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The main utilization forms and current developmental status of geothermal energy for building cooling/heating in developing countries

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1 Introduction

In the past decade, with the improvement of people's indoor environment demand, the energy consumption of buildings for cooling/heating has increased significantly [1]. The increasing energy consumption caused by using traditional air-conditioning systems not only exacerbates the global energy crisis but also has an important effect on the environment, especially in terms of ozone depletion and global warming [2,3]. To decrease the cooling/heating energy consumption of buildings, various renewable energy technologies (e.g., wind energy, solar energy, and geothermal energy) are utilized to reduce the application of traditional air-conditioning systems. Different from wind energy and solar energy, geothermal energy has the advantages of being consistently stable and highly efficient due to the soil's thermal inertia [4]. In addition, geothermal energy is not limited to specific countries; it can supply energy continuously and reliably everywhere in the world. As one of the most used renewable energy, geothermal energy has attracted more and more attention [5,6]. Due to the large latent heat of the underground soil, when the outdoor environment temperature changes periodically, the soil temperature is basically constant at a certain depth. That is to say, the soil temperature at a certain depth is lower/higher than the atmospheric environment in summer/winter. Therefore, geothermal energy can be effectively utilized to provide the cooling/heating capacity for buildings in summer/winter [7].

Geothermal energy is important renewable energy with the characteristics of environmental protection, green, reliable, and sustainable, which is mainly the heat

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generated and stored under the crust when the earth was formed [8]. However, the commonly mentioned geothermal energy generally refers to the fraction of the Earth's heat that can be found in the shallow strata for space heating/cooling, power generation and domestic hot water, etc. Plenty of studies show that there are many ways to utilize the geothermal energy potential, and the basic idea is to use shallow geothermal and deep geothermal energy to develop the energy resources stored within the earth [9].

In the past decades, the importance of geothermal energy exploitation has increased on both political and social agendas all around the world [10]. A lot of research works have been carried out on the utilization of various geothermal energy technologies in buildings. Almost all the results show that making full rational use of geothermal energy technology can effectively decrease building energy consumption and improve the indoor thermal environment, which are also conducive to the improvement of the outdoor environment and carbon dioxide emission reduction [11]. In recent years, more than 30 review papers on geothermal energy utilization have been published on the website of ScienceDirect, which is a well-known database of academic journals in the world. Researchers have summarized the research status of geothermal energy in various fields and countries from different aspects. For instance, Lebbihiat et al. [12] comprehensively reviewed the historical development, current status, research practices, utilization opportunities, and barriers of geothermal energy in Algeria. Sayed et al. [13] summarized the environmental impacts of geothermal energy systems considering all the stages as well as the whole service life. Lund et al. [14] presented some review works of geothermal energy for direct utilization based on the country update papers of more than 60 countries and regions in 2020. Similar comprehensive review works were carried out in their other published papers in 2015 [15] and 2010 [16].

However, in the existing studies, there appears to be no comprehensive review of geothermal energy utilization for building cooling/heating in developing countries. The main objective of this chapter is to present the main utilization forms, current application, developmental status, and existing issues in the practical application of different geothermal energy technologies for building cooling/heating in developing countries.

2 Literature review and categories of geothermal energy utilization

2.1 Literature review on geothermal energy development for building cooling/heating in the developing countries

In recent years, the application of geothermal energy in buildings in developing countries has received increasing attention. Many researchers have analyzed the important role of geothermal energy in improving the indoor thermal environment and reducing building energy consumption from different aspects. To conduct a more comprehensive understanding of the application and development trends of geothermal energy in the field of building energy-saving in developing countries in recent years, this paper summarizes the research publications of geothermal energy application in the field of building energy-saving in the developing countries during the past 20 years.

The annually published papers on the application of geothermal energy in some representative developing countries from 2000 to 2021 are summarized to further analyze and predict the research tendency for building cooling/heating in summer/winter. These published papers were retrieved on the website of https://www.sciencedirect.com/, which was one of the most used literature search websites in academia. The main keywords of "Geothermal energy, China," "Geothermal energy, Mexico," "Geothermal energy, India," "Geothermal energy, Iran," "Geothermal energy, Indonesia," "Geothermal energy, Brazil," and "Geothermal energy, Pakistan" were selected and input in the search box of title, abstract, or author-specified keywords using the advanced search function. Table 1 and Fig. 1 show the search results of the academic publications about the application of geothermal energy in buildings in some representative developing countries.

Based on the above statistical data in Table 1, a total of 371 papers have been published for the application of building cooling/heating in some representative developing countries during the past two decades. In China, the existing studies on the improvement of building thermal performance are the most extensive with a total number of 156 published papers from 2000 to 2021, which indicates that the geothermal energy system has been widely recognized and applied in the field of building energy saving in China. In addition, these statistical data also show that geothermal energy has received more and more attention in Brazil and Mexico. As shown in Fig. 1, the number of published papers on the application of geothermal energy for building cooling/heating presents an overall upward trend in the considered developing countries. It should be noted that the deadline for data statistics of the number of published papers is May 2nd, 2021. The increasing numbers of the published paper data also indicate that geothermal energy has received increasing attention for reducing building energy consumption and improving the indoor thermal environment in developing countries.

2.2 Categories of geothermal energy utilization for building cooling/heating

Based on the above analysis, plenty of existing studies have shown that geothermal energy is one of the most promising energy-saving technologies for building cooling/heating, and thus it has an important role in decreasing building energy consumption and reducing carbon dioxide emissions in practical application [17]. According to different classification standards, geothermal energy can be divided into many types, such as high-, medium-, and low-temperature geothermal energy system based on the soil temperature, vertical buried-pipe and horizontal buried-pipe geothermal energy system based on the buried pipe form, open and closed cycle geothermal energy system based on heat exchange medium circulation form, etc. In this section, based on the type of heat-exchange medium and source form of pile hole, the most

Table 1 The statistics of published papers on the application of geothermal energy in some representative developing countries from 2000 to 2021.

Year	Input keywords						
	Geothermal energy, China	**Geothermal energy, Mexico**	**Geothermal energy, India**	**Geothermal energy, Iran**	**Geothermal energy, Indonesia**	**Geothermal energy, Brazil**	**Geothermal energy, Pakistan**
2021	14	4	1	6	1	1	1
2020	32	9	8	7	4	5	1
2019	23	7	3	6	1	1	0
2018	16	4	3	6	4	1	1
2017	8	6	3	5	2	0	1
2016	13	4	5	4	4	0	2
2015	10	4	0	5	3	0	1
2014	10	6	2	0	3	0	1
2013	7	3	1	3	1	0	0
2012	6	1	1	2	2	1	0
2011	4	3	1	2	0	0	1
2010	5	1	2	3	2	0	1
2009	2	0	1	4	0	0	3
2008	2	1	0	0	1	0	0
2007	1	0	1	0	0	1	0
2006	1	3	1	1	0	1	0
2005	0	1	0	0	1	0	0
2004	0	2	0	1	0	1	0
2003	1	2	0	0	0	0	0
2002	1	3	1	0	0	0	0
2001	0	2	0	0	1	1	0
2000	0	3	0	1	0	0	0
Total	156	69	34	56	30	13	13

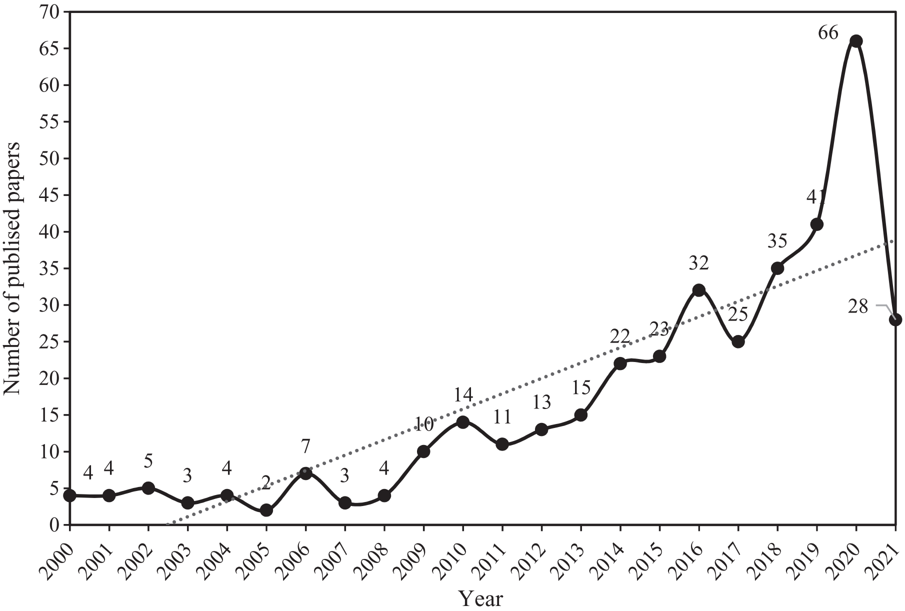

Fig. 1 Number variation of yearly published papers from 2000 to 2021.
Source: ScienceDirect.

common geothermal energy utilization can be classified into three categories: ground source heat pump (GSHP) system, underground duct system (UDS), and abandoned wells energy (AWE) system.

The GSHP system is a high-efficiency heat pump using shallow geothermal energy (the general design depth is 50–200 m), which collects and transmits the heat from the underground soil through a series of buried pipes filled with liquid heat transfer medium [18]. The generated geothermal energy is sent to air-conditioning equipment units for the improvement of operating energy efficiency or directly supplied to the buildings for cooling/heating in summer/winter. According to the different heat sources, the GSHP system can be divided into the ground coupled heat pump (GCHP) system and groundwater heat pump (GWHP) system [19]. The typical GSHP systems including the GCHP system and GWHP system are illustrated in Fig. 2. From the available literature, it can be seen that these GSHP systems have been paid attention to by various countries, and a large number of studies on their application in buildings are being carried out in the world. In some developing countries, e.g., China, Mexico, and Iran, the GSHP systems have been widely used in many practical projects, which has become an important measure to reduce building energy consumption, decrease carbon emissions, and improve the indoor thermal environment.

The UDS system, as one of the most common utilization forms of geothermal energy, has been considered a highly promising shallow geothermal ventilation technology in developing countries. The UDS system mainly utilizes the shallow soil with a stable and appropriate temperature to cool/heat outdoor hot/cold air in summer/

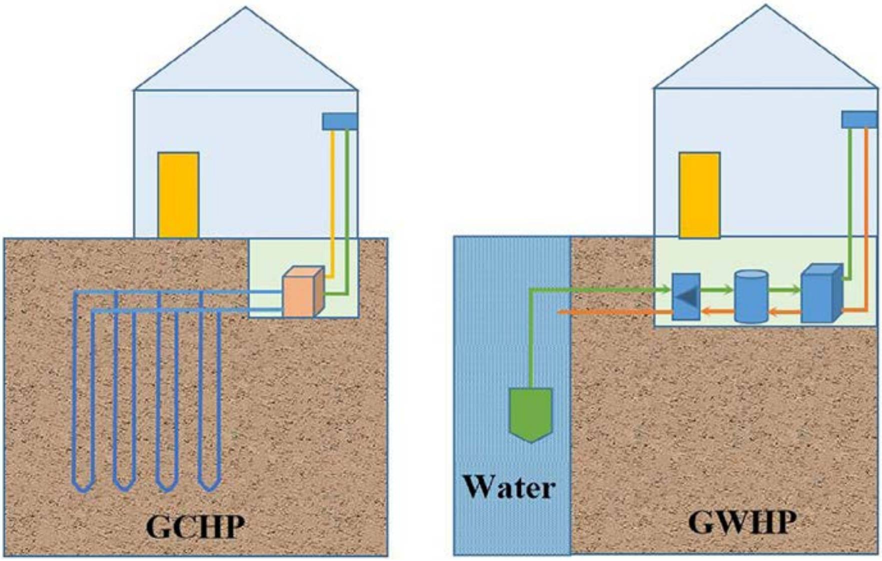

Fig. 2 The schematic design of the typical GSHP systems.

winter. Then the cooled/heated air is sent directly to the buildings through the fan, to regulate the indoor thermal environment [20]. Compared to the conventional GSHP system, the UDS system does not require outdoor unit equipment, and the fresh hot and cold air produced by the UDS system directly provides the cooling/heating capacity for the buildings only through one draught fan. Therefore, the construction cost and operation energy consumption of the UDS system is relatively low in the practical application for building cooling/heating. In recent years, the UDS system has been widely used to reduce the building energy consumption and improve the indoor thermal environment by using underground soil to cool/heat the outdoor air in summer/winter [10]. In academia, the UDS system can also be called the underground tunnel ventilation (UTV) system [21], earth air tunnel heat exchanger (EATHE) system [22], ground-air heat exchanger (GAHE) system [23], earth to air heat exchanger (EAHE) system [24], etc. The operation principle diagram of the typical UDS system is illustrated in Fig. 3.

The AWE system is a promising environmentally friendly energy-saving technology, which utilizes the middle-deep interval geothermal energy from the abandoned oil/gas wells to provide the ideal hot source for satisfying the energy demands of heating and power generation in developing countries. In the past decades, more and more oil/gas wells in the world have been abandoned due to the depletion of oil/gas reservoirs. Statistics show about 20–30 million abandoned wells all over the world, with an average well depth of more than 1000 m. The bottom temperature of these abandoned wells can reach 125–175°C [25]. Therefore, if the abandoned well energy can be fully utilized in the form of geothermal transformation, the energy consumption for building cooling/heating will be greatly reduced. In addition, it can also

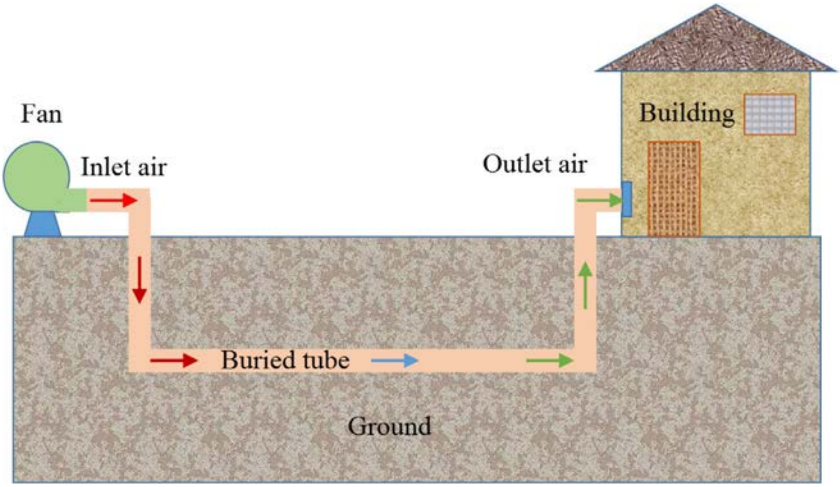

Fig. 3 The operation principle diagram of the typical UDS system.

reduce or avoid the serious pollution problems caused by abandoned wells, such as greenhouse gases and methane gases [26,27]. Compared to the conventional GSHP system, the abandoned oil and gas wells only need appropriate modification for the existing wells without considering new drilling, and thus the high cost of drilling can be saved, which makes the utilization of middle-deep geothermal energy more economical and feasible. At present, many researchers have carried out various studies on the application of abandoned oil/gas wells in the field of heating and power generation [28]. The schematic diagram of the typical AWE system is illustrated in Fig. 4.

3 Common utilization of the GSHP system and its current application and development

In the past few decades, plenty of GSHP systems have been widely utilized for the cooling/heating demands of various buildings in developing countries due to the attractive advantages of low environmental impact and high energy efficiency. The common GSHP system is mainly composed of the ground heat exchanger, heat pump unit, and secondary unit. The ground heat exchanger is the system's energy source, also known as the main unit, which is commonly made by high-density polyethylene (HDPE) loops in different combinations. The common underground buried tube forms mainly include the U-shape tube, double U-shape tube, W-shape tube, 3-U-shape tube in parallel, 3-U-shape tube in series, and spiral shape tube [29], as shown in Fig. 5. The heat pump unit is a power supply equipment that uses geothermal energy to provide the cold and heat capacity for buildings. The secondary unit mainly transports the heat generated by the heat pump to the buildings, to satisfy the cold/heat requirements of the residents. In this section, the common utilization of the GCHP system and GWHP

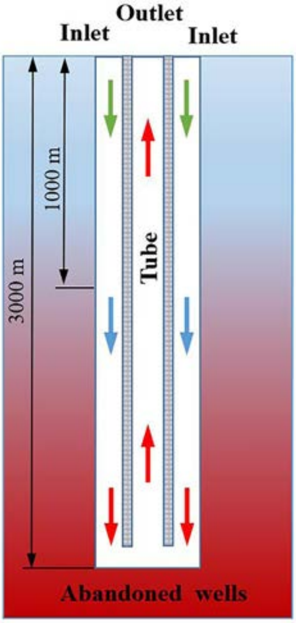

Fig. 4 The schematic diagram of the typical AWE system.

system and their current developments are summarized to comprehensively analyze the application potential of the GSHP system for building cooling/heating in developing countries.

3.1 GCHP system

The GCHP system uses the underground soil as a heat source/sink to provide the cooling/heating capacity for various buildings, which can provide a higher-energy efficiency compared with the conventional air-source heat pump (ASHP) due to the more stable and appropriate soil temperature at a certain depth. According to the form of buried tubes, the GCHP system could be divided into a horizontal buried tube system and a vertical buried tube system [30]. In the horizontal GCHP system, the

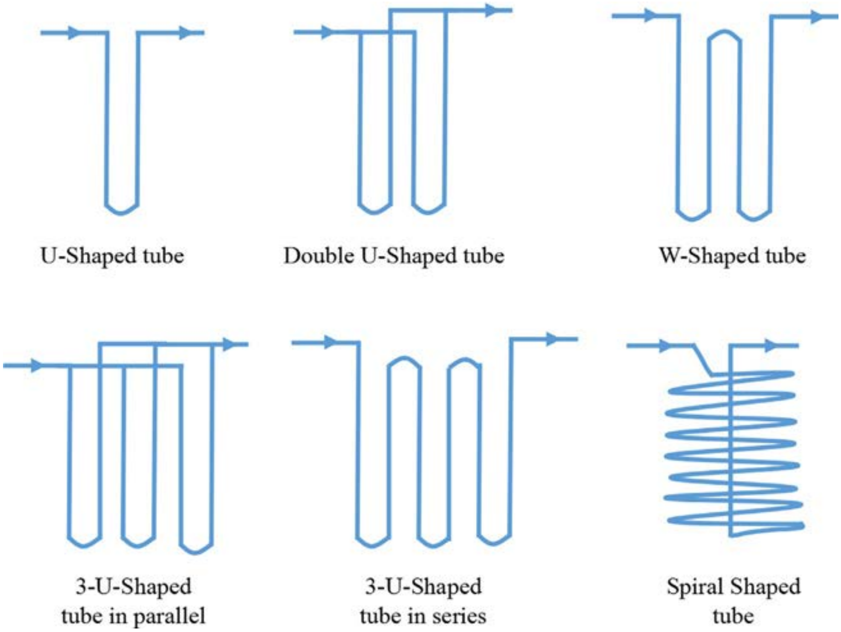

Fig. 5 The common underground buried tube forms of the GSHP system.

buried tubes are usually composed of a series of parallel tubes, and the buried depth is about 1–2 m. The main disadvantage of the horizontal GCHP system is that the soils around the buried tube are more susceptible to the fluctuations of ambient air temperature because they are close to the ground surface. In addition, the installation of the horizontal GCHP system requires more floor space. For the vertical GCHP system, the underground buried tubes consist of a single, tens, or even hundreds of boreholes with the diameter ranging from 100 to 200 mm based on the building areas. The common buried tube forms are one and double U-tubes with a diameter of about 19–38 mm and a buried depth of 20–200 m [31]. The typical GCHP systems with horizontal and vertical buried tubes are illustrated in Fig. 6.

With the increasing awareness of the geothermal energy application and the strengthening of energy conservation in many developing countries (e.g., China), relevant policies have been promulgated, which could greatly promote the development of both horizontal and vertical GCHP systems for building cooling/heating. In practical application, the vertical GCHP system is the most commonly used technology, which has attracted the greatest attention in the research field due to its advantages of less land occupation and wide applicable scope [32]. Plenty of studies on the application of vertical GCHP systems in the various buildings have been conducted to explore their cooling/heating capacity potentials in some developing countries [33]. These studies have shown that the application of vertical GCHP systems in various buildings can greatly reduce building energy consumption and improve the indoor thermal environment [30].

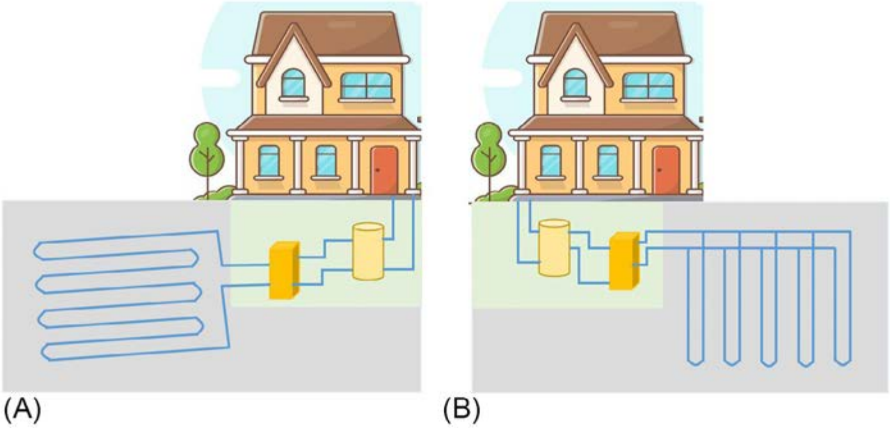

Fig. 6 The typical GCHP systems: (A) Horizontal buried tubes; (B) Vertical buried tubes.

During the long-term operation of the GCHP system, the soil around the buried tubes continuously provides the energy for the heat exchange medium in the tube, which easily leads to the heat imbalance of the soil around the buried tubes, and thus reduces the heat exchange efficiency of the GCHP system. To decrease this issue, it is necessary to achieve the intermittent operation of the GCHP system or input the heat into the soil regularly. Thus, the GCHP system needs to be combined with other energy-saving technologies, to maximize the efficient use of renewable clean energy. At present, the common coupling technologies that can achieve good application effect with the GCHP system include the solar photovoltaic/photothermal system [34], solar heat pump system [35], ASHP system [36], distributed energy system [37], energy storage system [38], etc. Almost all the studies show that the various hybrid GCHP systems have a great energy-saving potential for building cooling/heating. In addition, it is possible to improve the application feasibility of the GCHP system for unbalanced climates in developing countries.

3.2 GWHP system

The GWHP system is a highly efficient shallow geothermal utilization technology which uses the groundwater extracted from the wells or abandoned mines as a low-level heat source, through a small amount of electric energy input based on the heat pump technology, to achieve the heating or cooling supply in buildings [39,40]. Specifically, in summer, the GWHP system absorbs the cooling capacity from underground water through a heat pump unit and converts it into a high-grade cooling capacity to reduce the indoor temperature of buildings, to achieve the purpose of indoor cooling. In winter, the heat pump unit absorbs heat from the underground water provided by the water intake well to heat the buildings, and the heated underground water returns to the ground through the return well. If the groundwater quality is good, it can directly enter the heat pump for heat exchange; such a system is called the open loop GWHP system. In practical engineering, the closed-loop heat pump circulating water system is commonly used. The main reason is that the plate heat exchanger is used to separate the groundwater from the circulating water through the heat pump, to prevent the influence of sediment and corrosive impurities in the groundwater on the performance of the heat pump unit [41]. The operation principle diagram of a typical GWHP system is illustrated in Fig. 7.

In the existing studies, the typical GWHP system can be classified as three types based on the different intake and return water modes, and the specific structure is shown in Fig. 8. For a single well, the utilized water is discharged to the surface water (Fig. 8A) or recharged to the extracting well (Fig. 8B). As shown in Fig. 8A, this mode is suitable for the ground with good permeability, and the surface water is close to the extracting well. Besides, it still has a risk of recharging water pollution. The mode in Fig. 8B extracts and recharges water in the aquifer to save the land occupation and investment. However, with the operation time increasing, the temperature difference between the extracting and recharging water will be reduced, and the system cannot operate under the design conditions. The GWHP system with double wells is the most common form of utilization in developing countries, as shown in Fig. 8B. The water is extracted from the extracting well and recharged into the recharging wells after heat exchange. The extracting well is usually placed upstream of the recharging well. The distance between two adjacent wells should be designed to prohibit heat interference between them [42].

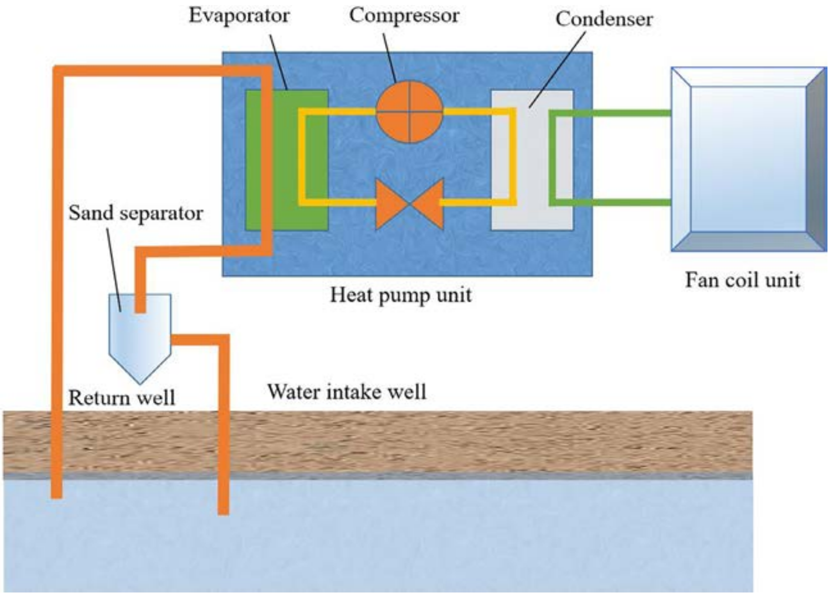

Fig. 7 The operation principle diagram of a typical GWHP system.

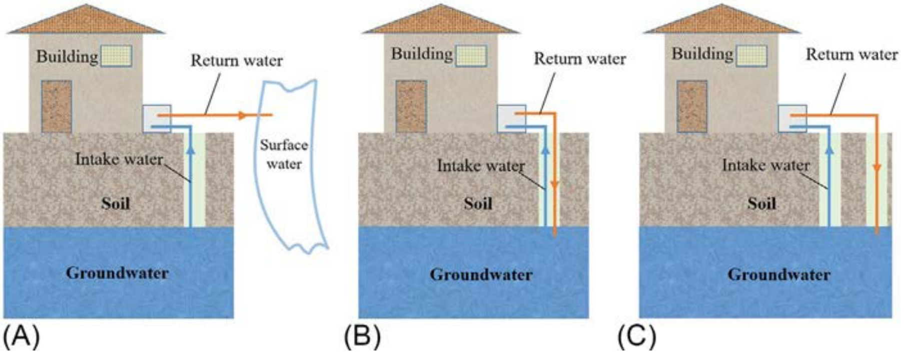

Fig. 8 The typical GWHP systems with different intake and return water modes: (A) Recharge to surface water; (B) Recharge to same well; (C) Recharge to different wells.

In recent years, as an environmental protection, energy-saving, and advanced air-conditioning mode, the GWHP system for building cooling/heating has been developed rapidly in developing countries [43]. However, the system is suitable for the situation where groundwater resources are abundant and the local resource management department allows the exploitation and utilization of groundwater. In addition, the GWHP system requires abundant and stable groundwater resources as a prerequisite. Since the cost of well drilling is not directly proportional to the water intake, the investment benefit of a larger system may be higher. The economy of the groundwater source heat pump system is also closely related to the depth of groundwater. Therefore, before using the GWHP system, it is necessary to make a detailed hydrogeological survey and drill a survey well to obtain the data of underground temperature, underground water temperature, water quality, and water yield, so as to reasonably configure the whole system [44].

4 Common utilization of the UDS system and its current application and development

The UDS system, as an environmentally friendly geothermal energy technology, has been widely used for space cooling/heating in developing countries [45]. The soil can provide a cold/heat source in summer/winter for the flowing air in the buried tube of the UDS system due to the stable soil temperature below a certain depth all the year round. After heat exchange, the air is sent into the building by the fan, to improve the indoor thermal environment and provide fresh air for buildings. In recent years, plenty of researchers have investigated the energy-saving potential of UDS systems for building cooling/heating, which has accelerated the practical application and development of the UDS system in developing countries [46,47].

At present, the UDS system is mainly focused on the theoretical research and practical application research. The theoretical research is aimed at the establishment and calculation of the heat exchange model of the UDS system, and the practical application research is mainly focused on the analysis of influencing factors of the heat exchange capacity of the UDS system and its energy-saving effect in engineering applications. Almost all the results show that the UDS system could effectively reduce building energy consumption and improve the indoor thermal environment. In current studies, the common utilization of UDS systems includes the horizontal UDS system, vertical UDS system, UDS-PCM system, and UDS system-advanced energy-saving technologies. Based on these categories, the application and development of the UDG system for building cooling/heating in developing countries will be investigated and analyzed in the following chapter.

4.1 Horizontal UDS system

The horizontal UDS system is designed with one or more rows of horizontal buried tubes, which is one of the most common shallow geothermal ventilation systems for building cooling/heating. It is commonly known that the buried tube depth of the horizontal UDS system is generally less than 5 m, and the most common buried depth is in the range of 2–4 m [24,48]. The common horizontal UDS system for building cooling/heating is shown in Fig. 9A and B.

The existing studies show that the UDS system with the horizontal buried tubes commonly occupies a large area because of its buried tube structure characteristics. In order to decrease the occupancy area of the horizontal UDS system, Khabbaz et al. [49] proposed a UDS system with three parallel PVC pipes for a residential building cooling in Morocco, which belonged to the hot semiarid climate areas. The horizontal single buried pipe was designed with a 72 m length, 0.15 m diameter, and 2.2–3.2 m buried depth. The schematic diagram of the horizontal UDS system with three parallel PVC pipes is presented in Fig. 10. The results showed that the UDS system was a good semipassive system for building cooling based on the experimental

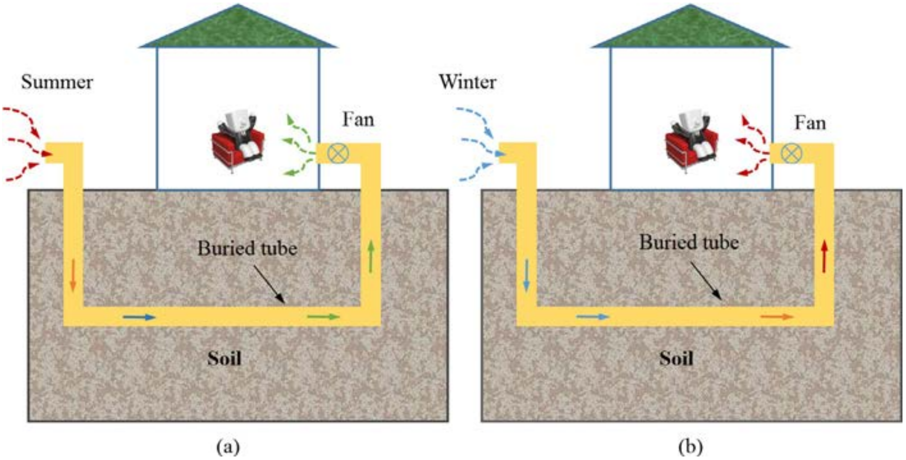

Fig. 9 The common SGV system: (A) cooling in summer and (B) heating in winter.

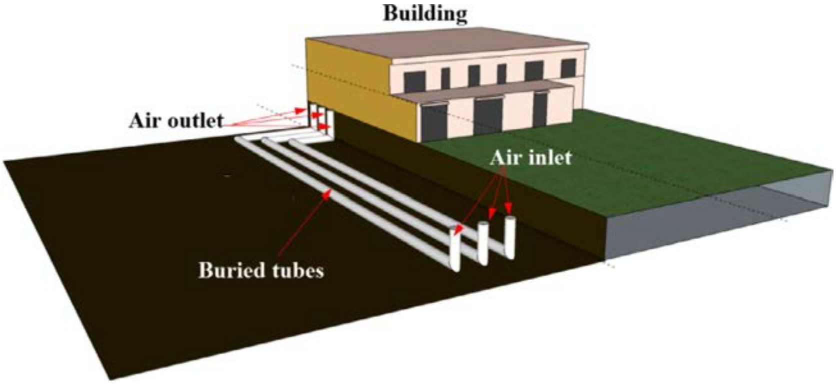

Fig. 10 Schematic diagram of the horizontal UDS system with three parallel PVC pipes. Reprinted from M. Khabbaz, B. Benhamou, K. Limam, P. Hollmuller, H. Hamdi, A. Bennouna, Experimental and numerical study of an earth-to-air heat exchanger for air cooling in a residential building in hot semi-arid climate, Energ. Buildings 125 (2016) 109–121. Copyright with permission from Elsevier.

results. As the outside temperature exceeded 40°C, the indoor environment temperature could still be maintained at about 25°C. The simulation results showed that the UDS system could perform a maximum outlet air temperature drop of around 19.5°C and 18.3°C for the SGV system with one and three buried pipes. When the inlet air temperature was 44.6°C, the achieved specific cooling capacity was 58 and 55 W/m^2 for one pipe and three pipes, and the corresponding outlet air temperatures were 25°C and 26°C.

In the practice application, the multilayer configuration of buried tubes of the horizontal UDS system has also been investigated for building cooling/heating in developing countries. The multilayer configuration is one in which the buried tubes of the UDS system are set one on the other at different depths with an obvious height difference. To explore its thermal performance, Li et al. [50] proposed a novel UDS with double-layer buried tubes, which could be an effective solution to save land occupation. The structure chart of the UDS system is shown in Fig. 11. This UDS system was designed with a buried depth of 2.5 m for the upper tube and 5.0 m for the lower tube. The total buried length was 36 m including the vertical tube, and the corresponding upper and lower tubes were 15.0 and 16.0 m, respectively. Results showed that the maximum indoor temperature and maximum heating capacity using the UDS system were 22.2°C and 7718 W, respectively, and the corresponding average temperature drop was 13.6°C during the cooling operation. In addition, the average annual COP of this proposed system could be calculated as 8.5.

In addition to the efficient application of the UDS system, the current research trend of UDF system is possible to be focused on the development of some simple and accurate models, which makes the simulation calculation of the UDS system more easy to operate and its integrated design with various buildings more feasible.

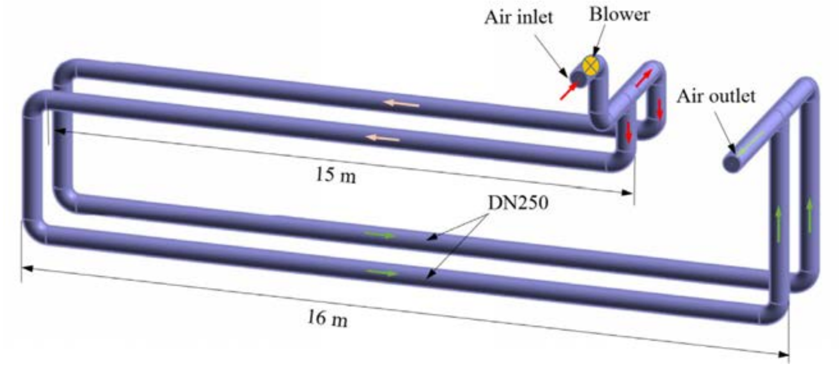

Fig. 11 Structure chart of the UDS system with double-layer buried tubes.
Reprinted from H. Li, L. Ni, Y. Yao, C. Sun, Annual performance experiments of an earth-air heat exchanger fresh air-handling unit in severe cold regions: operation, economic and greenhouse gas emission analyses, Renew. Energy 146 (2020) 25–37. Copyright with permission from Elsevier.

Minaei et al. [51] developed a new transient model based on a thermal resistance capacity circuit to evaluate the system's performance and assess the transient heat transfer of flowing air in the tube. The calculated results of the model were compared with the experimental and numerical results with good agreement between them. Using this model, the effects of buried depth, air velocity, and system operation strategy (continuous or intermittent) on the cooling/heating potential of the UDS system were studied further. Compared to the continuous operation mode, the intermittent operation mode can restore the system's cooling capacity in summer and heating capacity in winter, which indicates that shortening the daily operation time would be instrumental in improving the heat recovery rate of the system, so as to improve the system's thermal performance.

4.2 Vertical UDS system

The vertical UDS system is not a new concept which has been mentioned in previous studies. Its main feature is that all the underground buried tubes are set vertically with a falling gradient of 90°. The depth of buried tubes is generally more than 10 m; the soil temperature at this depth is basically stable at 18–20° all the year round in various areas due to its not being commonly affected by the outdoor climate conditions and weather variations [52]. However, the research on the application of vertical buried pipe systems in buildings is rarely involved in the previous literature; the possible reason is that the UDS system with vertical buried tubes owns a relatively high construction cost in its practical application. Based on the existing literature, Zhengxuan Liu and his research team may be the first to attempt to carry out the experimental and numerical research on the application of the UDS system with vertical buried tubes in developing countries [52,53]. Their study concluded that the vertical UDS system had several apparent advantages of small land occupation, high energy efficiency, and timely discharge of condensate, compared to the conventional UDS system with the horizontal buried tubes [54,55]. These advantages can effectively increase the application scope of the UDS system and the application effect under different working conditions in buildings.

Concerning the practical application effect of the vertical UDS system, Liu et al. [53] conducted a series of studies to investigate its temperature regulation capacity, cooling/heating potential, and economic feasibility. The schematic diagrams and construction pictures of the vertical UDS system are presented in Fig. 12. Results show that the vertical UDS system had a great energy-saving potential in the practical

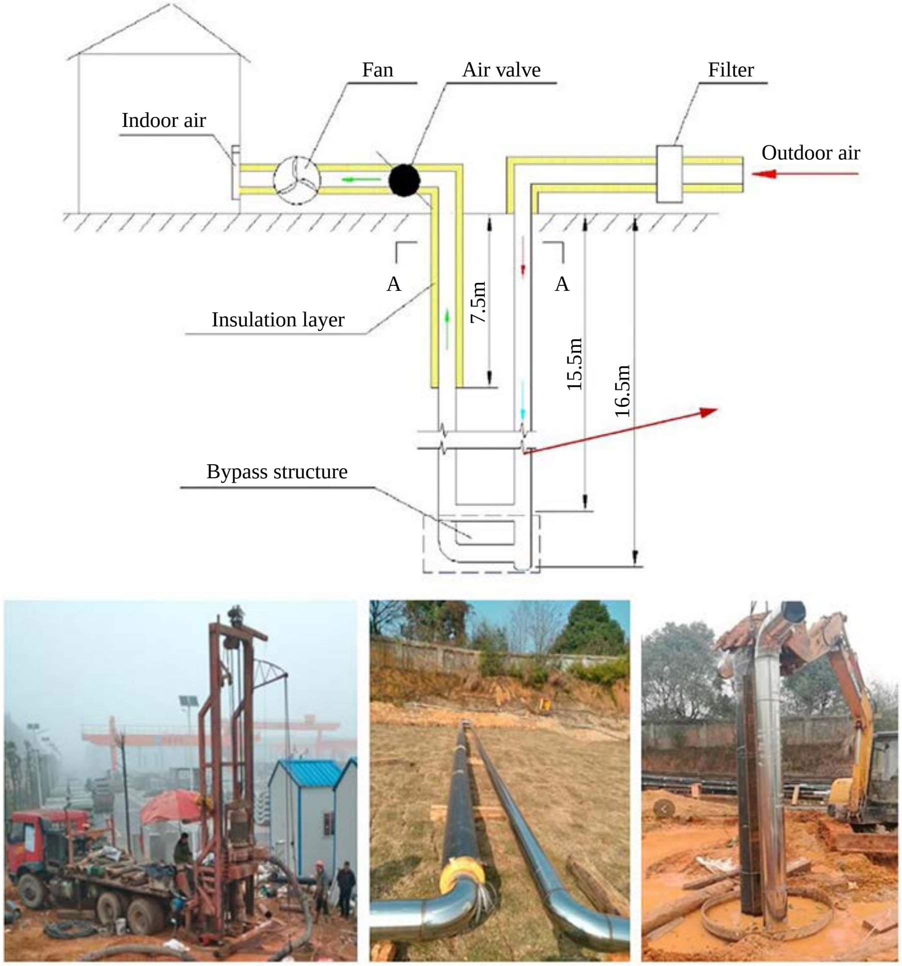

Fig. 12 The schematic diagrams and construction pictures of the vertical UDS system. Reprinted from Z. Liu, Z. Yu, T. Yang, L. Roccamena, P. Sun, S. Li, et al., Numerical modeling and parametric study of a vertical earth-to-air heat exchanger system, Energy 172 (2019) 220–231. Copyright with permission from Elsevier.

application of buildings, which could provide a quite good cooling effect in summer and preheating capacity in winter for the various buildings. Specifically, as the outside air temperature exceeded 39°C, the outlet air temperature of the proposed system was still in the range from 22.4°C to 24.4°C at the air velocity of 1 m/s in summer. In winter, the outlet air temperature would remain from 16.0°C to 18.0°C. For the proposed system, for a given economic life span of 20 years, its energy payback time and carbon dioxide emission mitigation potential were calculated as 8.2 years and 7170.42 kg, respectively. In addition, the monetary payback period of the proposed system was calculated as 17.5 years. The above results demonstrate the thermal performance feasibility and economic viability of the vertical UDS system for building cooling/heating in summer/winter.

4.3 UDS-PCM system

Phase change material (PCM) absorbs and releases huge latent heat during its phase change process, which has been widely used in various systems to improve the overall performance [2]. Therefore, the UDS integrated PCM (UDS-PCM) system is suggested to be a meaningful attempt to effectively improve the performance of the UDS system for building cooling/heating in developing countries. For nearly 2 years, some researchers had explored the effects of phase change energy storage on the thermal performance of UDS systems [55,56]. These works are mainly divided into two types: one is that reducing the outlet air temperature fluctuation of the UDS system by integrating the PCM in the ventilation system, to improve the thermal comfort of the buildings. Another is that the PCM was installed around the buried tubes to improve the energy storage capacity of the surrounding medium and the supplied cooling/heating capacity of the UDS system.

Liu et al. [57] explored the vertical UDS system integrating the annular PCM component to evaluate its thermal performance in hot summer and cold winter areas in China. In this coupled system, the annular PCM component was installed from the outlet to 3.6 m depth inside the vertical buried tube. The schematic diagram and site construction pictures of the vertical UDS-PCM system are presented in Fig. 13. Results showed that the annular PCM could effectively decrease the air temperature fluctuation at the outlet of the UDS-PCM system. Specifically, compared to the UDS system without PCM, the annular PCM component used around the outlet of the UDS system could decrease the outlet air temperature fluctuation by 31% and 29% under air velocities of 1 and 2 m/s. In addition, the static payback period of the UDS-PCM system was calculated as 20.8 years.

For the application of another layout of the phase change energy component, Zhou et al. [58] proposed a UDS system integrating the PCM set around the buried tube to explore its effects on the energy consumption and cooling/heating potential in buildings. In this coupled system, the PCM was filled between the tube and soil, and the schematic diagram of the UDS-PCM system is shown in Fig. 14. Results showed that the UDS-PCM system had a better performance for building cooling with an improvement of about 20.24% in summer, compared to the conventional UDS system. A similar PCM structure was discussed by Liu et al. [59] to investigate the impacts of design

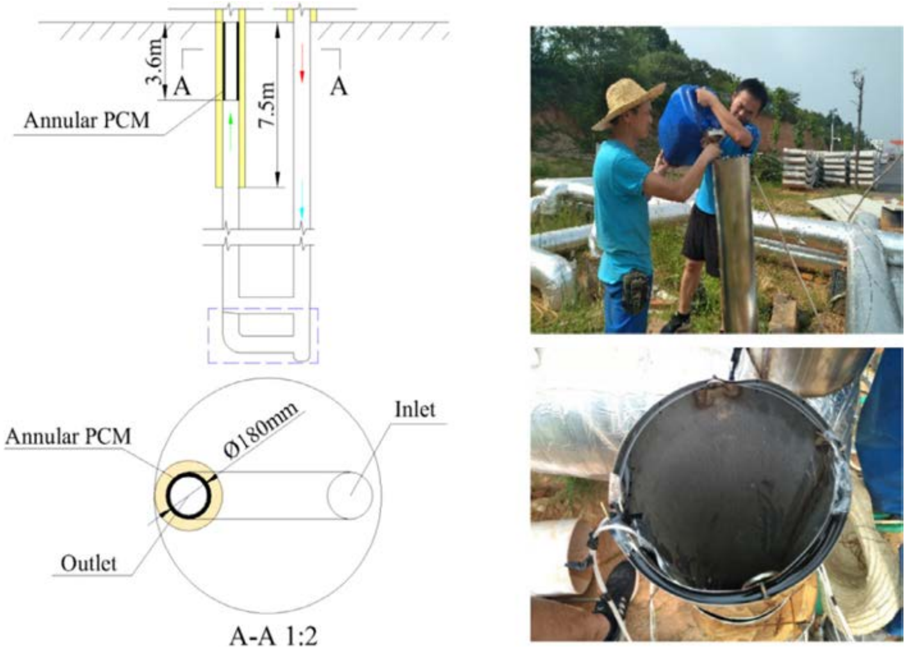

Fig. 13 The schematic diagram and site construction pictures of the vertical UDS-PCM system. Reprinted from Z. Liu, Z. Yu, T. Yang, M. El Mankibi, L. Roccamena, Y. Sun, et al., Experimental and numerical study of a vertical earth-to-air heat exchanger system integrated with annular phase change material, Energy Convers. Manag. 186 (2019) 433–449. Copyright with permission from Elsevier.

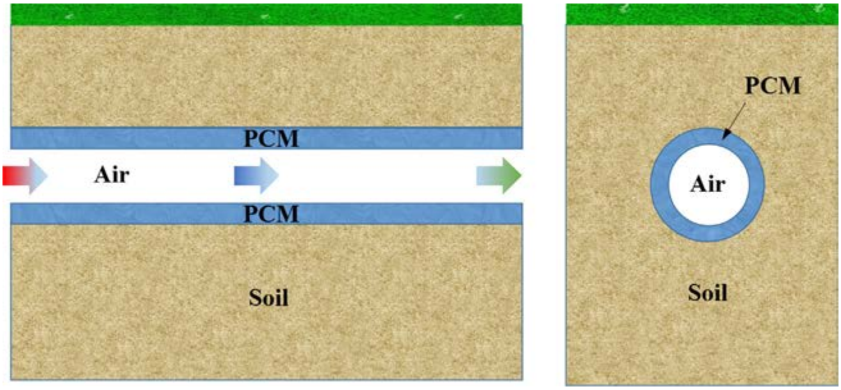

Fig. 14 The schematic diagram of the UDS-PCM system.
Reprinted from Q. Liu, Y. Huang, Y. Ma, Y. Peng, Y. Wang, Parametric study on the thermal performance of phase change material-assisted earth-to-air heat exchanger, Energ. Buildings 238 (2021) 110811. Copyright with permission from Elsevier.

and operation parameters on the system's thermal performance. The results indicated that the most suitable air velocities for improving the heat transfer performance of the UDS-PCM system were 4.5 and 6.8 m/s for the charging and discharging processes. In addition, the authors recommended applying the UDS-PCM system to some new and existing buildings in China.

4.4 UDS-advanced energy-saving technology system

At present, some research works on the UDS system integrating solar chimney and solar photovoltaic/thermal (PV/T) have been conducted to broaden the application scope and energy efficiency of UDS systems in buildings. The research on the coupling technology of the UDS system and the solar chimney system has been conducted in some studies. The common operational principle of the UDS-solar chimney system can be seen in Fig. 15. In this system, the solar chimney could provide the power for the UDS system [60]. Specifically, when solar radiation irradiates the glass cavity of the solar chimney, the air in the cavity will be heated. The density of hot air is lower than that of cold air, and thus the hot air with low density can be promoted from the bottom to the top in the cavity. The migration of hot air will lead to the wind pulling effect in the solar cavity, which will drive the UDS system to inhale outdoor air and maintain the indoor air pressure balance. When the outdoor hot air is sent to the underground buried tubes of the UDS system, heat exchange between the flowing air and underground soil occurs to provide fresh cold air for the indoor environment of the building [61].

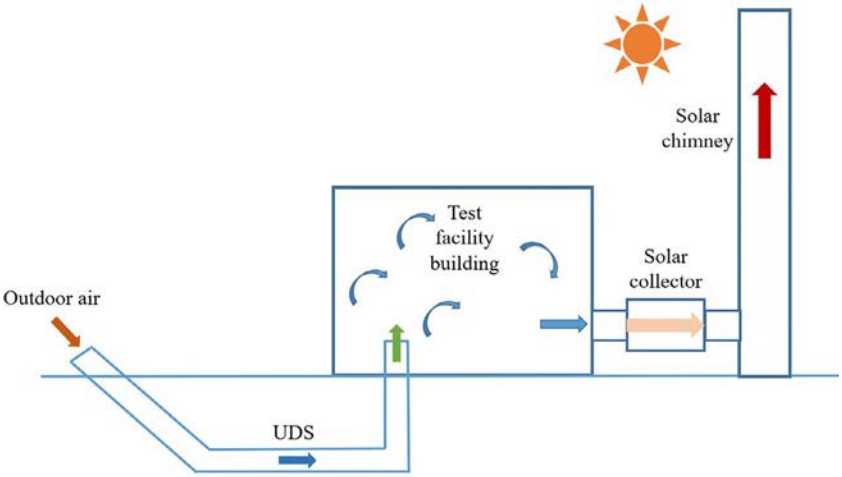

Fig. 15 Schematic diagram of the UDS system integrating solar chimney system. Reprinted from H. Li, Y. Yu, F. Niu, M. Shafik, B. Chen, Performance of a coupled cooling system with earth-to-air heat exchanger and solar chimney, Renew. Energy 62 (2014) 468–477. Copyright with permission from Elsevier.

Maerefat et al. [61] investigated the coupled system between the UDS and solar chimney to analyze its thermal performance under the different solar radiations, outdoor air temperatures, and design configurations. Results showed that the solar chimney could supply enough power for the UDS system in the daytime without any power. In addition, the reasonable design of the coupled system could provide the indoor thermal comfort environment for several hours in hot summer. Serageldin al. [62] proposed a passive cooling/heating and ventilation system between the UDS system and solar chimney to investigate the indoor temperature and thermal energy performance in Egyptian conditions. Results showed that the proposed coupled system could attain a temperature drop of around 9 °C for indoor environments in summer. The total annual electrical energy was 42.9 kWh/m^2 and the corresponding carbon dioxide emission saving was 4.545 tons/year.

In recent years, the coupled technology of the UDS system and solar photovoltaic has been applied for improving the thermal environment of buildings in developing countries, especially for greenhouse buildings [63]. Nayak et al. [64] developed a simplified numerical model to explore the year-round effectiveness of the coupled system between the UDS system and solar photovoltaic/thermal (PV/T) for cooling/heating of the greenhouse in New Delhi, India. Results showed that the indoor temperature could be increased by 7–8°C using the UDS system coupling with the PV/T system in winter. The generated effective heat energy of the coupled system was 33 and 24.5 MJ in daytime and nighttime. In addition, the year-round heating capacity and net electrical energy saving of the coupled system were calculated as 24,728.8 and 805.9 kWh, respectively.

5 Common utilization of the abandoned wells energy system and its current application and development

With the progress of industrial development, emerging natural resource extraction wells have appeared all over the world. When petroleum or natural gas reservoirs are depleted beyond an economically feasible point, the wells are abandoned, decommissioned, and reclaimed. When the petroleum/gas wells are estimated to be economically unfeasible, they would be abandoned and would be referred to as "dry" wells. Abandoned petroleum/gas wells are an enduring liability to the companies that drill them, as the specific company is responsible for the possible environmental contamination and litigation in the case of a failed decommissioning of a well [65].

Generally, petroleum and gas wells are abandoned once they become depleted or unprofitable. According to the research of Caulk et al. [66], there were about 147, 127 wells indicated as abandoned, plugged, and buried in the United States. The number of abandoned wells produced in developing countries cannot be ignored. According to the research of Mehmood et al. [67], approximately 60% of total abandoned oil wells (AOWs)/abandoned gas wells (AGWs) dried in Pakistan were nonproducing. Therefore, there is great potential to utilize the geothermal energy of the AOWs /AGWs.

The cost of decommissioning a well is high. If an AOW/AGW is treated improperly, it will adversely contaminate the surrounding environment [68]. One effective and environmental way to mitigate this problem is integrating the heat exchangers in the AOW/AGW to extract geothermal energy. Compared to the conventional vertical pipes, utilization of the drilled wells could improve the energy utilization by utilizing the high ground temperatures at deeper depth, which reaches up to 5000m below the ground surface. According to Augustine et al. [69], the wells were drilled to 5000m in 2003 at a cost of $ 5 million per well. As the drilling costs account for 42%–95% of the total enhanced geothermal system power plant costs, it is extremely valuable to take advantage of the predrilled and extendable abandoned wells.

5.1 Application of the AWE system

This section presents the current situation and the prospects of using AOW/AGW all around the world for harvesting geothermal energy. Investigations on the suitability of utilizing the abandoned wells all around the world for enhanced geothermal systems are presented. Specifically, there are three categories, i.e., geothermal heat pump system, electric generation, and indirect heating for desalinating produced water.

5.1.1 Geothermal heat pump system

The AOWs/AGWs have rich geothermal energy due to the relatively higher bottom-hole temperatures; thus, they can be retrofitted to be the ground heat exchangers integrated with the geothermal heat pump systems. Compared with the conventional vertical pipes, the energy extracted from a single drilled well would be significantly improved and maximized by exchanging energy with high ground temperatures. Nian et al. [70] numerically explored the thermal performance of a 3000m AOW, heating a

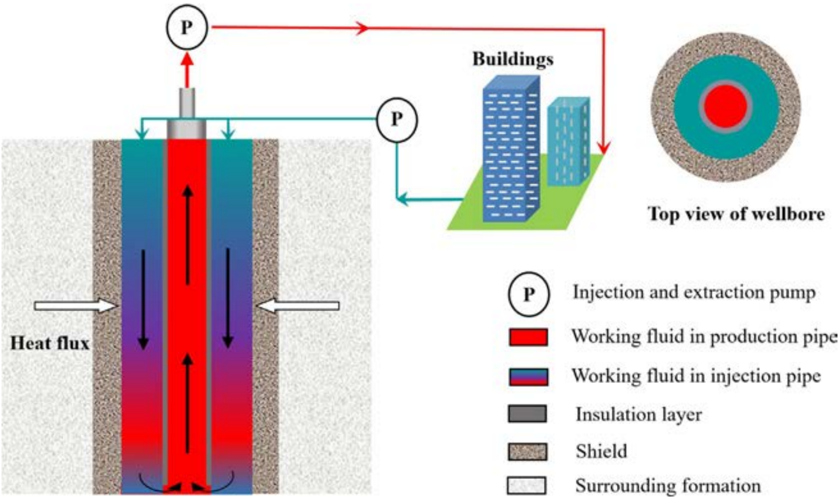

Fig. 16 Schematic diagram of geothermal heating from an abandoned oil well. Reprinted from Y.-L. Nian, W.-L. Cheng, Evaluation of geothermal heating from abandoned oil wells, Energy 142 (2018) 592–607. Copyright with permission from Elsevier.

building with an area of 10,000 m^2. Fig. 16 shows the schematic diagram of the system. By utilizing the novel system, the building's indoor temperature of around 26°C is achieved when the HTF flow rate is set as 20 m^3/h. Moreover, the system could heat a maximum area of 11,000 m^2 and the bottom-hole temperature could recover to a steady-state 1 year apart. Annual heating production is about 5.5×10^{12} J during the entire heating period. Moreover, it has a reduction of 457 tons as the carbon dioxide emission is considered. It is delighted to find that the largest annualized cost of the novel system was approximately 50% of that of a conventional heating system.

Sun et al. [71] numerically explored the carbon dioxide circulating in a geothermal horizontal well, with the diagram shown in Fig. 17. Based on the parametric study of the injection parameters on the geothermal productivity, it is concluded that the standard of choosing parameters for measuring the rate of geothermal production was related to the parameter reflecting the heat transfer rate or fluid temperature rise. Moreover, a small mass injection rate and pressure are recommended to achieve better economic performance.

Moreover, Gharibi et al. [72] demonstrated the feasibility of utilizing the AOW as a geothermal resource. Based on the parameters of a real AOW in southern Iran, a 3-D numerical model of a U-tube heat exchanger was developed and simulated. In addition, an optimization study was conducted based on the parametric study of mass heat flow, fluid inlet temperature, insulation length, and pipe diameter. Results showed that

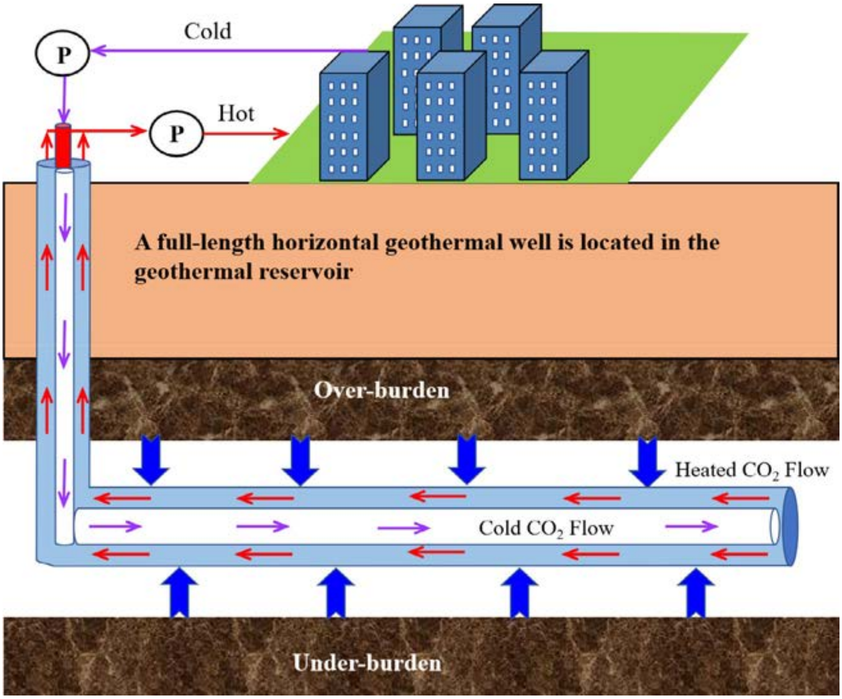

Fig. 17 Heat transfer fluid circulating in the full-length horizontal geothermal well. Reprinted from F. Sun, Y. Yao, G. Li, X. Li, Geothermal energy extraction in CO_2 rich basin using abandoned horizontal wells, Energy 158 (2018) 760–773. Copyright with permission from Elsevier.

the proposed heat exchanger worked steadily in a long-term operating period. In the case with 288.16 K inlet temperature and 0.03 m/s inlet velocity, the outlet temperature reached 324.73 K in the first year and the temperature rise declined 0.6 K after 5 years.

5.1.2 Geothermal power generation system (GPGS)

Besides the direct utilization of geothermal energy for building heating, research on the utilization of power generation has been carried out based on the principle of the organic Rankine cycle. Cheng et al. [73] enhanced the geothermal utilization efficiency by developing thermal reservoirs. The structure diagram of the geothermal power system cycle is shown in Fig. 18. Results showed that the thermal reservoirs could enhance the geothermal utilization efficiency of the AOWs and steadily maintain the comprehensive power generation efficiency at about 13%.

Cheng et al. [74] explored the feasibility of applying the AOW for GPGS by using the organic Rankine cycle. Results showed that the geothermal energy from the AOWs with a well deeper than 3000 m and a geothermal gradient higher than 0.04 K/m would be worth exploring. Similar works were conducted by Bu et al. [75], where the AOW, serving as a heat exchanger, was utilized to extract geothermal energy. In addition, parametric studies were conducted to reveal the regulation of the recommended values of the main parameters. They pointed out that the flow rate of the fluid and the geothermal gradient have an ignorable impact on the geothermal energy extracted from the abandoned wells. Moreover, a distance between adjacent wells of 40 m is recommended to avoid thermal interference. With an optimal setting, there is 36,833.26 US $/year saving, taking the electricity cost into account.

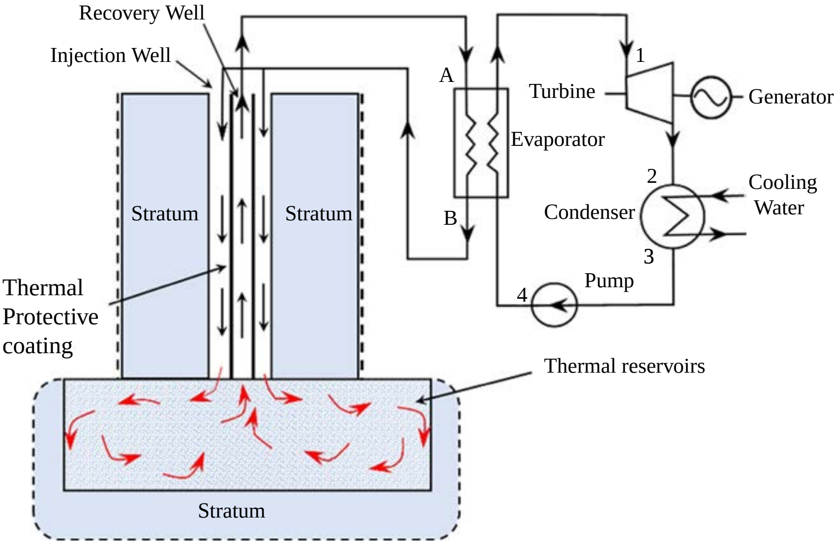

Fig. 18 Schematic diagram of geothermal power generation using AOW/AGW.
Reprinted from W.-L. Cheng, J. Liu, Y.-L. Nian, C.-L. Wang, Enhancing geothermal power generation from abandoned oil wells with thermal reservoirs, Energy 109 (2016) 537–545. Copyright with permission from Elsevier.

Wight and Bennett [76] proposed and evaluated an approach using water as the wellbore fluid in combination with abandoned wells and a closed wellbore. The wellbore was therefore used as a coaxial borehole heat exchanger. A total of 2500 wells in Texas are set as the research object, using the geothermal gradient and surface temperature. By using the binary cycle power plant with a multistage heat exchanger, a net power figure of 109–630 kW was obtained. Harris et al. [68] numerically explored the outlet temperatures and heat extraction rates from the system based on a given geometry organically Rankine cycle. It specifically pointed out that 2 MW of thermal energy and 200 kW of power could be generated with 4000 m deep vertical wells and a 4800 m horizontal section. In addition, these wells could function as the heat source for GPGS for several decades.

To give a wide range of power generation rates in different scenarios, Table 2 summarizes the studies conducted in previous research.

5.1.3 *Desalinating produced water system*

Another notable function of the abandoned wells is the desalinating produced water system. By retrofitting the AOW into geothermal wells, low-temperature geothermal resources in the abandoned wells could be used to desalinate produced water. A schematic diagram of the system is shown in Amin et al.'s [83] research, as shown in Fig. 19. The produced water stream was treated on the ground surface and would no longer be injected back into the retrofitted geothermal well or the closed-loop flow system. The extracted hot water from the abandoned wells provided the powers for the desalination unit. It was positively proposed that the generated clean water represents a constant and resilient source of freshwater, which could be used for continued oil/gas operations, agriculture and to meet the nonpotable municipal demands.

Table 2 Classical GPGS application integrated with AWs in previous literature.

Author	Net power	Depth	Geo. gradient	Study length
Kujawa et al. [77]	140 kW	3950 m	25°C/km	1 year
Davis and Michaelides [78]	3.4 MW	3000 m	42°C/km	–
Cheng et al. [74]	239 kW	6000 m	50°C/km	300 days
Noorollahi et al. [79]	133 kW	3861 m	29.6°C/km	Not listed
Wight and Bennett [76]	217 kW	6000 m	50°C/km	300 days
Feng et al. [80]	350 kW	–	–	30 years
Alimonti and Soldo [81]	121 kW	5800–6100 m	23°C/km	1 year
Harris et al. [68]	2 MW	4000 m	–	Several decades
Kharseh et al. [82]	11 kW	4000–7000 m	11–30°C / km	25 years

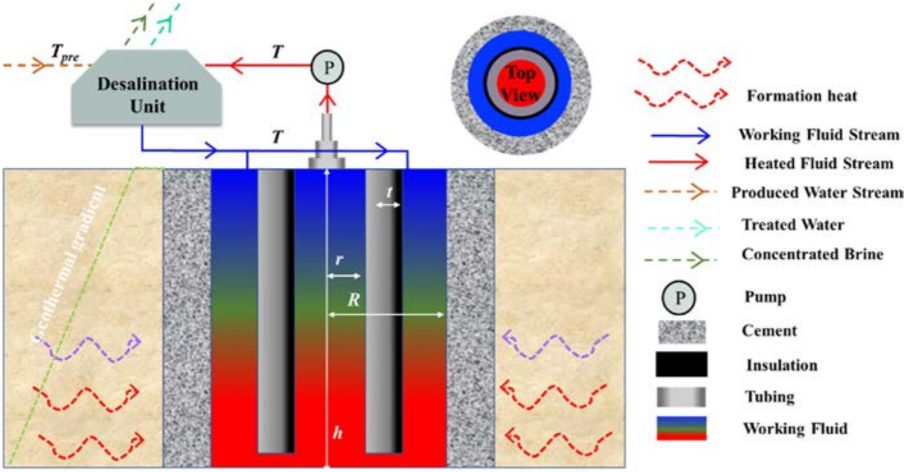

Fig. 19 Schematic diagram of a retrofitted geothermal well and its associated closed-loop flow system.
Reprinted from A. Kiaghadi, R.S. Sobel, H.S. Rifai, Modeling geothermal energy efficiency from abandoned oil and gas wells to desalinate produced water, Desalination 414 (2017) 51–62. Copyright with permission from Elsevier.

5.2 Influential of geothermal utilization efficiency

The benefits are ubiquitous, and the only drawback is the challenging optimization of design and operating parameters [66]. Therefore, parametrical or optimization studies should be carried out to guarantee the maximum utilization of geothermal energy. According to previous research, parameters affecting the heat transfer rate are generally summarized in Fig. 20. The influential parameters include three categories, namely geometry parameters, geothermal parameters, and working parameters.

In the research of Caulk et al. [66], it was found that the flow rate has a negative impact on the temperature rise but a positive effect on the COP. Specifically, it shows that the COP was larger with moderate flow rates and greater depth. Operating parameters such as the geo-flow rate, heat extraction rate, the temperature difference

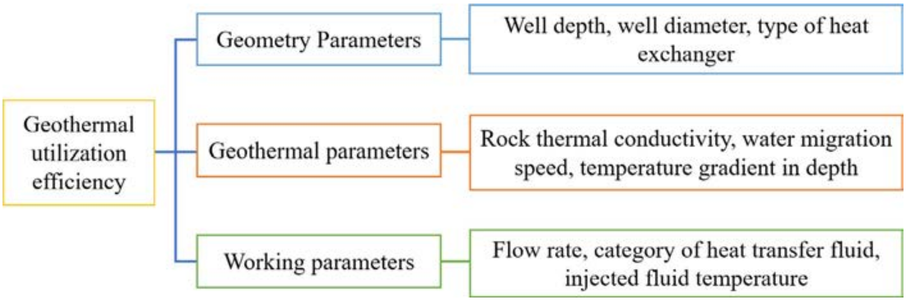

Fig. 20 Influential parameters of AW energy.

between the HTF inlet and outlet are the main parameters when exploiting the geothermal resource. Nian and Cheng [25] specifically explored the optimal working parameters to make maximum utilization of the geothermal resource for power generation. Especially, the maximum electricity generation during 25 years in Qatar could be achieved based on the heat extraction rate of 275 kW, the geofluid flow rate of 3.7–4.4 kg/s, and the temperature difference between the well's inlet and outlet of 15–17°C.

Similarly, Hu et al. [28] found that the performance of heat exchangers can be controlled by varying the injected flow rate, temperature, and thermal conductivity of the pipe container. Based on their investigation, it was concluded that there was great potential for utilizing the energy using the coaxial borehole heat exchangers.

6 The existing issues and in-depth analysis on the practical application of geothermal energy for building cooling/heating

In recent years, the GCHP system is one of the fastest-growing and most popular forms of the heat pump industry in developing countries, because it is relatively less restricted by some conditions. The difficulties in the development of the GCHP system mainly focus on the thermal response experiment as well as the unbalanced cold and heat extraction. In terms of the thermal response experiment, many countries necessitate it when the application area exceeds a particular threshold (e.g., more than 5000 m^2 in China), although there are currently few GCHP projects that have been executed according to the standards [84,85]. In some developed countries such as Europe and the United States, GCHP system is mainly used in commercial buildings and single residential projects. The thermal response test is required if the GCHP system is utilized in commercial buildings. Single residential projects, on the other hand, are not subject to any required standards. Furthermore, in the practical use of the GCHP system, the heat and cold balance is a critical concern. Some existing projects in diverse developing countries do not conduct yearly load calculations or balance calculations of annual heat emission and absorption during the system design stage. As a result, after 2 or 3 years of system operation, some flaws began to appear in many projects [86].

For the GWHP system, if there is no reliable recharge measure, it will cause serious consequences. The geological problems such as ground subsidence, ground fissure, and ground collapse caused by large-scale exploitation of groundwater are becoming increasingly prominent [87]. For the GWHP system, if 100% groundwater recharge to the original aquifer is implemented in strict accordance with the requirements of the government, the supply and supplement of groundwater is balanced overall, so the ground subsidence will not be caused by pumping and irrigating groundwater. However, in the practical application, because the plugging problem of recharge has not been fundamentally solved, the groundwater may be directly discharged from the surface. Once the geological environment problems appear, they are often catastrophic and irreparable.

It can be seen from the above review that the UDS system with horizontal buried tubes is still the most common form of shallow geothermal ventilation for effectively reducing building energy consumption and improving the indoor thermal environment in developing countries. However, the most controversial problem in the practical application of the UDS system is how to solve the condensation water produced on tube walls in summer [20]. If the condensate on the tube wall for a long time cannot be solved in time, it will lead to the problem of mold breeding in the tube, thus affecting the air supply quality of the UDS system. At present, many researchers propose to increase the gradient of buried tubes so that the condensate can be concentrated in a certain position of the pipeline for centralized treatment. In practical application, some scholars set the gradient of the buried pipeline as 1–5°. Obviously, the gradient of the buried tube is relatively small, so it is still difficult to drain the condensate on the tube wall timely. However, the increase of the buried tube slope will greatly increase the construction cost and difficulty. In addition, the commonly used UDS system with horizontal buried tubes covers a large area, especially for the single row buried tube system. The foundation pit area of the UDS system with horizontal buried tubes is usually more than $50\,m^2$, which will greatly limit the use of the horizontal buried pipe system in areas with high building density [88,89]. Although some researchers have proposed using the multirow or multilayer buried tube system to solve this problem, its land occupation area is still large, and the construction cost will also increase greatly.

To solve the issue of the UDS system with horizontal buried tubes, Liu et al. [52,54] proposed the UDS system with vertical buried tubes to reduce the energy consumption and improve the indoor thermal environment of buildings in China. The UDS system with vertical buried tubes has a relatively small floor area (the foundation pit area is usually less than $1\,m^2$) and a large buried tube slope of 90°, which is conducive to condensing timely centralized treatment. However, the practical application has proved that the construction cost of a UDS system with vertical buried tubes is relatively high. Therefore, the following studies should be carried out, mainly on how to solve the condensate treatment problem of the UDS system with horizontal buried tubes timely and how to reduce the construction cost of the UDS system with vertical buried tubes.

Many abandoned wells in developing countries present an opportunity for the development of low-cost renewable geothermal energy. However, according to the previous literature, it remains several challenges for further utilization [25]. The prediction of hydraulic fractures in various stress regimes remains to be solved. Moreover, continuous effort is required to estimate the influence of thermal gradient and lithology on heat force and heat exchange rate per unit length. In addition, the benefits of utilizing the AWE were ubiquitous with the prerequisites that the designing parameters are optimized. Therefore, more studies should be carried out to optimize the design and working parameters to take the largest advantages of geothermal energy. Specifically, for the application of power generation, economic optimization should be carried out for the power plants using AOW due to its high cost.

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