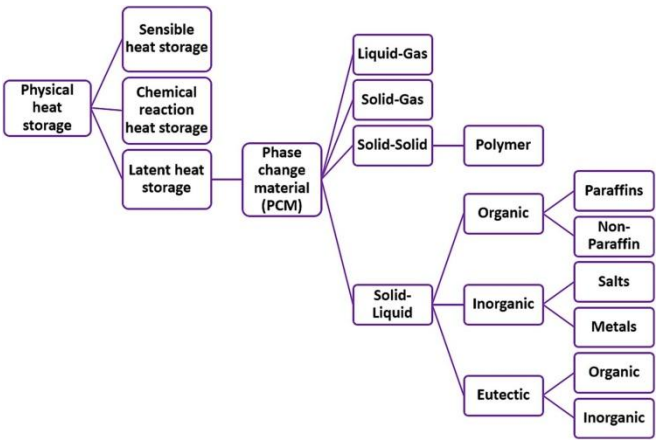


Figure 3. Heat storage and PCM classification based on various phase change processes: liquid-gas, solid-gas, solid-solid and solid-liquid transitions [41].

Based on the previous discussion, the prevailing challenges are addressing the issue of thermal imbalance, or "thermal drift", which occurs due to unequal heating and cooling loads over time. This imbalance reduces the effectiveness of the system in the long term. Hybrid ground source heat pumps (HGSHPs) offer a solution by integrating supplementary heating or cooling sources, such as boilers, solar collectors, cooling towers, and fluid coolers, to balance thermal loads and improve performance. However, the design and operational strategies, including the temporary suspension of borehole heat exchangers or the circulation of working fluids to recover ground temperature, remain areas requiring optimization. Another challenge lies in utilizing PCMs to mitigate thermal imbalance and maintain moderate ground temperatures. PCMs store and release heat during phase transitions, such as solid-liquid or liquid-gas changes, effectively reducing soil thermal imbalance and improving system performance. Despite their potential, the integration of PCMs as working fluids, filling materials or structural foundation components in geothermal systems requires further research to optimize their effectiveness and implementation. Studies on hybrid systems and PCMs have demonstrated improved performance, but challenges persist in refining designs, control mechanisms, and material properties to enhance the energy effectiveness and economic viability of GSHP systems in diverse operational contexts.

3. Heat transfer in energy geo-structures

With the development of GSHP systems, researchers have focused on combining heat pump technology with underground geotechnical structures (such as piles, retaining walls, and tunnels) as energy geo-structures to provide geothermal space heating and cooling for airports, shopping malls and residential areas [47]. Energy geo-structures involve installing heat exchange pipes in underground geotechnical structures and exchanging heat with the soil. The energy provision of energy geo-structures (such as energy piles, energy walls, and energy tunnels) is a secondary function, in addition to their first function of structural purposes [48].

3.1 Energy piles

Energy piles have heat exchange pipes installed in the pile body, so that it can serve as a borehole heat exchanger in addition to its primary function of supporting buildings [48]. A field test of an energy pile heat pump system found that the annual average coefficient of performance of the energy pile heat pump system is 3.8, which is 40-51% higher than that of the corresponding air source heat pump system [49].

Many studies have focused on the thermal and thermo-mechanical behaviour of energy piles. Studies concerned with the former have been mainly concerned with the optimization of the pipe configuration embedded within the pile body, and corresponding analytical solutions of its thermal response. Taking advantage of the large diameter cross section of pile, the heat exchange rate can be increased by increasing the contact area between the thermal pipes and the pile body [50,51].

In terms of their thermal behaviour, when energy piles are constructed in large buildings, they often appear in groups and are heated or cooled at the same time. The thermal interaction between piles will reduce the thermal effectiveness of the heat pump system. Tiwari and Basu [52] found that in comparison with purely conductive heat flow in the ground, the presence of natural convection may reduce pile thermal interaction within a large pile group by up to 90% and elevate the average heat rejection capacity per unit pile length by around 25%. Cui and Zhu [53] studied the annual performance of a pile group using a three-dimensional transient heat transfer model, and found that soil with a low volumetric heat capacity and high thermal conductivity could achieve a rapid temperature recovery.

The studies on the thermo-mechanical behaviour of energy piles mainly focused on how to minimize the disturbances to the pile displacement and bearing capacity caused by temperature changes, so that not to affect the design criteria of the pile foundation. Maintaining the design criteria is usually achieved by reducing the range of temperature changes experienced by the energy pile or increasing the factor of safety in the pile design [54].

You et al. [55] conducted structural response tests on cement fly-ash gravel energy piles and found that the distribution of the thermal axial stress along the piles was uneven during heating and cooling. The cement fly-ash gravel pile is widely used for building foundations, constructed by mixing cement, fly ash, gravel, sand and water in foundation soils using long spiral drilling machine [55]. Heating usually does not change the bearing capacity of the pile, but cooling decreases the bearing capacity of the pile. Therefore, cooling should be carefully considered in the design of the cement fly-ash gravel energy pile. The schematic diagram of a cement fly-ash gravel pile-soil composite foundation is shown in Fig. 4 [55]. Yang et al. [56] studied the effect of pile end constraints and sand compactness on the thermo-mechanical properties of the energy pile through laboratory experiments. The study showed that the strain of end-bearing piles gradually increased along the pile depth due to the large constraint of the bearing rocks at the tip of the pile, while the strain distribution of friction piles is large at both ends and small in the middle [57].

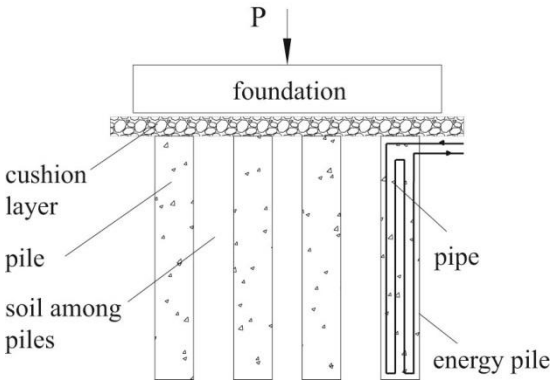


Figure 4. Sketch of cement fly-ash gravel energy pile [55].

Based on the previous discussion, the prevailing challenges in the use of energy piles lie in optimizing their thermal and thermo-mechanical performance. Energy piles integrate heat exchange pipes within the pile body, allowing them to function as borehole heat exchangers while supporting buildings. However, when applied in large-scale projects, thermal interactions between closely spaced piles reduce system effectiveness, necessitating further studies on heat transfer mechanisms, such as natural convection and soil thermal properties, to enhance thermal performance. The thermo-mechanical behaviour of the piles and their surroundings also presents significant challenges, for example, temperature-induced stresses, can affect the structural stability of the pile foundation. Uneven thermal stress distribution and increased settlement during cooling stages need to be addressed to ensure that energy piles meet design criteria. This often requires reducing the temperature changes experienced by the energy pile or increasing the safety factors in its design. Moreover, material-specific challenges, such as those observed in cement fly-ash gravel energy piles, highlight the need for careful consideration of cooling effects and structural responses. Variations in strain distribution due to pile end constraints and soil compactness also require deeper investigation to refine design strategies and improve the reliability of energy piles in diverse construction contexts.

3.2 Energy walls and tunnels

Plane energy geo-structures, such as energy walls [57] and energy tunnels [58], are relatively recent (since the beginning of the 21st century) developments. On the one hand, compared to borehole heat exchangers, plane energy geo-structures can make better use of underground space. Consequently, they are more suitable for use in densely populated cities. On the other hand, compared to energy piles, they have advantages such as, a large contact area with the ground, a large spacing between inlet and outlet pipes, a reduced risk of thermal short circuiting, and are considered to have a high thermal effectiveness.

Many scholars have analysed the factors affecting the effectiveness of energy wall, including pipe configuration and spacing [59], velocity and direction of subsurface flows [60],

insulation layer [61], boundary conditions [62], and concrete properties [63]. Hu et al. [64] conducted field tests of energy wall's thermal performance to analyse the influence and interaction of pipe burial depth, flow rate, heating load, and operation mode. They found that the thermal performance of the energy wall increases with increasing burial depth of the heat exchange pipe, and that the heat exchange power and energy utilization ratio both increase with the development of flow rate [65]. Freitas et al. [65] found that the wall thickness and wall geometry have an important influence on its heat exchange potential.

In recent years, with the construction of deeper tunnels, the problem of high ground temperatures has gradually emerged. Energy tunnels are a new technology in which heat exchange pipes are directly placed between the primary lining and the waterproof plate, or in the lining segments and other parts of the tunnel, to carry out heat exchange with surrounding rocks. Energy tunnels mainly use the temperature difference between surrounding rock and the heat transfer medium in the heat exchange tube to extract the geothermal energy in the surrounding rocks, and to provide heating or cooling services for buildings near the tunnel. It can also be used for heating for tunnels in cold regions, and cooling in tunnels subjected to high ground temperature. The structure and ground heat exchanger of an energy tunnel are shown in Fig. 5 [66].

The heat transfer process in an energy tunnel is affected by the thermal conductivity of the surrounding rock, pipeline configuration and operation mode [67], air temperature and wind speed in the tunnel [68], and groundwater flow [66]. The research of Chen et al. [68] showed that the ventilation in the tunnel can produce turbulence effects at high wind speed, which can enhance heat exchange between the air and the tunnel lining. Luo et al. [69] investigated the effects of different flow rates and wind speeds on the temperature field and heat exchange characteristics of the surrounding rocks, and analysed the changes in heat transfer under different operational conditions. The findings revealed that tunnel ventilation initially enhances the heat transfer effectiveness of the geothermal heat exchanger, but subsequently decreases the overall heat transfer [69]. Zhang et al. [66] carried out a tunnel lining ground heat exchanger laboratory model test and found that the groundwater flow can enhance the heat exchange rate of the tunnel lining ground heat exchanger.

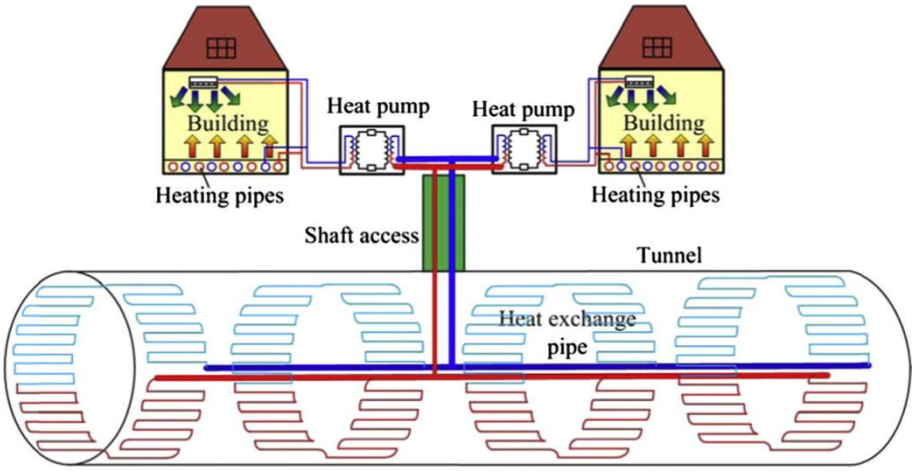


Figure 5. Heating and/or cooling system used in energy tunnels [66].

In addition, studies have shown that PCMs can be applied to energy tunnels to optimize system performance [70]. Elkezza et al. [70] found that PCMs in energy geo-structures can reduce the change of soil temperature, thermal interference radius, as well as potential structural damage caused by thermal stresses. Wang et al. [71] studied an innovative PCM modified lining system of a conventional energy tunnel. Their results showed that the new system would mitigate the thermal imbalances during tunnel construction, and it can improve the stability and effectiveness of energy extraction during tunnel operation.

In addition to energy tunnels, new concepts to use geothermal energy from underground excavations have also been proposed, such as mitigating the thermal hazards to geothermal energy utilization in high-temperature deep mine sites [72], extracting heat from backfilled mine stopes [73] or abandoned coal mines [74].

Based on the previous discussion, the prevailing challenges in plane energy geo-structures like energy walls and tunnels involve optimizing thermal effectiveness and structural integration. While offering advantages such as larger contact areas and reduced thermal short-circuiting, factors like pipe configuration, subsurface flows, insulation, and boundary conditions must be managed to enhance heat exchange. Energy tunnels face additional issues, including the effects of high ground temperatures, ventilation dynamics, and groundwater flow on heat transfer effectiveness. The integration of PCMs shows promise in stabilizing thermal performance and reducing soil temperature impacts but requires further refinement for effective implementation during both construction and operation stages.

4. Heat transfer in enhanced geothermal systems

An EGS schematic diagram is shown in Fig. 6 [75]. Research has shown that three physical indicators are critical for the energy performance of an EGS [76]: (1) reservoir

impedance, which refers to the power required to run an injection-production system; (2) the heat transfer volume, or the volume of rock effectively involved in convective heat transfer; and (3) the fracture volume available for fluid flow.

Current research on heat transfer in EGSs mainly focuses on the following areas: (1) fractures in reservoirs; (2) well distribution and fluid injection scenarios; and (3) working fluid properties.

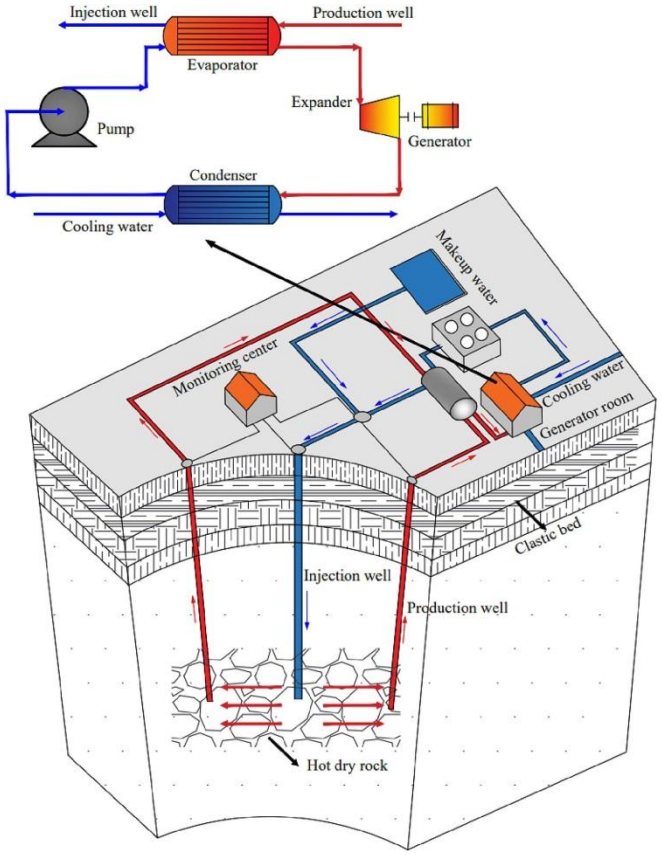


Figure 6. Schematic illustration of an Enhanced Geothermal Systems showing the injection-production well layout and power generation process [75].

4.1 Influence of fractures on EGS heat transfer

The performance of an EGS is significantly affected by the spatial configuration of the fracture network which includes fracture density, connectivity, and aperture. Sensitivity analysis demonstrates that priority should be given to the fracture density and connectivity of the fracture network, followed by the mean fracture apertures. Other studies have also shown that the geometric connectivity of fracture network, usually determines the overall permeability and flow structure within the reservoir [77].

Many studies have modelled the heat transfer characteristics of a fluid flowing through a single fracture. Based on artificial samples, Huang et al. [78] studied and evaluated the influence of the fracture roughness on seepage and heat transfer. Huang et al. [79] simulated the heat transfer performance of water in single fractures with different fracture roughness,

also showed that the larger the fracture roughness, the higher the heat transfer effectiveness. Frank et al. [80] used fractal dimension and profile waviness to characterize the heat transfer process of water flowing in a single fracture in granite, and found that the fracture surface topography had a significant impact on the distribution of local heat transfer coefficients.

The heat transfer performance of fracture network in EGS, including optimization of fracture spacing and fracture density [81,82,83], geothermal fluid reinjection strategies, and multi-well EGS in fractured hot dry rock reservoirs has been evaluated [84,85,86]. The equivalent continuous model, the dual-continuum model, the discrete fracture-matrix model, and the embedded discrete fracture model are the four classical methods used for numerical modelling of a fractured reservoir (Fig. 7) [87]. Each reservoir simulation model has its limitation: (1) The equivalent continuous model (ECM) and dual-continuum model (DCM) cannot handle reservoirs with dominant fractures whose length scales are much larger than the grid block size, especially for the hydraulic fractures in EGS; (2) The discrete fracture-matrix model (DFM) is theoretically applicable to fractured reservoir system, but its practical implementation in case of large-scale models and 3D unstructured grids is very difficult due to the high computational costs. (3) The embedded discrete fracture model (EDFM) approach was proposed first by Lee et al. [88], and has been widely applied in recent years.

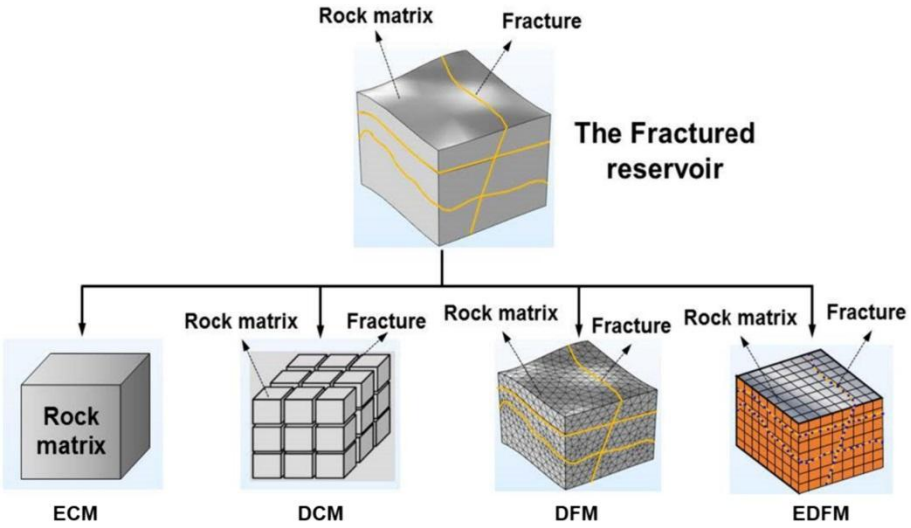


Figure 7. Representation models in fractured modelling showing equivalent continuous model (ECM), dual-continuum model (DCM), discrete fracture-matrix model (DFM), and embedded discrete fracture model (EDFM) [87].

The embedded discrete fracture model has good application prospects in mass and heat transfer problems in the three-dimensional discrete fractures with complex geometry and spatial distribution. Yu et al. [87] proposed a numerical approach based on the concept of embedded discrete fracture modelling, to estimate heat production performance from an EGS. However, the embedded discrete fracture modelling method assumes that the matrix pressure

is linearly distributed along the vertical fracture direction, leading to low accuracy during early production. To improve calculation accuracy, Shi et al. [89] proposed a modified embedded discrete fracture model using a boundary element method to calculate mass and heat transfer between the matrix and fractures.

The temperature and stress changes in the EGS reservoir can have a strong effect on reservoir permeability [90]. In order to study EGS in a more comprehensive way, the influence of thermal-hydraulic-mechanical coupling problem (Fig. 8 [91]) on the heat transfer mechanism of fractures must be considered. Zhang et al. [91] found that the geometrical connectivity of fracture networks plays a dominant role in determining the thermal-hydraulic-mechanical processes and the thermal performance of EGS. The connectivity of fracture network integrates multiple properties of fracture networks, including the fracture length, intensity, location and orientation. Liu et al. [92] proposed a thermal-hydraulic-mechanical coupling model considering the deformation of fractal fractures, and investigated the parameters affecting thermal breakthrough numerically. The results showed that owing to complex fracture geometry, the fracture permeability evolution presents certain heterogeneity, which is related to fractal dimension, in-situ stress, and geothermal wells configuration. The cool water in fractures with larger fractal dimension can better interact with the bedrock and further affect the thermal breakthrough [92].

The thermal stress generated by cold fluid injection into high-temperature reservoirs will cause changes on the reservoir permeability. After long-term operation, the internal thermal stresses evolution of rocks may cause the initiation and expansion of micro-fractures, as well as particle spalling at fracture surface [93]. In Fig. 9 [94], fracture is supported by discrete contacting asperities on two opposite surfaces. Cold water is pumped into the hot fracture, and cools down the fracture surface, inducing thermal strain in the asperities and therefore causes aperture change. Cao et al. [95] proposed a dynamic model of fracture width that takes thermal stress into account, and found that neglecting the impact of thermal stress on fracture width leads to an underestimation of produced energy. Xu et al. [96] studied the optimization of an EGS project based on the impact of fracture damage from fractures, and found that because of the fracture damage, higher mass flow can be selected to optimize the heat extraction.

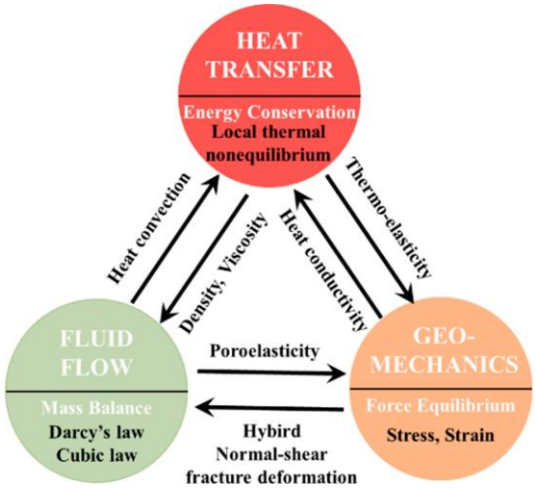


Figure 8. Heat transfer, fluid flow and geomechanics coupling processes in Enhanced Geothermal Systems [91].

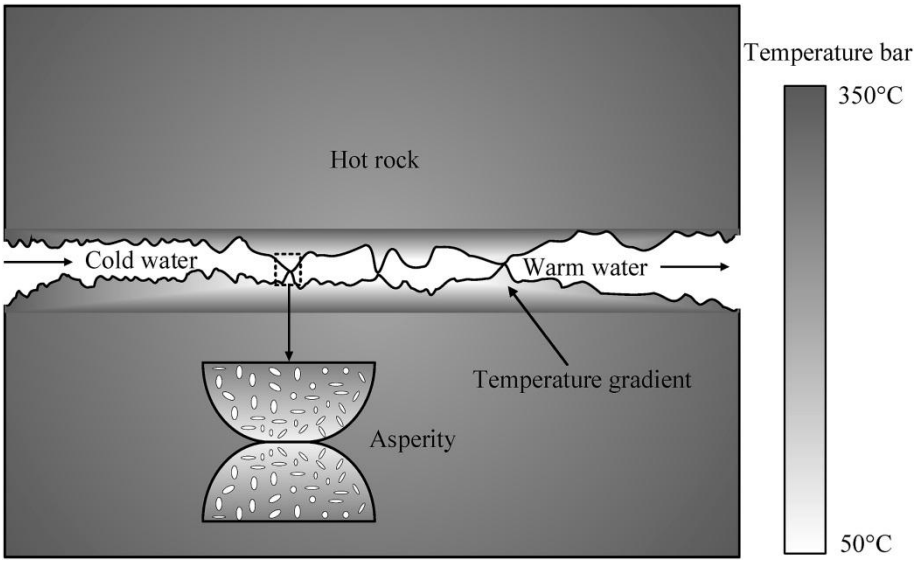


Figure 9. Fracture heat exchange model diagram showing cold water injection induce thermal strain in the asperities and therefore cause aperture change [94].

Geochemical reactions between working fluids and reservoir rocks at high pressures and temperature can lead to mineral dissolution and precipitation, resulting in changes to rock composition and fracture structure, thus also affecting flow, heat and mass transport through the rocks. Li et al. [97] studied the heat transfer process of water flow in the single fracture by considering dissolution between water and fracture surfaces of reservoir rock under high pressure and temperature conditions. The local heat transfer coefficient increased by less than 1% after eight weeks of water-rock reaction, which suggests that the effect of mineral dissolution reaction has a negligible effect on heat transfer [97]. Wu et al. [98] quantified the contributions of fluid pressure and temperature gradient to the evolution of fracture aperture and permeability, and investigated the effect of rock and fracture permeability evolution on heat extraction.

4.2 Effects of well configuration and fluid injection scenarios on EGS heat transfer

A wide range of well configurations are possible for EGS development, such as “one injection well and one production well” “one injection well and multi-production wells”, “multi-injection wells and one production well”, “multi-injection wells and multi-production wells”, and so on. An appropriate well configuration mode can not only increase the heat extraction rate but also prevent early thermal breakthrough [99]. Ma et al. [100] found that multi-well configuration is more suitable than double-well (a single injection + production well) configuration. Sun et al. [101] found that heat extraction from a multi-well EGS is equivalent to the sum of a corresponding number of double-well EGS. Furthermore, the lifespan of multi-well system is significantly longer than that of double-well system due to the influence of the multi-well flow reduction coefficient.

Under high temperatures and non-uniform in-situ stresses during heat production, the geothermal wellbore system experiences complex stress, which can lead to integrity failures of the casing, cement sheath and cement interfaces [102]. Zhang et al. [103] found that the casing-cement interface and cement-formation interface, as well as the cement sheath, are the weak points for potential integrity failure in geothermal wells, with the casing-cement interface being particularly vulnerable.

Optimal fluid injection scenarios are crucial in reducing the risk of thermal breakthrough and improving geothermal energy extraction performance. Lu et al. [104] found that increasing injection rate in a stepwise manner can improve the heat extraction performance, and maintain a more stable and sustainable geothermal system. The injection strategy of the fluid into the reservoir is an important factor in the development of an EGS, and the premature thermal breakthrough may be avoided with an optimal injection strategy [105].

4.3 Influence of the working fluid on EGS heat transfer

Currently water is the only working fluid used in EGS. However, significant water loss to the geothermal reservoir can occur [106], and water availability can be a major challenge in areas with limited water resources. Brown [107] first proposed a concept of using supercritical carbon dioxide (s-CO2) for hydraulic fracturing of hot dry rock reservoirs and heat extraction as a geothermal working fluid, which was referred to as CO2-EGS. The use of s-CO2 for geothermal energy production has gained increasing attention, due to: (1) s-CO2 has unique physical properties (lower density and viscosity) than H2O; and (2) CO2 loss during the heat mining process could be considered as a means of CO2 geological sequestration.

Numerous investigations have analysed the feasibility of CO_2-EGS. It was found that the performance of CO_2-EGS is primarily affected by the initial temperature, porosity, and permeability distribution pattern, rather than the initial pressure [108]. Zhou et al. [109]

compared the physical field evolution and heat extraction performance under different working fluid conditions. When the hot dry rock matrix is initially at temperatures of 150 ℃ and 200 ℃, using CO_2 as the working fluid leads to a faster decrease in outlet temperature and a sustained higher heat extraction ratio compared to water. Yang et al. [110] found that under most conditions, the heat extraction rate of CO_2 is 1.4-2.2 times that of water in the early stage and the final cumulative heat recovery is 0.8-1.9 times that of water. Many simulation results have shown that CO_2-EGS has better heat extraction performance than H_2O-EGS [111]. Wang et al. [112] found that the CO_2-EGS has higher heat productivity than the H_2O-EGS, and the advantage of CO_2-EGS is more notable at low reservoir permeability and low reservoir temperature.

In addition to CO_2, Nitrous oxide (N_2O) has been proposed as a geothermal working fluid by Olasolo et al. [113]. N_2O has physical properties similar to CO_2, with its supercritical point (36.5 ℃, 7.3 MPa) close to that of CO_2 (31 ℃, 7.4 MPa), and its viscosity lower than that of CO_2 which is conducive to its fluid flow in the reservoir. Liu et al. [114] analysed and compared the heat extraction performances of N_2O, CO_2 and H_2O in EGS. The results indicated that the heat extraction performances of N_2O and CO_2 in EGS are almost the same under the same conditions. Taking into account the stable production time and the stability of supporting equipment, the performances of N_2O and CO_2 are better than H_2O [114].

5. Heat transfer in closed-loop geothermal systems

In CLGS, the heat transfer fluid flows in a closed pipeline, and there is no direct physical contact with the reservoir. Heat exchange occurs between pipelines and reservoir, and between working fluid and pipeline [115]. In addition, compared to conventional geothermal systems, the pressure required to circulate heat transfer fluids in closed-loop pipes is significantly lower, the flow rate and operating state are easier to monitor and adjust, and there are many choices of substances that can be employed as heat transfer fluids.

CLGS uses a heat exchanger installed in the borehole to circulate fluid [116]. According to wellbore configurations, CLGS can be divided into two categories: coaxial CLGS, and U-shaped CLGS. In the coaxial CLGS, an insulation tube is incorporated in a single vertical well to separate the injection and production fluids. Different from the coaxial, the U-shaped CLGS is composed of an injection well, a production well, and a horizontal section that connects injection and production wells [117].

5.1 Coaxial closed-loop geothermal systems

A coaxial heat exchanger consists of an inner pipe and outer pipe. An insulated pipe

separates the injection fluid and production fluid. The principle of the coaxial CLGS is shown in Fig. 10 [118]. The annular space between the outer and inner pipes forms the fluid injection channel. The fluid returns to the surface through the inside of the inner pipe. The geometric model is a vertical cylinder that consists of an injection channel, production channel, inner pipe (insulation pipe), outer pipe (steel pipe) and filling material (grout). The outer pipe is generally smooth pipe; the inner pipe is generally threaded pipe or corrugated pipe [118].

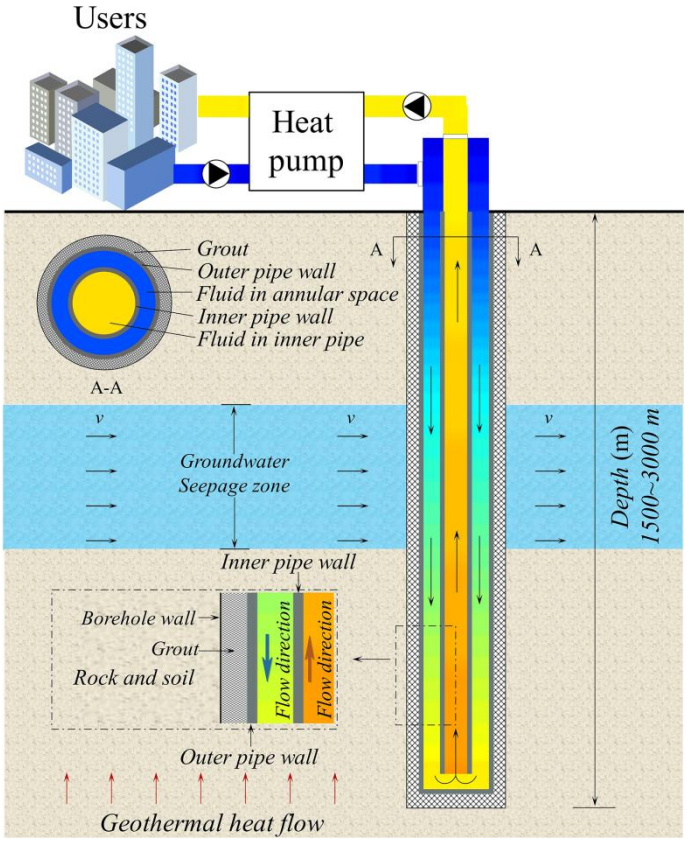


Figure 10. Heat exchange principle of a coaxial closed-loop geothermal systems [118].

At present, many scholars have studied the heat extraction performance and influencing factors of coaxial CLGS. Song et al. [119] investigated the effects of critical parameters, including inlet temperature and cement thermal conductivity, on the heat extraction effectiveness of coaxial CLGS, with ground water flow involved. Wang et al. [120], and Bidarmaghz and Narsilio [121] assessed the effect of convection on the heat extraction from coaxial CLGS. Liu and Taleghani [122] conducted a systematic study on factors affecting production effectiveness of coaxial heat exchanger. The simulation results indicated that increasing the cement thermal conductivity increases both produced fluid temperature and thermal power. The effect of cement thickness is correlated with the value of its thermal conductivity. As the circulation rate increases, the temperature of the produced fluid decreases while thermal power still increases gradually. Iry and Rafee [123] investigated the coaxial heat exchanger with various diameter ratios of inner and outer pipe. The result showed that

the temperature difference between the inlet and outlet of the heat exchanger increases as the diameter ratio decreases. Lund [124] comprehensively analysed the effect of design parameters and geological conditions for coaxial heat exchangers buried 1-3 km deep. The results show that the performance of the well is mainly influenced by its design and mass flow rate. Zhang et al. [125] studied the heat extraction performance of nine working fluids in a coaxial heat exchanger geothermal system, evaluated their applicability as working fluids under the same working conditions, and studied the influence of wellbore, reservoir and fluid parameters.

The effectiveness of coaxial CLGS is quite limited because of the small contact area between the ground and heat exchanger pipes; therefore, some studies been conducted on approaches to improve the performance of coaxial CLGS. Liu and Taleghani [126] increased the heat transfer from surrounding hot rocks to the wellbore by artificial fractures propped with high-thermal-conductivity proppants. It was found that highly-conductive fractures could enhance heat extraction through CLGS significantly. Bakhshi et al. [127] investigated the effect of some parameters, including the shapes of the grooves and teeth, internal and external pipe materials, heat transfer, and heat losses on the performance of coaxial heat exchangers. The best thermal performance was achieved with 5 mm deep triangular teeth and grooves, and this increased the fluid inlet and outlet temperature difference by 6.5%. Huang et al. [118] proposed an efficient numerical model that considers groundwater seepage. The findings demonstrated that groundwater seepage can increase the temperature recovery capacity of rock and soil, and the thermal performance of the coaxial heat exchanger will be underestimated if groundwater seepage is neglected.

5.2 U-shaped closed-loop geothermal systems

In order to further improve the ability of geothermal energy utilization, and to meet the heating needs for larger building areas, the U-shaped CLGS was developed. U-shaped CLGS is to use a buried horizontal heat exchanger pipe connects two vertical boreholes at a depth of 1-3 km. The system was mainly comprised of three sections called descending (injection) well connected to horizontal well section followed by ascending (production) well section as shown in Fig. 11 [128]. Working fluid injected into the descending well segment and goes through the horizontal segment to extract geothermal energy, and then comes out through the ascending well.

Compared with the coaxial heat exchanger, the U-type heat exchanger uses a single tube, which avoids the reverse heat transfer problem between the fluid inside and outside the inner pipe, eliminates the risk of thermal short circuit between the upper and lower fluid, and therefore has better thermal performance [129]. At the same time, there is a long horizontal

section at the bottom of the borehole, which can increase the heat exchange area between the pipe and the surrounding high-temperature rock and soil, so as to extract more heat.

Some studies focus on the feasibility and thermal recovery performance of U-shaped CLGS. Song et al. [130] employed an unsteady state heat transfer mathematical model to study the heat extraction performance of the U-shaped CLGS. The study suggested that insulation is required in the production well, till the point where the temperature of the hot fluid was equal to the surrounding ground temperature. Sun et al. [131] introduced a mathematical model to study CO_2 flow and heat extraction inside the U-shaped CLGS. The study incorporated two new concepts such as effective distance and critical position. The critical position was the point on the production well where the hot circulating fluid temperature was equal to the surrounding rock temperature. Whereas the effective distance is the length of the U-shaped pipe that was responsible for the heat extraction, which is the distance from the inlet to the critical position. The results concluded that the critical position was crucial in selection of the optimum inlet parameters. Ma et al. [132] studied the effects of insulation length, wellbore diameter and horizontal well length on the heat extraction capacity of U-shaped CLGS. It was found that the length of the insulation layer largely depended on the reservoir characteristics, borehole and operating parameters.

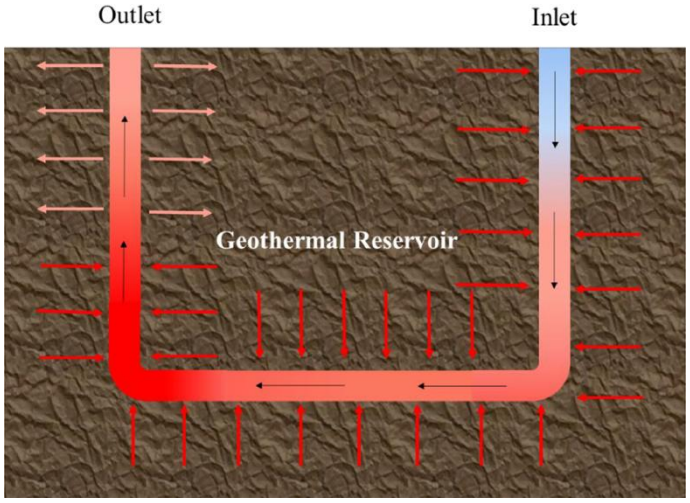


Figure 11. Schematic of a U-shaped closed-loop geothermal system showing working fluid injected into the descending well segment and goes through the horizontal segment to extract geothermal energy, and then comes out through the ascending well [128].

6. Closing remarks and outlook

This vision article accompanies a Special Issue of Applied Thermal Engineering dedicated to Heat Transfer in Geothermal Energy Extraction. This issue contains original research articles selected for publication in Applied Thermal Engineering, all with a focus on

processes, technologies and systems for the exploitation of geothermal energy.

Research into geothermal energy extraction has mainly focused on four technologies: ground source heat pumps (GSHPs), energy geo-structures, enhanced geothermal systems (EGSs), and closed-loop geothermal systems (CLGSs). In general, attention has been mostly paid to heat and mass transfer, and thermodynamic processes relevant to the aforementioned technologies. However, due to the complexity of geological conditions in geothermal reservoirs, all four geothermal technologies still face challenges, especially deep geothermal technologies. This vision article summarizes relevant research published in the special issue (and beyond) on these challenges, analyses and looks to the future of geothermal energy extraction issues. Key conclusions are given below.

6.1 Ground source heat pumps

Most current GSHP research is concerned with the factors affecting the operation and performance of coupled heat exchangers, and hybridization with supplementary energy sources. Although significant research has been done in this field, some challenges remain:

(1) The type of soil has a crucial effect on important properties such as the thermal conductivity and diffusion coefficient of the geological environment around GSHP, and these parameters largely determines the performance of these systems. The thermal properties and characteristics of different types of soil deserve further research attention.

(2) Varying groundwater levels strongly affect the thermal properties of soil, which can lead to deviations (underestimation or overestimation) of the outlet fluid temperature and, thus, overall system performance. Groundwater seepage can improve thermal performance, and reduce soil heat imbalances. However, it is difficult to obtain precise data on the water level, and challenging to build a precise model of this aspect of the system. More research on data measurement and monitoring is needed before more precise models can be developed.

(3) The long-term operation of GSHP systems will lead to thermal imbalance in the soil and a performance loss. In order to address this challenge, geothermal energy can be combined with other supplementary energy sources in hybrid GSHP systems, and PCMs can also be used as working fluids or borehole filling materials to provide additional thermal inertia and to limit variations to the average ground temperature.

6.2 Energy geo-structures

Energy geo-structures include energy piles, energy walls, and energy tunnels. Research on this emerging technology has mainly comprised feasibility analyses and simulations of the effects of important influencing factors on system operation and performance. Some key research directions in the further development of energy geo-structures are:

(1) It is necessary to continue to study the changes of pile-soil interface characteristics under long-term operating conditions, including the role of multiple cooling and heating cycles, and to evaluate quantitatively the influence of thermal deformation of energy piles on their bearing capacity.

(2) The response of a group of energy piles depends on various variables influencing the interaction between the piles, such as the pile spacing, the soil-to-pile thermal expansion coefficient ratio, and the pile stiffness, which are also coupled. For optimal designs and operation of energy piles, it is vital to study these mutual interaction mechanisms and to quantify the coupled influence between these different factors.

(3) The use of thermal conductive fillers such as PCMs in energy geo-structures was found to result in higher heat transfer. However, this leads to enhanced heat flow between pipes, reduced temperature gradients between the inlet and outlet loops. In future work, possible solutions to minimizing this thermal short circuiting should be explored.

6.3 Enhanced geothermal systems

At present, research on EGSs mainly focused on the influence of fractures, well configurations, fluid injection scenarios, and working fluid properties on the thermal performance in these systems. Although EGS research has made great strides in recent years, major challenges still remain due to the complexity of the geological conditions, including:

(1) The accurate characterization of real reservoir fracture networks, and the accurate and reliable calculation of multi-scale fracture network models, are key to EGS heat transfer. In the future, it is necessary to continue to explore characterization methods for reservoir fracture morphology aiming at achieving accurate reservoir modelling. A better understanding of the fluid flow and heat transfer mechanisms in fractures is also needed.

(2) Long-term EGS operation leads to reservoir fractures and mechanical damage, but also chemical change, such as dissolution and precipitation of minerals in the fractures. Therefore, further study is needed to understand matrix and fracture properties, and their coupled interaction with thermo-hydro-mechanical-chemical processes, as well as the long-term performance of reservoirs based on mineralogical and chemical changes caused by water-rock interactions.

(3) Optimizing injection-production well configurations and fluid injection scenarios are crucial in reducing thermal breakthrough risks, and improving geothermal energy extraction performance. Well configuration and fluid injection scenarios can be optimized using advanced methodologies, e.g., combining numerical simulations with genetic algorithm optimization.

(4) A working fluid that is attracting increased attention is s-CO_2. At present, research into new working fluids mainly includes feasibility analyses and heat transfer performance comparison. It remains, however, necessary to continue study of multiphase flow and multi-component heat and mass transfer processes in geothermal environments, including multi-field/physics coupling. New experimental and/or numerical methods are needed to quantitatively explore relevant heat transfer characteristics by considering the fracture morphology and physical properties of the working fluid.

6.4 Closed-loop geothermal systems

Research on coaxial and U-shaped CLGSs has focused on heat transfer enhancement and the role of influencing factors on heat transfer performance and system operation. Further research on the following elements is needed:

(1) At present, research in this field has mainly considered single well CLGSs. To further improve performance, solution models for the heat transfer characteristics of multiple wells or well groups should be developed, ideally based on our knowledge of single well heat transfer, and the regional heat transfer of well groups should be further studied.

(2) Changing the type or arrangement of the heat exchanger to increase the heat transfer area can improve system performance. At present, the fluid flow paths used in CLGSs are relatively simple, so it is possible to study heat exchanger clusters with different arrangements and new heat exchange equipment such as direct expansion heat exchangers.

(3) The difference of fluid properties can affect heat transfer in these systems. Future research should comprehensively consider the thermal performance and system operation of various working fluids under different conditions and consider the selection of optimal working fluids.

(4) The thermal performance of CLGSs may deteriorate over time, yet most current studies are based on short-term simulation cycles that do not fully consider the impact of long-term operation. Therefore, long-term studies should be conducted to understand explicitly the real working condition and long-term performance of CLGSs.

In summary, the use geothermal energy, either shallow or deep, is widely acknowledged as having significant potential to play a leading role in future energy systems, in particular for building cooling/heating applications, as well as for power generation using different single or combined cycles [133,134]. Although GSHPs, energy piles, and coaxial CLGSs are relatively common and have received some attention, challenges remain, while further efforts are needed before more novel technologies such as energy walls, energy tunnels, enhanced geothermal systems and U-shaped closed-loop geothermal systems can be widely utilized.

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