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# Evaluating the long-term sustainability of geothermal energy utilization from deep coal mines

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ABSTRACT

Deep underground mines offer a great potential as low-enthalpy geothermal resource to be adopted in direct regional heating. In this paper, a parallel horizontal ground heat exchangers (pHGHE) system is introduced to utilize the geothermal resource in deep coal mines, however, the sustainability of the system in a long-run performance has not been well addressed in the previous study. This work presented a quantitative evaluation on the long-term sustainability of pHGHE system installed in backfilled stopes of deep coal mines. A novel numerical model is applied to characterize the heat transfer occurring between the horizontal pipes and backfill stopes. The proposed model was first verified to an analytical solution to determine the model reliability and accuracy. The validated numerical model was further applied to a typical underground backfilled stope of Anju coal mine in China. The results demonstrated that the maximum sustainable specific heat extraction rate must not exceed 40 W/m to maintain a 50-year exploitation period. A total thermal capacity of 17 GWh could be realized during each extraction cycle under the current conditions, which could provide heating to more than 170,000 m$^2$ of residential building area. Accordingly, sensitivity analysis was performed to identify the key parameters influencing system sustainability. In addition, the effects of groundwater flow on the thermal interaction and long-term sustainability of the pHGHE systems were examined. Groundwater flow can be beneficial to the long-term sustainability of the system.

This work confirms the feasibility and sustainability of geothermal resource utilization in backfill stopes of underground coal mines. The insights gained in this study can provide technical guidance for the design of geothermal systems in similar coal mines.

## 1. Introduction

In recent decades, fossil fuel has served as the principle energy source for space heating purposes in numerous countries worldwide. Particularly in China, a heavy dependence on coal for heating purposes occurs, accounting for 83% of the overall heated area (Li et al., 2020). To achieve Carbon Neutrality aims, a notable reduction in energy cost and carbon footprint is expected stemming from the utilization of renewable energy. In recent years, many deep coal mines in China have depleted their resources, and hence about to be closed. A great deal of underground open space remains after mining, which comprises shafts, tunnels and backfilled stopes. These mined-out areas are sometimes flooded with water from rainfall or groundwater. Due to their relatively high temperature, the deep mine-out areas have been considered as good geothermal resources for building heating (Fraser-Harris et al., 2022). Geothermal energy is an environmentally friendly and sustainable energy. It has been widely adopted in China for regional heating purposes as a clean and economical option. Therefore, geothermal energy extracted from deep coal mines exhibits a great potential as an environmentally friendly heat source (Thomas, 2017).

Geothermal energy recovery from underground coal mines offers

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## Nomenclature

*Roman letters*

| | |
|---|---|
| $A$ | the variation amplitude of the temperature at the surface °C |
| $c$ | specific heat capacity J kg$^{-1}$ K$^{-1}$ |
| $H$ | heat source/sink W m$^{-3}$ |
| $L$ | the pipe-to-pipe distance m |
| $q$ | heat flux W m$^{-2}$ |
| $R$ | thermal resistance K W$^{-1}$ |
| $S$ | specific exchange area m$^2$ |
| $T$ | temperature °C |
| $t$ | time ss |
| $t_p$ | wall thickness of the pipe m |
| $u$ | fluid circulation velocity m s$^{-1}$ |

*Greek letters*

| | |
|---|---|
| $\beta$ | the longitudinal heat dispersity coefficient m |
| $\Phi$ | heat transfer coefficient W m$^{-2}$ K$^{-1}$ |
| $\rho$ | density kg m$^{-3}$ |
| $\Lambda$ | the hydrodynamic thermos dispersion of the circulating water W m$^{-1}$ K$^{-1}$ |
| $\lambda$ | thermal conductivity W m$^{-1}$ K$^{-1}$ |

*Superscripts*

| | |
|---|---|
| $r$ | the circulation water |
| $f$ | fluid |
| $s$ | solid |

*Subscripts*

| | |
|---|---|
| $k$ | pipelines(k=inlet /outlet) |
| $s$ | surrounding coal mine |

*Abbreviation*

| | |
|---|---|
| BHE | Borehole Heat Exchange |
| FE | Finite element |
| GMRES | Generalized Minimal Residual |
| OGS | OpenGeoSys |
| pHGHE | parallel horizontal ground heat exchangers |

remarkable advantages. (1) Major economic profits could be achieved since no additional drilling costs are incurred. The exploitation of geothermal resources from coal mines for regional heating could offset notable economic costs. (2) *Via* the exploitation of geothermal resources in underground mine areas, the temperature in these areas is reduced, leading to further prevention of the thermal damage risk.

The application of geothermal energy extracted from mines started in the 1980s (Farr et al., 2016). One of the pioneering studies in geothermal heat mining involves the Springhill project in Canada (Ghoreishi Madiseh et al., 2012). Mine water with a relatively high temperature was applied to heat a factory with an approximate surface area of 14,000 m$^2$. One of the most successful projects involving mine-water utilization is located in the municipality of Heerlen, the Netherlands, where a low-temperature district heating system has been in operation since 2008 (Ferket et al., 2011). This mine-water project has been upgraded to a full-scale hybrid sustainable energy structure denoted as Mine Water 2.0 (Verhoeven et al., 2014). A typical flooded mine in the Upper Peninsula of Michigan, USA, was established to examine the use of mine water to heat a 15,000 ft$^2$ (1394 m$^2$) building (Bao et al., 2019). Over the last decade, numerous demonstration projects have been established in the UK to evaluate the use of geothermal energy extracted from abandoned coal mines (Burnside et al., 2016). Mine water originating from the Markham Colliery is now used to heat site buildings in Markham, the UK, through a ground source heat pump (GSHP) (Banks et al., 2019). Attempts to transform underground coal mines into geothermal resources in China started in the 21st century, and currently, most of the project implementations remain at the planning stage. A geothermal recycling system has been built in the Zhang Shuanglou deep coal mine, China, for the purpose of both cooling and heating (Guo et al., 2017). For a detailed summary of the existing projects worldwide, the reader may refer to the review articles by Hall et al. (2011) and Ramos et al. (2015).

Generally, geothermal heating systems installed in coal mines can be categorized into two distinctive types, namely, open and closed-loop geothermal systems. To date, most aforementioned projects are open-loop types, in which underground water is extracted to the surface from underground mine cavities. Research has extensively focused on the thermal performance of the open-loop geothermal energy extraction process (Loredo et al., 2016). A 3D numerical model has been built to simulate groundwater flow and heat transfer in a flooded mine in Canada, and further optimization has been conducted to improve the maximum heat extraction rate (Raymond and Therrien, 2014, 2008). Rodríguez and Díaz (2009) presented a semiempirical analysis of the utilization of mine galleries as geothermal heat exchange conduits for space heating based on a doublet mine-water extraction-reinjection form. Guo et al. (2018) estimated the geothermal potential in abandoned coal mines with a dual-porosity model considering the effects of fractures. Perez Silva et al. (2022) conducted numerical simulation to assess the seasonal thermal energy storage and recovery potential in flooded coal mines, and a financial analysis is made to reveal the economic perspective of this technology.

Although open-loop systems are scalable and sometimes more efficient, they are sometimes related to certain environmental risks (Banks and Banks, 2001). Mine-water pumping and reinjection may lead to pressure buildup, which may cause mine shaft failure. Furthermore, mine water usually includes abundant mineral components originating from coal, such as pyrite. The oxidation of pyrite results in the acidic mine water and has a potential risk to pollute soil or groundwater (Banks et al., 1997). In contrast, increasing attention has been paid to closed-loop geothermal systems (Banks et al., 2019), in which mine water is not directly in contact with the rocks but exchange heat *via* a vertical or horizontal clean-water circulation loop (Lund et al., 2004). In particular, mined-out stopes offer a great opportunity to install heat exchange tubes prior to backfilling. Ghoreishi-Madiseh et al. (2015) developed a novel idea involving the installation of vertical geothermal heat exchange tubes in backfilled mine stopes for geothermal heat extraction. More recently, the horizontal ground heat exchange (HGHE) system are becoming more widely applied. Li et al. (2020) proposed the installation of horizontal heat exchange pipes in mined-out backfill stopes in combination with seasonal thermal heat storage. Zhang et al. (2020) established a numerical model in Fluent software to assess the heat release performance of a single horizontal U-tube buried in a the backfill of a deep mine. Al-Ameen et al. (2018) investigated the recycling potential of low-cost construction and industrial waste materials as potential backfills in the HGHE system. Furthermore, an economic and comparative study was performed by Mohammad Zadeh Bina et al. (2020a) to address the difference between horizontal heat exchange pipes and traditional vertical pipes buried in the shallow underground.

A key issue associated with HGHE systems installed backfilled stopes of coal mines is geothermal resource sustainability, which has not been addressed in the previous research. Horizontal heat exchangers inevitably exert thermal impacts on the subsurface environment by influencing the temperature distribution in backfilled stopes and surrounding rocks. Thermal replenishment of heat exchangers in the pore space mainly occurs *via* conduction, natural advection or thermal convection through water. Particularly, the existance of groundwater flow imposes complex effects on the subsurface thermal regime (Hecht-Méndez et al., 2013). Therefore, the resultant thermal interference and risk of a deteriorated long-term sustainability act as a major concern to further up-scale this technology in a much larger scale. A proper assessment of the sustainability of intensive geothermal utilization is of great importance for the extended application of these low-carbon and cost-efficient energy alternatives. In this context, there has been limited investigation on the resolution of these challenges in HGHE systems in deep coal mines.

Quatitatively assessing the sustainability of the system is an important step to design a geothermal extraction system in coal mine. And it is also the main concern of the mine owner and shareholders, since it can maximize the economic lifetime profits. Thus, the main goal of this study is to clarify the scientific question: Over a period of 50 years, how much is the sustainable specific heat extraction rate *via* a typical closed-loop geothermal system from a deep coal mine, and how much is the corresponding total amount of heat?

Motivated by the above considerations, a typical deep coal mine in China characterized by a relatively high temperature is selected as the target field of this work. Multiple parallel horizontal heat exchange pipes are designed in backfill stopes in the mined-out area. A numerical study dedicated to the prediction of the long-term sustainability of intensive geothermal heat extraction while integrating site-specific information is presented based on the open-source software OpenGeoSys. The established model is validated against analytical analysis to ensure its accuracy. Particular attention is paid to the influence of groundwater flow, while the implications of further optimized strategies are summarized.

## 2. Geological setting and system configuration

The Anju coal mine plant is selected as the research site. As shown in Fig. 1(a), the Anju coal mine plant is located in Shandong Province, NE China, which covers an area of approximately 1700 km$^2$. This coal mining area has been highly exploited for many years, and its network of tunnels covers more than 30 mines. The depth of mining operations ranges from 1000–1200 m below ground level. Fig. 1(b) depicts the general layout of the Anju coal mine, with several temperature logging boreholes labeled. The contours indicate the distribution of the geothermal gradient in this area. The mined-out stope located near borehole X2 is selected as our study area, which exhibits a higher geothermal gradient and temperature. Fig. 1(c) shows the geological stratification along the profile A-B as shown in Fig. 1(b).

Temperature logging occurred in the different boreholes. Fig. 2(a) shows temperature log measurements in borehole X2. The thermal regime is characterized by a typical conductive behavior. At a depth of ca. 1000 m in borehole X2, the temperature reaches approximately 45.6 °C. Fig. 2(b) summarizes the stratigraphy of the study area. The shallow subsurface mainly comprises Quaternary terrace deposits (sand and gravel) up to a depth of ca. 200 m. Beneath these Quaternary layers, a Jurassic sandstone layer is detected. The aforementioned Jurassic volcanic rock layer exhibits a thickness of ca. 100 m. From ca. 750 to 1000 m a Permian layer is observed. This Late Permian sandstone occurs on the top of an Early Permian sandstone layer. A relatively thin Carboniferous sandstone layer is observed from ca. 1000 to 1200 m. The

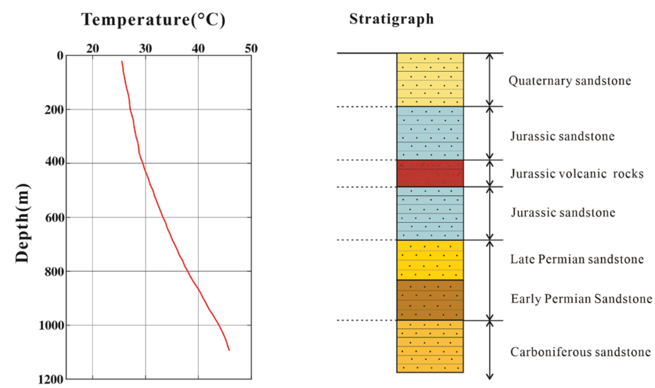


**Fig. 2.** Temperature measurement profile in drilling borehole X2.

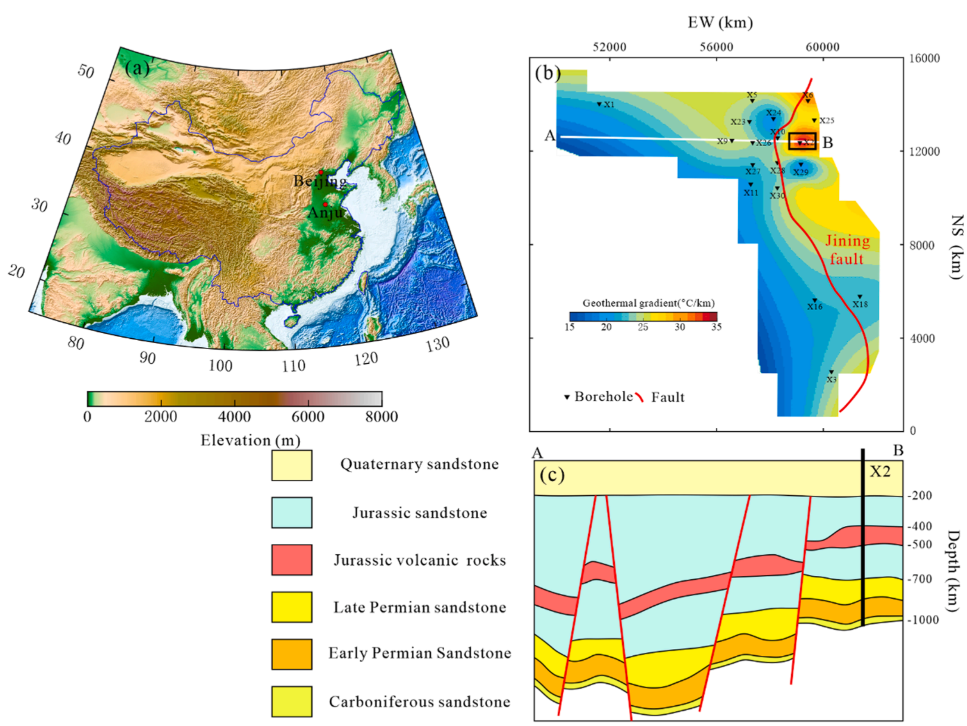


**Fig. 1.** (a) Location of the Anju coal mine in China, (b) geothermal gradient distribution in the Anju coal mine, and layout of the different temperature logging boreholes. (c) Schematic cross-section of the Anju coal mine (profile A-B) showing the hydrostratigraphy.

thermal conductivity of the target layer is determined *via* lab measurements of multiple core samples. It is evident that the measured thermal conductivity varies between 1.852 and 3.006 W/m K, with an average value of 2.578 ± 0.434 W/m K, according to an internal report in Cheng et al., (2019).

A schematic of the parallel horizontal ground heat exchangers (pHGHE) system in an underground stope is shown in Fig. 3. An array of horizontal heat exchange pipes is installed in the mined-out space parallel to the workface. The pipes are connected to each other in parallel.

When heat is required during the winter months, cold water can be circulated through these pipes, which is heated by the backfill materials and surrounding rocks. Heated water flows to the heat pump coupled with a short-term storage water buffer tank to heat clean water. Heated clean water is then circulated through a secondary circuit to inhabited areas for space heating, thus replacing the traditional coal burning district heating stations.

## 3. Method

In this work, the dual-continuum modeling approach for the horizontal heat exchange pipe has been adopted and implemented in the open-source finite element code OpenGeoSys (OGS) (cf. Kolditz et al. 2012, Chen et al. 2021).

### 3.1. Dual-continuum approach

#### 3.1.1. Governing equation

Here, the subsurface is modeled as a 3D continuum, while the horizontal heat exchange pipe is represented by 1D line elements as the second continuum. The heat transfer between different heat exchange pipe compartments, namely the circulating fluid within the pipes, the grout zones and the borehole wall, is modeled by means of a thermal capacity-resistor network in analogy to electrical circuits, i.e., the amount of heat flux is dependent on the temperature difference (cf. Diersch 2013). The heat fluxes q (cf. Eq. (1)) are driven by the temperature difference $\Delta T$ between these components and the heat transfer coefficient $\Phi = 1/(R\cdot S)$, which is the inverse of the product of thermal resistance $R$ and specific exchange area $S$:

$$q = \Phi \Delta T \tag{1}$$

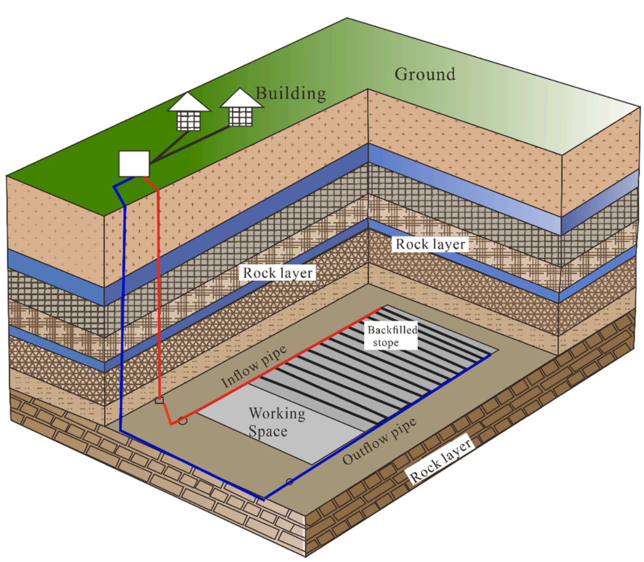


**Fig. 3.** Schematic of the parallel horizontal ground heat exchangers (pHGHE) system in underground backfilled stopes. The heat exchange tube installed in the backfill stope is indicated as a black line. The red line indicates the inflow pipe, and the blue line indicates the outflow pipe.

Heat transfer inside the pipes is mainly controlled by the heat convection driven by the water circulation in the pipe at a certain flow rate **u**, and the governing equation is written in:

$$\rho^r c^r \frac{\partial T_k}{\partial t} + \rho^r c^r u \cdot \nabla T_k - \nabla \cdot (\Lambda^r \cdot \nabla T_k) = H_k \tag{2}$$

$\rho^r$ is the density of the circulation water. $c^r$is specific heat capacity, $H_k$ is the heat source/ sink term. and the $\Lambda^r$ denotes the hydrodynamic thermos-dispersion of the circulating water, which is further defined by:

$$\Lambda^r = (\lambda^r + \rho^r c^r \beta_L \| \boldsymbol{u} \|)\delta \tag{3}$$

$\lambda^r$ is the thermal conductivity, $\| \boldsymbol{u} \|$ is the fluid circulation velocity, $\beta_L$ refers to the longitudinal heat dispersity coefficient.

Heat transfer in the surrounding coal mine backfilling materials is describes by the following governing equation:

$$\frac{\partial}{\partial t}\left[\phi \rho^f C^f + (1-\phi)\rho^s C^s\right] T_s + \nabla \cdot \left(\rho^f C^f \boldsymbol{v} T_s\right) - \nabla \cdot (\Lambda^s \cdot \nabla T_s) = H_s \tag{4}$$

$\rho^f$, $c^f$ are the density and specific heat capacity of the fluid moves in the porous media, while $\rho^s c^s$ denotes the density and specific heat capacity of the solid.

#### 3.1.2. The boundary conditions

One parameter that needs further explanation is the boundary condition that will be imposed on each horizontal heat exchange pipe. In most cases, the inflow temperature of the heat exchange pipe is controlled by the operation logic of the heat pump, and subsequently by the thermal load from the building. Therefore, several different types of heat exchange pipe boundary conditions have been provided in the model:

1) Power curve and constant flow rate

In this boundary type, the thermal load on each heat exchange pipe is specified according to a predefined time-dependent curve. Meanwhile, a fixed flow rate values will be maintained throughout the simulation. The temperature difference between the inlet and outlet will be dynamically calculated based on the thermal load, the circulating fluid properties, and the given flow rate.

1) Fixed inflow temperature curve

With this type of boundary condition, the heat exchanger inflow temperature is specified according to a time dependent curve and serves as input in the models. Then, the outlet temperature is dynamically simulated by the model.

#### 3.1.3. Numerical scheme

The standard Galerkin finite element (FE) method is employed for spatial discretization of the coupled equation system of Eqs. (2)–(4) with boundary conditions. A fully implicit backward Euler scheme is applied for the time integration. The Newton method with line search scheme is employed for the linearization, while a GMRES solution strategy with ILUT preconditioning is applied to solve the linear equation systems.

### 3.2. Model validation

Prior to applying the model to the prediction of long-term sustainability of the system, a model validation procedure is performed. A benchmark case which is originally dedicated to simulating the shallow horizontal heat exchanger is selected for comparison. The OGS model is validated against an analytical solution proposed in Lamarche (2019). The detailed benchmark set-up is described as follow: a single horizontal heat exchange pipe is buried underground at a depth of 2 m. The pipe length is 100 m. The inlet temperature ($T_{in}$ in°C) varied as time (t in hour) and is given in Eq. (5).

$$T_{in} = \begin{cases} -\frac{1}{1000}t + 10, & 0 \le t \le 4380\ (h) \\ 5, & t \ge 4380\ (h) \end{cases} \tag{5}$$

The ground surface temperature variation is described by Kusuda and Achenbach (1965):

$$T_s(t) = T_o - A\cos(\omega\ t\ ) \tag{6}$$

$T_s$ is the surface temperature, $T_o$ is the mean temperature far from the boundary, $\omega$ is the annual frequency, A is the variation amplitude of the temperature at the surface. In this case, A is set to 10. More details on the benchmark setting can be found in Lamarche (2019).

The numerical model mesh is depicted in Fig. 4. In total there are 38,884 nodes and 72,800 prism elements. The inlet temperature will be imposed at the entry of the pipe section. A linear profile will be imposed during half of the year (4380 h), and a constant temperature is imposed for the rest of the year. The time-varying temperature profile given by Eq. (6) is imposed at the top surface of the domain (z=0) as Dirichlet-type boundary condition. One day (86,400 s) was selected as the time step size for the numerical simulation. Fig. 5 shows simulated the outlet temperature evolution for one year. A good agreement can be found between the numerical model and analytical solution.

## 4. Model setup

To accurately evaluate the long-term sustainability of the pHGHE system installed inside the backfill stopes of coal mines, a 3-D modelling scenario is constructed using validated OGS model to simulate the heat extraction process and temperature evolution in the mine backfill material.

The backfill stope at the field site is designed to be 3 km in length, with a height of 5 m and a width of 120 m, which accommodates 1499 pipes in total. The simplified domain of 160 m*80 m*2000 m adopted in the model is shown in Fig. 6. The model size is chosen such that the boundaries are far enough from the the backfill stope zone and the heat extraction processes are not influence the temperature of the boundary faces. The simplification method is similar to the method explained in detail in Li et al. (2020), which can be summarized as follow: The thermal impact of a given heat exchange pipe varies with its position, and the heat exchange pipes at different positions exhibit a varying heat transfer behavior. The outermost pipes experience the least interference, while in contrast, the innermost pipe(s) experience(s) the most notable interference. This enables the adoption of a reduced number of pipes to represent all the pipes in the model. A trial and error procedure is applied to determine the reduced pipe number. In each test, we increase the number of pipes. The trial and error tests stop until the outlet temperature of the innermost pipes meets the stopping criterion compared to the previous test. The stopping criterion is defined such that the estimated relative error of temperature decreases below 1e-3. Under these circumstances, the obtained number of pipes can be considered to represent all the pipes.

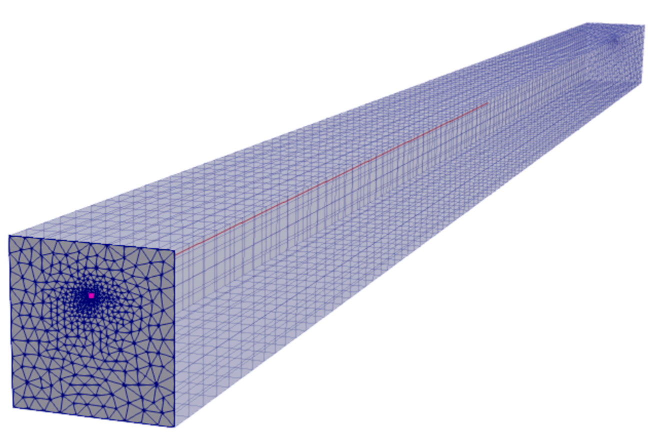

**Fig. 4.** Mesh generated for the benchmark simulation, the horizontal heat exchanger pipe is represented by the red line.

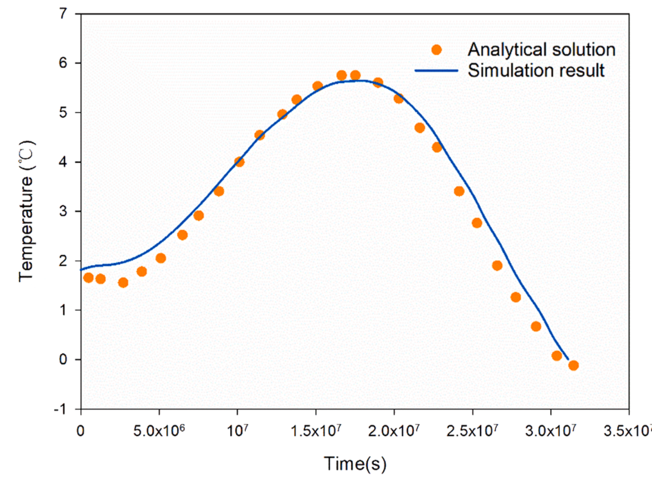


**Fig. 5.** Outlet temperature over one year (Scatter points are the analytical solution from (Lamarche, 2019), the curve represents the simulation results).

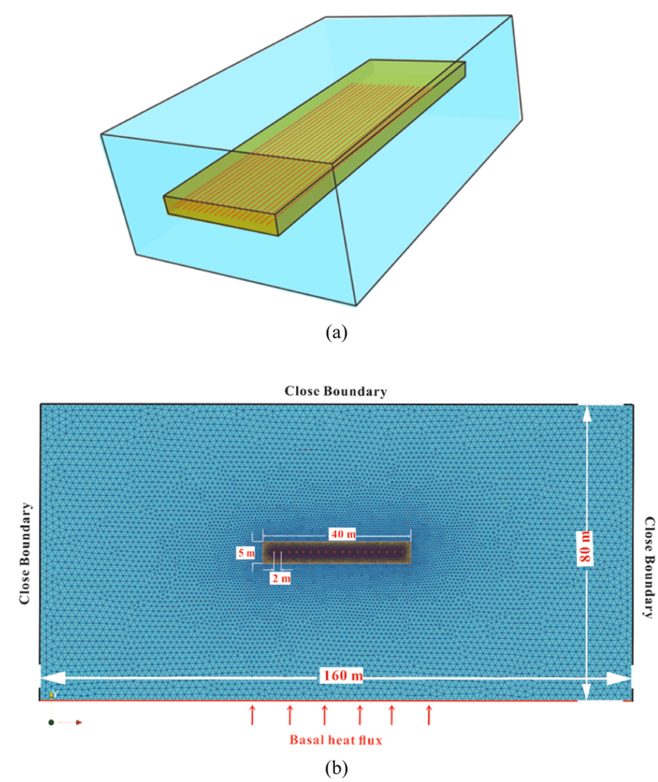


**Fig. 6.** Geometry of the numerical model: (a) 3D model; (b) cross-sectional profile. The heat exchange pipes installed in the backfill are indicated as red solid lines.

The geometry and discretized mesh representing an underground backfilled stope containing heat exchange pipes are shown in Fig. 3. Two material groups are represented as (1) the backfill zone and (2) the surrounding rock formation, which are marked with different colors. The domain is discretized into 337,463 tetrahedral elements, with the mesh surrounding the pipes further refined to capture the high thermal gradient between the pipes and backfill materials, and the minimum element length is 0.3 m. Several simulations are conducted with even more refined meshes, and convergence of the simulated temperature distribution is confirmed. It is indicated that mesh independence is achieved in terms of the simulation results presented in this work. Furthermore, to ensure the stability of the numerical model, the time step size is set to 1 day and kept constant during the simulation spans.

*Initial conditions:* The initial temperature of the whole domain is assumed to be 45 °C according to the temperature conditions reported in Section 2. The circulation flux is assumed to be 4e-4 $m^3/s$.

*Boundary conditions:* A fixed heat load is applied to each pipe during heating operation with an continuous operation period of 24 h/day. Using the trial and error method, the maximum heat extraction rate is set to 40 W/m. In this study, geothermal gradients are investigated in association with a basal heat flux. A Neumann boundary condition is applied to the bottom face of the domain, characterized by a constant basal heat flux. Depending on the the geothermal conditions of the investigated area, this value is set to 68 mW $m^{-2}$. In regard to the rest boundary faces (topand lateral boundaries), closed boundary conditions are applied, indicating that no mass or heat exchange occurs with the external environment.

The thermo-physical properties of the backfill material and surrounding rock were determined and integrated into the model, as listed in Table 1. It is assumed that the system is intermittently operated for 50 years. Typically in China within a given year, the thermal extraction duration lasts 4 months from November 15 to March 15, and the rest of the time is the thermal recovery period.

## 5. Results and discussion

Following the calibration procedure, the validated numerical model was run for a total of 50 years to predict the sustainability of the system, along with the long-term thermal impact on the backfill and surrounding rock in the study area.

To assess the system sustainability under different scenarios, the sustainable heat extraction rate is introduced and defined first. For practical reasons, the system is considered to be sustainable, as the maximum thermal extraction rate can be continuously achieved throughout the 4-month heating season, while the minimum temperature of the backfill does not drop below a certain value (here, it is set to 0 °C due to the potential freezing risk).

### 5.1. Sustainability analysis

Based on the temperature distribution plot in Fig. 7, the behavior of the pipes at the different positions varied. The outermost pipes (as indicated in Fig. 6) exhibited the lowest temperature interference, i.e., the temperature of the surrounding backfill was higher than that of the remaining pipes. Moving from the outside to the center, the interference between neighboring pipes increases and more energy was extracted

**Table 1**
Model parameters determined based on the backfilled stope of the Anju coal mine in China.

| Type | Parameter | Value |
|---|---|---|
| Rock | $\lambda_r$ thermal conductivity of rock | 2.5 W/m K |
| | $\rho_r$ density of rock | 2400 kg/$m^3$ |
| | $C_{pr}$ specific heat capacity of rock | 2000 J/kg K |
| Backfill | $\lambda_b$ thermal conductivity of the backfill materials | 2.5 W/m K |
| | $\rho_b$ density of the backfill materials | 2400 kg/$m^3$ |
| | $C_{pb}$ specific heat capacity of the backfill materials | 2000 J/kg K |
| Water | $\lambda_w$ thermal conductivity of water | 0.6 W/m K |
| | $\rho_w$ density of water | 998 kg/$m^3$ |
| | $C_{pw}$ specific heat capacity of water | 4187 J/kg K |
| Pipe | $d$ diameter | 0.0254 m |
| | $t_p$ wall thickness of the pipe | 0.001587 m |
| | $\lambda_p$wall thermal conductivity | 2.78 W/m K |
| | $L$ pipe-to-pipe distance | 2 m |

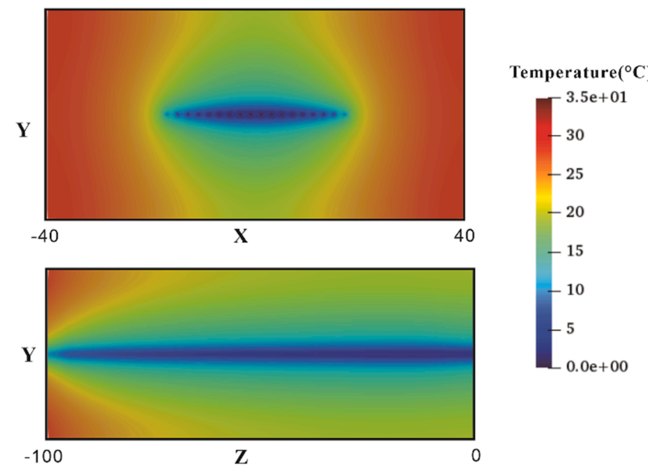


**Fig. 7.** Three-dimensional temperature contours of the backfilled stope at the end of the 50th heat extraction cycle (the upper part shows an X-Y cross-section, and the bottom part shows a Y-Z cross-section).

from the backfill between neighboring pipes, causing the temperature of the backfill adjacent to the center pipe(s) to be the lowest, as shown in Fig. 7. Heat transfer around a given pipe inevitably interfered by neighboring pipes, and such inteference effects was enhanced with increasing number of neighboring pipes and with decreasing overall influencing distance. It was also observed that the backfill adjacent to the pipe inlet attained a lower temperature than that of the pipe outlet. This could be explained by the fact that the circulated fluid was heated from the inlet to the outlet and less energy was extracted from the backfill adjacent to the pipe outlet.

Fig. 8 shows a temperature curve of the backfill adjacent to the inlet of the center pipe, which demonstrates a periodic temperature evolution. During the heat extraction period, the backfill temperature first steeply declines and then stabilizes. Similarly, once heat extraction is stopped, the backfill temperature rapidly recovers and exhibits a slow increase thereafter. Under this site-specific configuration, the minimum temperature of the backfill almost approaches 0 °C at the end of 50 years of extraction. This indicates that a heat load of 40 W/m is the sustainable heat extraction rate per pipe length. It is also observed that during heat extraction, periodic temperature changes mostly occur in the nearby backfill and surrounding rock, while the distant rock does not

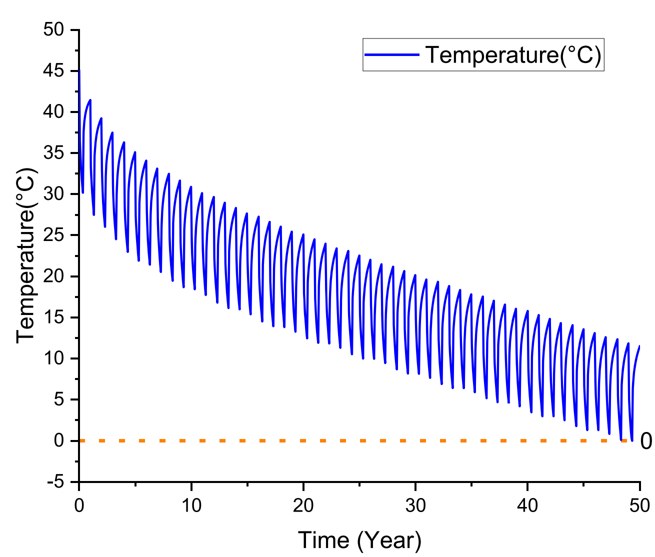


**Fig. 8.** Temperature evolution of the backfill adjacent to the pipe inlet over 50 years of extraction.

experience a similar periodic temperature evolution.

Considering in an full underground stope with a length of 3 km and containing 1499 pipes, the overall heat extraction rate of system are approximately 6 MW, and the corresponded total energy extracted over 4-months heating season reaches 17 GWh.

The specific thermal load of the residential buildings in Shandong Province ranges from 30 to 36 W/m$^2$ during the heating season (Chen et al., 2021). Here considering a typical thermal load of 35 W/m$^2$, the system can supply heating to more than 170,000 m$^2$ of residential building area. Overall, by using this technology, a total of 6732 tons $CO_2$ emission can be avoided per year.

### 5.2. Parameter study

To identify the design and operation parameters with profound contributions to sustainable thermal energy extraction *via* horizontal heat exchange pipes in backfill stopes, a numerical model is further applied to simulate various scenarios. Based on the developed numerical heat transfer model, the influences of multiple parameters (such as the pipe spacing, thermal conductivity of the surrounding rock and backfill, mass flow, ambient temperature, and saturation time) on system sustainability and thermal impacts are investigated in the following sections. Since the spatio-temporal variations cannot be fully addressed *via* field measurements and the actual operation of heat exchange pipe systems is not documented, the following parameters are considered to bear high degrees of uncertainty and hence require detailed analysis:

- inflow rate (in m$^3$/s)
- pipe length
- pipe-to-pipe distance (in m)
- thermal conductivity of the backfill stope and surrounding rock
- ambient temperature

#### 5.2.1. Impact of the inflow rate

According to Eq. (1), the inflow rate of the heat exchange pipe directly influences the heat transfer occurring between the fluid and surrounding backfill material. Hence, the effect of the inflow rate on a given backfilled stope should be investigated to provide guidance in system operation for sustainable utilization. Four scenarios with different inflow rates ranging from 0.05 to 0.4 kg/s were studied under the same configuration as that previously mentioned: (1) 5e-5 m$^3$/s, (2) 1e-4 m$^3$/s, (3) 4e-4 m$^3$/s and (4) 1e-3 m$^3$/s. The heat extraction rate applied to each pipe remained the same under all scenarios. Since the diameter of a single tube was set to 0.0254 m, the mean velocity of water in a single tube ranged from 0.1 to 1.9 m/s.

Fig. 9 shows the minimum temperature of the backfill adjacent to the inlet of the center pipe at the end of each heating cycle. It is evident that by increasing the inflow rate from 1e-5 to 4e-4 m$^3$/s, the minimum temperature greatly increased. However, with the rate increasing from 4e-4 to 1e-3 m$^3$/s, only a slight increase in the minimum temperature was observed.

We further examined the sustainable specific heat extraction rate under the different inflow rates, as shown in Fig. 10. The sustainable specific heat extraction rate was calculated to reach 25, 35, 40 and 42 W/m, respectively, under different inflow rates. This indicates that increasing the inflow rate enhanced the sustainable specific heat extraction rate of the system. However, only 5% increase was achieved by increasing the inflow rate from 4e-4 to 1e-3 m$^3$/s.

#### 5.2.2. Impact of the length of the pipe

To further investigate the influence of the pipe length, we assume several pipe lengths: (1) 50 m, (2) 100 m, (3) 200 m, and (4) 300 m. During the heating period, the specific heat load applied to each pipe is maintained at 40 W/m. It is assumed that only the pipe length is varied, while the other parameters remain constant.

Fig. 11 shows the minimum temperature of the backfill adjacent to the inlet of the center pipe at the end of each heating cycle. A higher minimum temperature is obtained in the case of a 50 m length than that obtained in the other three cases. However, by increasing the length from 200 to 300 m, only a slight difference in the minimum temperature is attained.

Fig. 12 shows the evolution of the sustainable heat extraction rate over 50 years for the different pipe lengths. According to the results, the overall sustainable heat extraction rate follows an almost linear increasing trend with increasing horizontal pipe length. In contrast, the sustainable specific heat extraction rate exhibits a descending trend. This can be explained by the fact that the flow temperature at the outlet increasingly approaches the backfill temperature with increasing pipe length. Considering that the rate of decline is not steep even for a length of 300 m, a relatively long horizontal heat exchange pipe could represent a good solution to explore larger thermal energy since no additional drilling cost is incurred with increasing length. However, by increasing pipe length, the pumping costs to circulate fluid in system is also increased which might further lead to a decrease of the overall efficiency. Therefore, a detailed analysis must be conducted to achieve a balance between the two aspects.

#### 5.2.3. Impact of the pipe-to-pipe distance

The energy density in the backfilled stope increases with the number of pipes installed with decreasing spacing, contributing to a higher energy performance. However, not only do the total costs increase when more pipes are installed with decreasing spacing but the thermal interference among the installed pipes also notably increases, and the backfill and rock temperatures are not recovered after several cycles. This constrains the system sustainability during long-term energy extraction. It is important to determine the optimum number of pipes that should be installed in underground backfilled stopes to maintain sustainable exploitation throughout the 50-year life cycle.

We compare several pipe-to-pipe distances: (1) 1 m, (3) 2 m, (4) 4 m, and (5) 6 m. However, the specific heat load applied to each pipe during heating operation is maintained at 40 W/m, and the other parameters

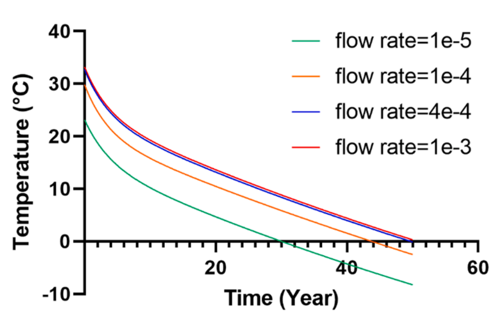


**Fig. 9.** Minimum temperature evolution after each heating cycle at the different flow rates in the pipe.

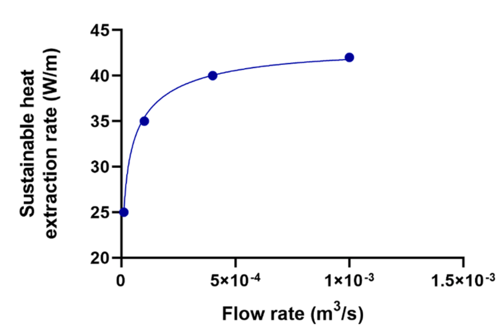


**Fig. 10.** Sustainable specific heat extraction rate per pipe length at the different inflow rates.

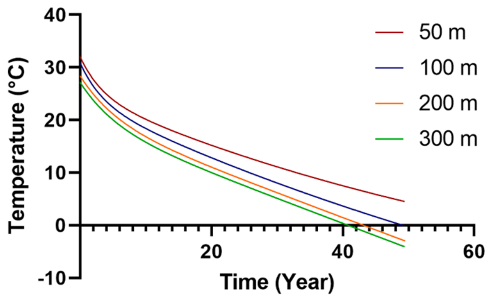


**Fig. 11.** Minimum backfill temperature evolution during each heating period over 50 years.

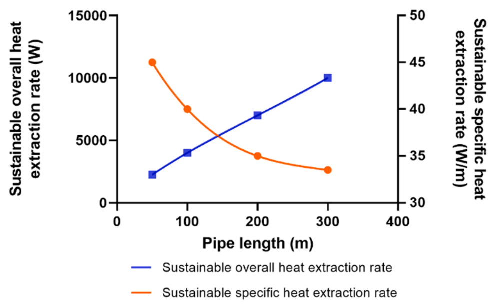


**Fig. 12.** Relationship between the pipe length and sustainable heat extraction rate.

are set the same to those under the previous configurations.

Temperature distribution in the backfilled stope at the end of the 50th heating cycle under pipe-to-pipe distances of 1, 2, 4, and 6 are shown in Figs. 13 and 14. Note that Fig. 13 shows the result at the 23 a, since the temperature already drops below zero. Comparing the temperature contours between the different pipe-to-pipe distances, it is observed that when the pipe-to-pipe distance was too large, high-temperature areas remained between the pipes not exposed to heat extraction at the end of 4 months.

We further quantitatively examine the sustainable heat extraction rate under the different pipe-to-pipe distances. The results are depicted in Fig. 15. In these cases, the sustainable heat extraction rate per pipe length decreased with the spacing between heat exchange pipes, as the thermal impact between adjacent pipes increased with decreasing spacing. In contrast, the total energy extraction was enhanced with increasing number of pipes. However, it was found that by decreasing the pipe distance from 2 to 1 m, the total energy extracted slightly increased. Considering that the total costs double with increasing pipe number, the technical-economic benefits require further detailed investigation.

### 5.2.4. Impact of the thermal conductivity

The effect of the thermal conductivity on the sustainable performance of the system was evaluated under various scenarios.

Two scenarios were run considering different thermal conductivities of the backfill and surrounding rock while maintaining the specific heat load applied to each pipe during heating operation at 40 W/m, while the other parameters were set the same to those under the previous configurations. Under scenario (1), the effect of the thermal conductivity of the backfill was first studied, and a lower value of 2 W/(m·K) was tested while maintaining the thermal conductivity of the surrounding rock the same, at 2.5 W/(m·K). Under scenario (2), the effect of the thermal conductivity of the surrounding rock with a lower value of 2 W/(m·K) was assessed while maintaining the thermal conductivity of the backfill the same, at 2.5 W/(m·K).

Fig. 16 shows the minimum temperature (solid lines) of the backfill adjacent to the center pipe inlet at the end of each heating period over 50 years. It is obvious that the thermal conductivity of the backfill and surrounding rock directly affect the sustainability of the system.

As shown in Fig. 16, the backfill temperature is lower than that in the reference case with decreasing thermal conductivity of the backfill, which suggests that heat exchange between the backfill and pipes is suppressed. To further reveal the influence of the rock thermal conductivity on energy production, Fig. 16 shows that the temperature decreases with the thermal conductivity. During extraction, more heat loss occurs, as the heat originating from the rock in more distant areas does not quickly replenish the pipe zone.

The minimum temperature curve, as shown in Fig. 16, indicates that the thermal conductivity of the backfill imposes a more significant influence on the sustainable heat extraction rate than that of the surrounding rock, which can be attributed to the fact that heat transfer

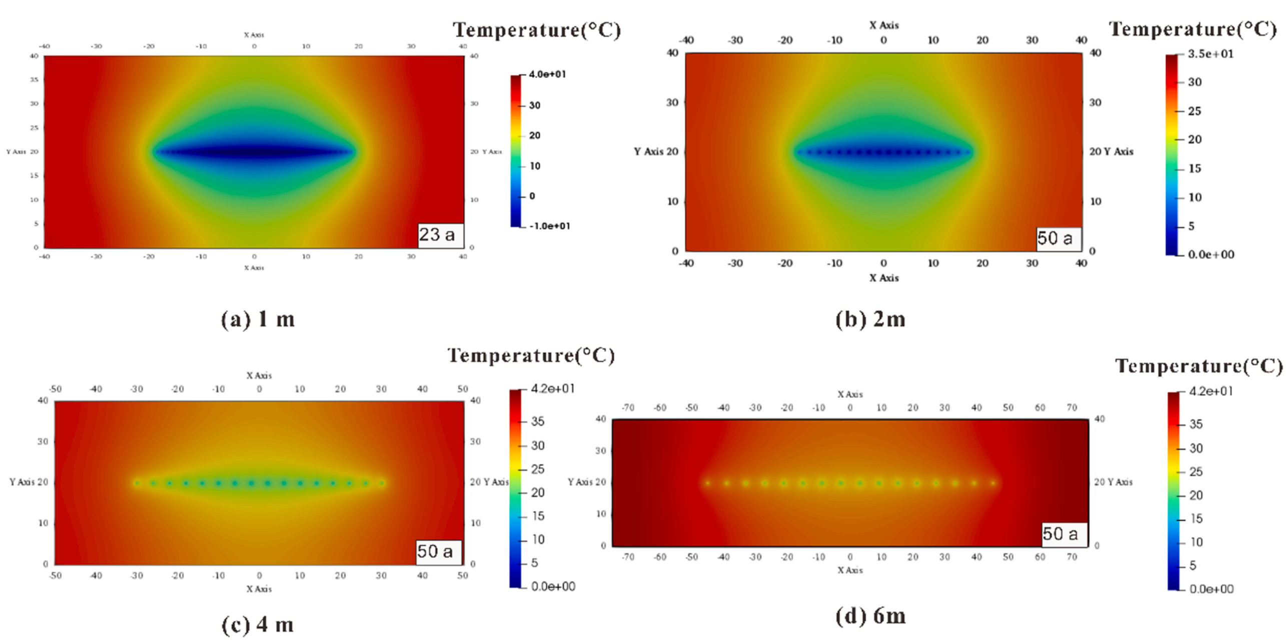


**Fig. 13.** The temperature distribution in the backfilled stope under the different pipe-to-pipe distances of 1, 2, 4 and 6 m.

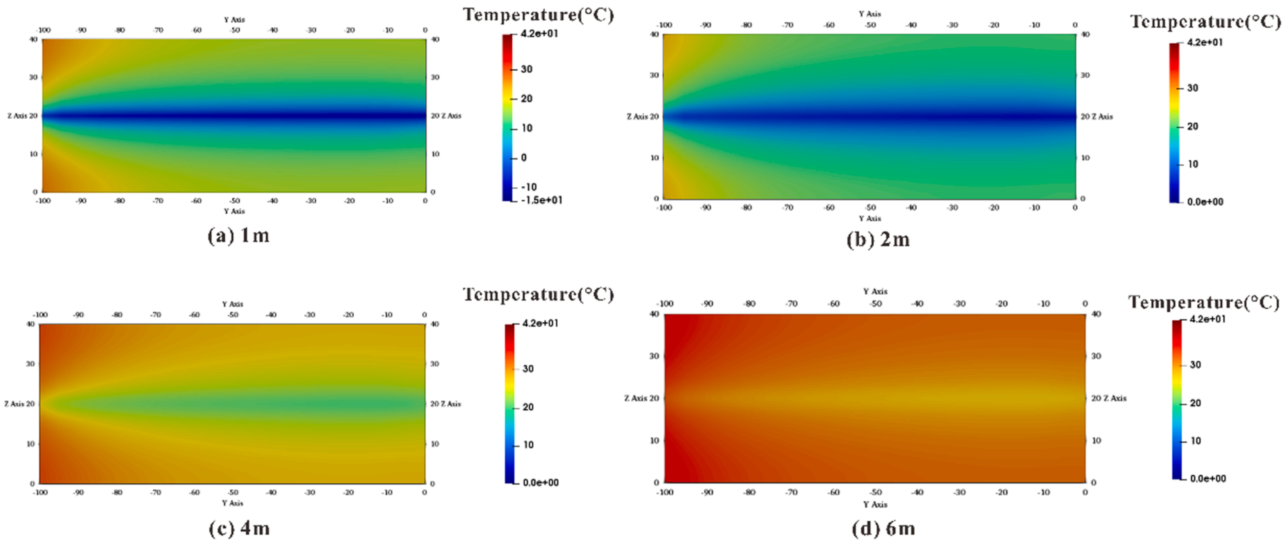


**Fig. 14.** Cross-sectional profile (Y-Z axis) of the temperature contours of the backfilled stope under the different pipe-to-pipe distances of 1, 2, 4 and 6 m.

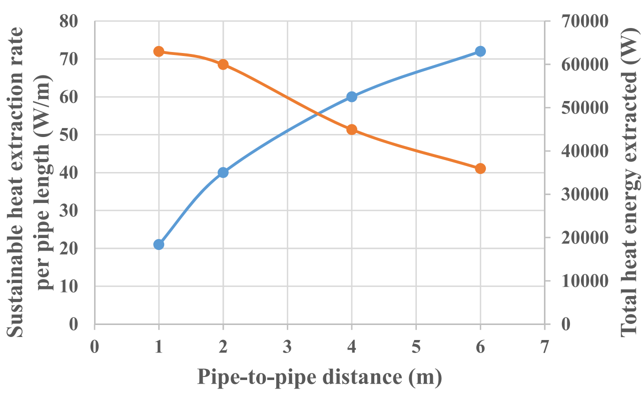


**Fig. 15.** Relationship between the pipe-to-pipe distance and the sustainable specific heat extraction rate (W/m).

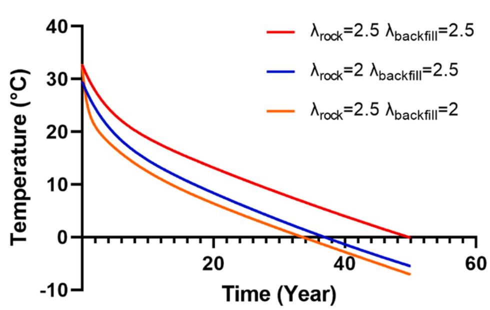


**Fig. 16.** Minimum backfill temperature evolution at the end of each heating period throughout the 50-year life cycle.

directly occurs between the backfill and pipes. Moreover, these observations provide a major opportunity to prepare backfill materials containing higher-conductivity components to enhance the system sustainability.

### 5.2.5. *Impact of the ambient temperature*

As the depth of the backfilled stope in an underground mine increases, the temperature of the surrounding rock increases based on the geothermal gradient. The effect of the ambient temperature in a given backfilled stope should be investigated to provide guidance in system design for sustainable utilization. Two scenarios were run considering different initial temperatures of 35, 45 and 55 °C while maintaining the heat load applied to each pipe during heating operation at 40 W/m, while the other parameters remained the same as those under the previous configurations.

Fig. 17 shows the lowest temperature of the backfill in the vicinity of the center pipe inlet at the end of each heating cycle. The plot shows that a higher temperature is obtained in the case of an ambient temperature of 55 °C than that in the other two cases. It is evident from Fig. 17 that increasing the ambient temperature increases the sustainable heat extraction rate.

Fig. 18 shows that a nearly linear increase in the sustainable heat exchange rate occurs with increasing ambient temperature. Compared to shallow underground mines where the temperature of the surrounding rock/soil usually reaches 15 °C (Giordano et al., 2016), the backfilled stope in a deeper underground mine provides access to higher ambient temperatures so that the heat exchange system in the above backfilled stope achieves a higher sustainable heat extraction rate.

### 5.3. *Discussion*

As indicated in the literature (Hein et al., 2016; Meng et al., 2019), groundwater flow always imposes notable effects on the sustainability and efficiency of a subsurface heat exchange system, although a certain groundwater flux and direction are necessary for this effect to be observed. Depending on various site-specific hydrogeological conditions, higher Darcy velocities enhance the heat transfer between pipes and the backfill, as well as the surrounding rock (Meng et al., 2019). At a large-scale heat exchange array site, groundwater flow inevitably leads

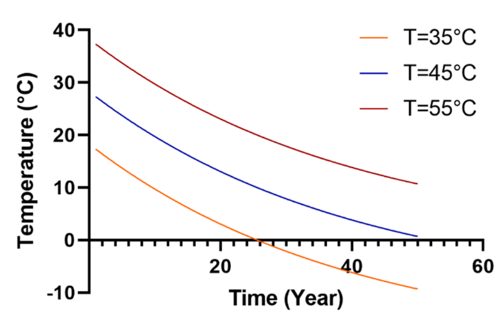


**Fig. 17.** Minimum temperature evolution at the different ambient temperatures.

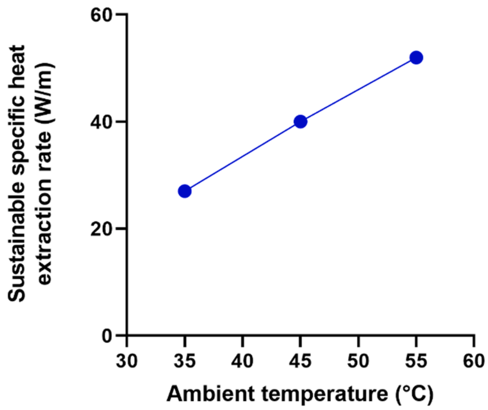


**Fig. 18.** Sustainable heat exchange rate with the ambient temperature.

to thermal redistribution.

Here, a preliminary attempt was made to examine the groundwater flow effects on the sustainability of pipe systems by considering a constant flow rate (1e-6 m/s, which is measured in this site (Cheng et al., 2019)) along the X-axis direction. The heat load applied to each pipe during heating operation is maintained at 40 W/m.

In Fig. 19, the spatial temperature distributions profile after the last heating season (50th year) under groundwater flow is shown. The groundwater flow creates the temperature redistribution in the backfilled stopes, and a cold plume is formed in the downstream. Along the groundwater flow direction, the temperature drops from the upstream pipe to the downstream pipe.

Under groundwater flow, the temperature disturbances near horizontal heat exchange pipes are lower, indicated by the fact that the temperature keeps droping from location A to location C, as shown in Fig. 20. The sustainable specific heat extraction rate is larger with groundwater flow taken into account due to the advective heat supply dominating over the conductive heat supply. Moreover, the sustainable energy extraction rate at the upstream pipes is larger than the downstream ones.

It can be also observed that the temperature under groundwater flow approaches steady state after several operation time, while thermal conduction environment (as indicated in the previous sections) a continuous decrease in temperature is exhibited. While the time cost to approach steady-state conditions mainly depends on the groundwater flow rate.

For this reason, information on the potential groundwater flow in the subsurface should be gathered and considered in the design process, and the spatial arrangement of horizontal pipes should be designed based on site-specific groundwater flow conditions.

## 6. Conclusion

In this work, a pHGHE system has been introduced to extract deep geothermal energy from deep coal mines. We quantitatively evaluate the long-term sustainability of the pHGHE system. A numerical model is established in OpenGeoSys to simulate the heat transfer occurring between pipes and the backfill and surrounding rock. The model is validated against an analytical solution prior to further application. The validated model is then applied under typical site-specific conditions of the Anju coal mine in China, where the important model parameters are determined.

In regard to the typical backfilled stopes of the Anju coal mine, the simualtion results show that the maximum sustainable heat extraction rate of a given heat exchange pipe must not exceed 40 W/m to achieve sustainable exploitation over a lifetime of 50 years. A overall heat capacity of 17 GWh can be achieved *via* this system in a single heating season, providing heating to more than 170,000 $m^2$ of residential building area.

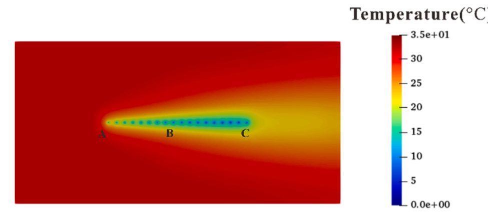


**Fig. 19.** Temperature contour profile at the end of the 50th heating cycle under groundwater flow.

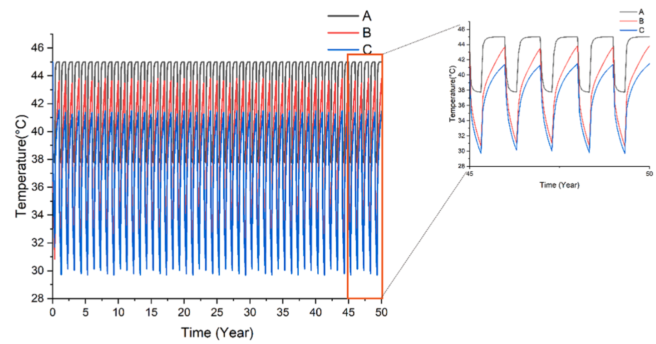


**Fig. 20.** Temperature evolution at the different pipe inlets (corresponding to the points labeled in Fig. 19).

The contributions of various parameters to the system sustainability are further investigated through sensitivity analysis. It is demonstrated that the maximum sustainable heat exchange rate increases with the inflow rate, pipe length, the backfill thermal conductivity and the ambient temperature, but decreases with the pipe-to-pipe distance and the thermal conductivity of the surrounding rock mass.

In addition, a detailed discussion on the influence of groundwater flow suggests the existence of groundwater flow can improve the sustainable specific heat extraction rate on each pipe and be benefit to the the long-term sustainability of the system.

This study verifies the feasibility and sustainability of geothermal utilization in underground mines for regional heating. The insights gained in this study can provide technical guidance for the design of such geothermal systems in similar coal mines.

## CRediT authorship contribution statement

**Yonghui Huang:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Yanlong Kong:** Conceptualization, Methodology, Writing – review & editing. **Yuanzhi Cheng:** Conceptualization, Methodology, Writing – review & editing. **Chuanqing Zhu:** Writing – review & editing. **Jixiong Zhang:** Conceptualization, Methodology. **Jiyang Wang:** Funding acquisition, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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