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Research paper

Numerical and experimental study of geothermal heat extraction from backfilled mine stopes

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ABSTRACT

Underground mines are valuable sources of geothermal energy. The present study evaluates the possibility of the novel idea of installing geothermal heat exchange tubes in backfilled mine stopes prior to backfill placement for the purpose of geothermal heat extraction. It aims to understand the heat transfer phenomenon that takes place during heat extraction from underground backfilled stopes. To investigate the feasibility of the novel technique of heat extraction from backfilled mine stopes, numerical and experimental heat transfer studies are conducted. To assess the performance of a stope-coupled geothermal heat exchanger system, a numerical model is developed. The model is capable of considering the effect of heat conduction as well as natural convection. The results of the developed model are compared with those from existing ground-coupled heat exchanger models. To further validate the developed numerical model, a series of experimental tests are conducted using a small-scale laboratory test setup built for this purpose. By introducing information gathered from a number of Canadian mines into the developed heat transfer model, effects of hydraulic conductivity, thermal conductivity, rate of heat extraction and arrangement of heat exchanger tubes are investigated.

1. Introduction

Mining has always been categorized as a highly energy intensive industry. The main source of the energy consumed in mining operation is fossil fuel. Relying on fossil fuel is unsustainable in two ways; firstly, these resources are few and geographic dependent which make it expensive to recover them and secondly, Greenhouse Gas (GHG) emissions from fossil fuel combustion have been identified as the main reason for the global climate change phenomenon that threatens the sustainability of future growth [1]. This scarcity of fossil fuel resources and the environmental issues associated with burning these fuels have encouraged scientists to look for alternative and renewable sources of energy. The major sources of renewable energy are solar, wind, hydro, geothermal and biomass [2,3].

Geothermal energy is recognized as one of the most promising and cleanest options for heat production and electricity generation. It has the advantages such as independency form climate conditions, relatively low emission and comparative low energy generation cost [4,5]. Geothermal resources and their applications are conventionally categorized based on their temperature, or the temperature at which heat is extracted from them. Geothermal resources are typically used for two purposes: electricity generation and direct usage. Electricity generation is possible in high temperature resources in which the steam and/or hot water is used to run turbines. The temperature of up to 85 °C has been recorded for electricity generation up to now [6]. Where the temperature of geothermal resource is less than 90 °C, it is generally used for direct usage or heat pump applications; water-to-water and water-to-air heat pumps [7]. While high temperature geothermal resources have been successfully used for electricity generation since the beginning of the twentieth century, the low temperature resources are proved to be reliable and inexpensive sources of energy for heating/cooling purposes.

Generally, geothermal heating/cooling systems are categorized into two distinctive types, namely open and closed-loop geothermal systems. In the open-loop geothermal system, underground water is pumped up to the surface to exchange heat with the working fluid of the Heating Ventilation Air Conditioning (HVAC) system. Therefore, this type of geothermal system is often associated with high electricity consumption (for water pumps) and environmental issues of

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underground water displacement. Also, an open-loop geothermal system is only applicable when an underground water aquifer is available [8]. Regardless of these challenges, open-loop geothermal systems are generally preferred, provided the pumping power is not so high as to render the application economically unfeasible [9]. The second type of the geothermal heating/cooling system is closed-loop system in which geothermal energy is extracted by circulating water (or any other working fluid) in a closed network of heat exchange tubes embedded into the ground. Compared to open-loop geothermal systems, closed-loop systems have lower electricity consumption, do not have environmental issues regarding underground water displacement and are not restricted by the availability of underground water aquifers. The relative mechanical simplicity and the considerable economic and environmental advantages of using closed-loop geothermal systems have made them an integral part of many modern HVAC systems [9]. As a result, there has been considerable research momentum towards the study of closed-loop systems. However, the application of geothermal systems is restricted by their relatively high drilling costs. Thus, any successful attempt in reducing the drilling costs of closed-loop geothermal systems will increase their economic benefits and therefore their applicability.

Extraction of geothermal energy from underground mines is significantly viable. Firstly, by using the huge underground excavated spaces created during the mining operation, there will be no drilling and excavation costs related to geothermal system. Secondly, by deploying a geothermal system in an underground mine, deep rock masses and higher rock temperatures become accessible, which can lead to the higher efficiency of a geothermal system. Due to the nature of ore body, every mining operation has limited life beyond which all mining activities halt and the site should be rehabilitated in a way that results in minimum damage to environment and less liabilities. Exploiting the geothermal resources of a mine can offset some economic costs by supplying green heat to the communities living in and around the mine area. Also, deep excavations of mining operations make relatively high temperature geothermal sources accessible and provide great opportunities for geothermal energy production [9]. Mines are often located in remote areas that impose expensive energy transportation rate. Mining operations are also associated with huge GHG emissions that, with the pending carbon tax legislations, are projected as an operational cost. As a result, any opportunity to harvest renewable geothermal energy from mine resources will help lower operational and GHG-related costs of mining activities [9]. The clean, renewable and inexpensive geothermal resources of underground mines can be used on mine sites for space heating, heap leaching or mine ventilation purposes. These resources can provide the nearby population with geothermal energy to increase the long term sustainability of these mining communities. The idea of harvesting geothermal energy from mines was first considered in the 1980's [10]. So far, only open-loop geothermal cycles have been used for geothermal energy extraction in which underground water is pumped to the surface from the underground cavities of a mine. One of the first successful implementations of geothermal systems in mines was the Springhill project, in Nova Scotia, Canada which has been extensively discussed [11,12]. In this project, an abandoned coal mine is used to heat a plastic factory with an approximate surface area of 14,000 m^2. There have been small- or large-scale projects in other countries that successfully extract geothermal energy from mine water. For instance, in Marienberg, Germany, Wismut mine provides 690 kW of heat capacity [13] and in Freiburg a mine gallery is used to provide heating/cooling for a relatively large building [14]. One of most successful projects was carried out in Heerlen, Netherlands, where the geothermal heat of mine water from an abandoned coal mine is used to provide heating/cooling for 350 dwellings, 3800 m^2 of commercial space and 16,200 m^2 of community buildings [15]. With successful application of low temperature open-loop geothermal systems in flooded mines, more attention has been focused on systematic work to find criteria for viability of different mines for large-scale heat extraction. Investigations carried out in an abandoned copper mine in northern Hungary have shown that the mine resource has the capacity of 2.88 MW [15]. In the USA, it is estimated that 2.0×1011 L/year of mine water can be extracted from the Pittsburg, Pennsylvania coal seam at 10–13 °C, which is very suitable for space heating [12]. In Canada, a preliminary study was carried on Con mine, a decommissioned gold mine beside the city of Yellowknife, Northwest Territories [16], in which the water temperature is above 35 °C in the deepest level of the mine. Another study carried out on Gaspé mines in Quebec, shows that more than 700 kW can be produced from flooded copper mines near Murdochville [17].

During the last decade, researchers have developed numerical tools to analyze the deliverable heating/cooling capacity of underground mines. Rodríguez and Díaz [18] proposed a semi-empirical method for assessing the geothermal heat capacity of underground mine galleries, assuming a “quasi-steady state” heat transfer between the water flowing inside the galleries and the rock. Their work showed the capability of this approach by presenting a rough estimate of the heat power and the outlet water temperature. However, the simplified nature of their model limits its practicality in cases where transient heat transfer in the rock mass is significant. Hamm and Sabet [19] used FLUENT software to simulate heat transfer in a vertical shaft and the rock mass of a flooded coal mine in Lorraine, France. Their results, revealed the advantages of off-the-shelf computer simulation programs for evaluation of geothermal energy recovery from abandoned mines. However, this approach will lead to extremely case-sensitive results, which highly depend on having reliable and specific data (usually not available) and cannot provide inclusive guidelines for the resource heat content and management. Raymond and Therrien [17] proposed calculating the producible geothermal heat capacity of Gaspé mines in Canada based on the average values of underground water temperature, heat pump return temperature and pumping flow rate. To analyze the pumping rate, they used a 3D finite element simulator called, HydroGeoSphere, to solve ground water flow equation (Darcy flow equations). However, their model is not capable of correlating pumping rate and ground water temperature and consequently it cannot assess the sustainability of the resource based on rate of heat extraction (or pumping rate). Later on, Ghoreishi-Madiseh et al. offered a numerical model in which sustainable rate of heat extraction was assessed based on the temperature of the produced heat [20]. To date, researchers have studied geothermal energy extraction from mine waters. However, not all mines have access to excessive amounts of water. Also, pumping mine water from deep mine galleries to the surface is not always economically viable. Another serious problem of this application is the contamination of the air by acid and other chemicals in the mine water due to its exposure at the surface.

Another potential application of geothermal energy systems is in underground backfilled mine stopes. These spacious stopes of an underground mine can accommodate the installation of heat exchange tubes of a closed-loop geothermal cycle [9,21]. The present paper investigates the novel idea of employing closed-loop geothermal cycles in underground mines. In closed-loop type geothermal cycles, extraction of energy from the geothermal source is carried out by circulating a fluid in a closed network of tubes implanted into the geothermal source, known as a ground-coupled heat exchanger (GCHE). In this novel technique, the GCHE is installed in the excavated space of the mine (i.e. a mine stope) prior to filling the stope with mine backfill. Filling stopes with cemented backfill (a mixture of water, binder and mine tailings) is a popular technique that ensures ground safety in the underground operation by preventing rock fall and acid mine drainage. After backfill placement in the GCHE equipped mine stope, mine backfill will exchange heat between the working fluid in the GCHE tube network and the surrounding rock walls of the stope. Since the pipe network is in closed-loop formation, the energy needed to circulate the working fluid is considerably less than that of open-loop geothermal systems. Also, because the underground water is not pumped to the surface, there will be no chemical contamination risks. Eventually, the implementation of mine-coupled heat exchangers will create a new generation of underground mines that can provide their communities with clean, inexpensive and renewable geothermal energy not only during the mining operation, but also after the mine has been closed. This new generation of mines will bring about more sustainable mining communities, which will not face the threat of abandonment after the depletion of ores. To best of the authors' knowledge, this is the first research work dedicated to the study of heat transfer in closed loop geothermal heat exchangers installed in underground mine stopes.

2. Mathematical method

Mined out stope can accommodate the installation of heat exchange tubes of a closed loop system. After the cemented backfill placed in the stope, it will play an important role in the transfer of geothermal heat by exchanging heat from the rock walls surrounding the stope to the heat exchange tubes. Here, this special type of geothermal system is called a Stope-Coupled Heat Exchanger (SCHE). Fig. 1 shows the schematics of a closed-loop geothermal system installed in a mine stope. In this research fully cured backfill will be the medium responsible for transferring heat from the stope rock walls to the heat exchange tubes. Thus, thermal properties of cemented backfill strongly affect SCHE performance which encouraged comprehensive study which was conducted by the authors to investigate the thermal properties of cemented backfill [22]. One of the advantages of SCHE is the possibility of access to both ends of heat exchanger tubes which is not the case in conventional ground coupled heat exchanger (GCHE) that is provided in U-tube shape. Therefore in any SCHE model, this characteristic must be accommodated.

This study proposes using dynamic adjustment of fluid inlet temperature to match the rate of extraction/injection with the demanded heating/cooling load while it can still capture the constant inlet water temperature. By using this method, a constant or a variable heat extraction/injection rate can be imposed. This method used direct modeling of heat transfer inside the heat exchange tubes. The proposed method is based on direct calculation (i.e., solving the coupled heat transfer equations) of the local heat flux exchanged between the fluid flowing through heat exchange tube(s) and the backfill. In numerical simulations of heat transfer in GCHEs, such as the models developed by Refs. [24–26], the temperature gradient along the length of a borehole heat exchanger is considered to be negligible, and therefore a 2D Cartesian heat transfer model would suffice. However due to change of bulk temperature of the working fluid in a borehole heat exchanger along the tube length as well as the effect of natural convection necessitates 3D modeling of heat transfer as is done in this model. Therefore, the physical domain of the model comprises a cubic control volume of backfill in which SCHEs are embedded and is surrounded by rock mass Fig. 2. SCHE tubes are installed vertically inside the stope. The proposed geometry of the SCHE tube network in Fig. 2 incorporates single tubes as well U-tubes, and is capable of simulating both of these tube arrangements. However, to focus on the canonical cases, it is assumed that the tubes are placed in an organized matrix formation so that the center to center distance between the tubes is equal. Any number of SCHE tubes may be interconnected in series to increase the outlet temperature of the circulating fluid, which is assumed to be water. The boundaries of the model are considered to be sufficiently far from the tubes so that extending these boundary walls does not change the interior flow and temperature fields.

Backfill is a porous medium, so the governing equation for heat transfer in the SCHE is the convective heat transfer in a porous medium with a heat sink function, which represents the heat gained from the backfill by the circulation of water in the tubes [27]. Therefore, the governing heat transfer equation is expressed by:

$$\rho_m C_m\left(\frac{\partial T}{\partial t}\right)+\rho_f C_f\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right) = k_m\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+q''' \quad (1)$$

where ρ_m, C_m, k_m, ρ_f, C_f, and q''' are, respectively, the density of backfill, the specific heat capacity of backfill, the thermal conductivity of backfill, the density of water, the specific heat capacity of

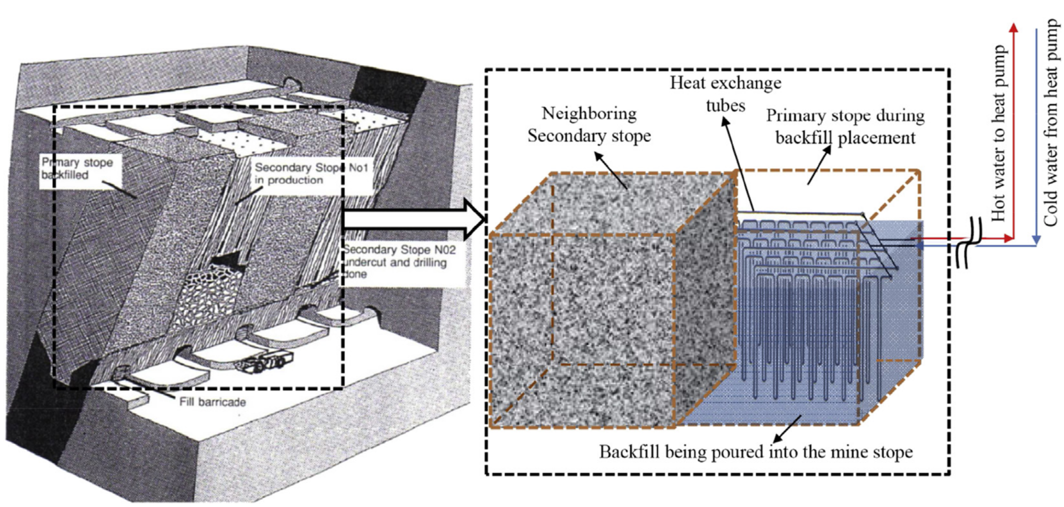

Fig. 1. Schematics of an SCHE (left figure from Ref. [23]).

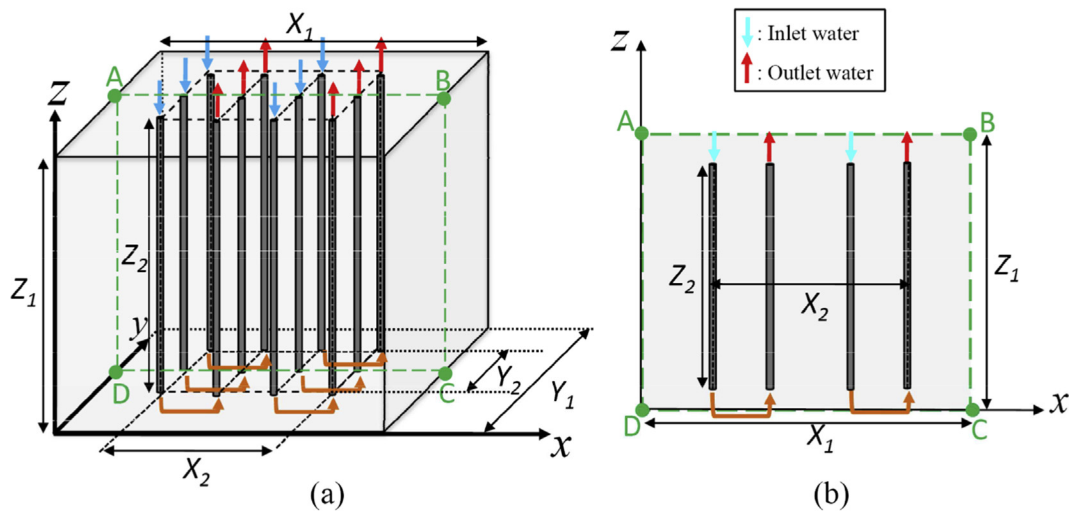

Fig. 2. (a) 3D representation of the model, and (b) mid-plane cross section view.

water, and the rate of heat generation per unit volume of the porous media (representative of a heat source/sink). Also u,v and w are, the x, y, and z components of the volume-averaged velocity of water in a porous medium, respectively. The convective heat transfer occurs under two scenarios: Hydrological pressure-driven convection due to water table existence and buoyancy-driven natural convection which were discussed extensively in Ghoreishi-Madiseh et al. [28].

The governing equations of conservation of mass and momentum (previously discussed by Ghoreishi-Madiseh et al. [28]) are respectively:

$$\vec{\nabla}\cdot\langle\vec{u}\rangle = 0 \tag{2}$$

$$\rho_f\left\{\frac{1}{\varphi}\frac{\partial\langle\vec{u}\rangle}{\partial t}+\frac{1}{\varphi}\left(\langle\vec{u}\rangle\cdot\vec{\nabla}\right)\left(\frac{1}{\varphi}\langle\vec{u}\rangle\right)\right\} = -\vec{\nabla}\langle p\rangle^f+\frac{\mu}{\varphi}\nabla^2\langle\vec{u}\rangle-\frac{\mu}{K}\langle\vec{u}\rangle-\frac{\rho_f D_F}{\sqrt{K}}|\langle\vec{u}\rangle|\langle\vec{u}\rangle+\rho_f\left(1-\beta\left(T-T_0\right)\right)\vec{g} \tag{3}$$

where φ is porosity, μ is the dynamic viscosity of water, K is permeability, β is the coefficient of thermal expansion of water, ρ_m is the density of backfill, ρ_f is the water density, and $\vec{g}$ is the gravity acceleration vector. Based on the volume averaging technique, $\langle\vec{u}\rangle = 1/V\int_V \vec{u}\,dV$ is the Darcy velocity, where V is a representative elementary volume of a porous medium. Similarly, $\langle p\rangle^f = 1/V_f\int_{V_f} p\,dV$ is the intrinsic average pressure of fluid taken over V_f (fluid representative volume). Also, D_F is the dimensionless form-drag constant, for which the results of [29] are used here. The energy balance equation (previously discussed by Ghoreishi-Madiseh et al. [28]) is expressed by:

$$\rho_m C_m\frac{\partial T}{\partial t}+\rho_f C_f\left(\langle\vec{u}\rangle\cdot\vec{\nabla}T\right) = \vec{\nabla}\cdot\left(k_m\vec{\nabla}T\right)+q''' \tag{4}$$

The first term on the right hand side of Equation (4) represents conductive heat component while the second term on the left hand side of this equation is the advective heat component. If fluid velocity is very small, conduction will be the dominating heat transfer mechanism. Fig. 3 illustrates a tube cell and its surrounding control volume. The tube diameter is so small, compared to the stope size, that it can be assumed to occupy no volume of the stope. However, heat exchange between the heat exchange tube(s) and the mine fill material must be considered. Thus, in Equation (4), the effect of the presence of heat exchange tubes is represented by q'''. Obviously, q''' is non-zero in locations where the tubes rest and zero elsewhere. It is also assumed that the backfill has an initial uniform temperature which will remain the same on all boundaries except for the top and the bottom boundaries that are assumed to have no heat exchange.

Based on the study of Ghoreishi-Madiseh et al. [30], q''' is calculated using the local rate of heat exchanged between the ground and the borehole tube.

$$q''' = -\dot{m}C_f\left(\overline{T_f}+\Delta\overline{T_f}-\overline{T_f}\right)\Big/\Delta V = -\dot{m}C_f\Delta\overline{T_f}\Big/\Delta V \tag{5}$$

where $\overline{T_f}$, $\dot{m}$ and ΔV are the bulk temperature of water, mass flow rate of water through the borehole, and volume of the finite volume cell surrounding the tube cell, respectively. To assess the heat transfer inside the heat exchange tubes, unsteady forced convection inside the tube(s) must be solved. Since the flow rate is constant and also because the length of the tube is much larger than its diameter, it is reasonable to assume that the flow field inside the tube(s) is steady and fully developed. This means that the velocity profile of fluid inside the tube is $W(r) = \overline{W_f}(1-(r/0.5D_{\text{in}})^2)$. Here, $\overline{W_f} = \dot{m}/(0.25\pi\rho_f D_{\text{in}}^2)$ is the fluid mean velocity and $\dot{m}$ is mass flow rate of water. Fig. 4 shows the model proposed for heat transfer inside the heat exchange tubes. As the model is axisymmetric, a two-dimensional axisymmetric cylindrical model is used.

The dynamic adjustment of inlet water temperature and the change in the temperature of backfill surrounding the tubes imply that the fluid thermal regime is unsteady, even though tube flow is steady and fully developed. However, it should be noted that the heat transfer inertia of the tube flow is much less than that of the backfill. Thus, it is reasonable to neglect the time derivative term of fluid temperature. The fluid temperature on the tube wall is assumed to be equal to the temperature of backfill at tube wall location (at $r = 0.5D_{\text{in}}$). Also, zero flux condition is assumed on the

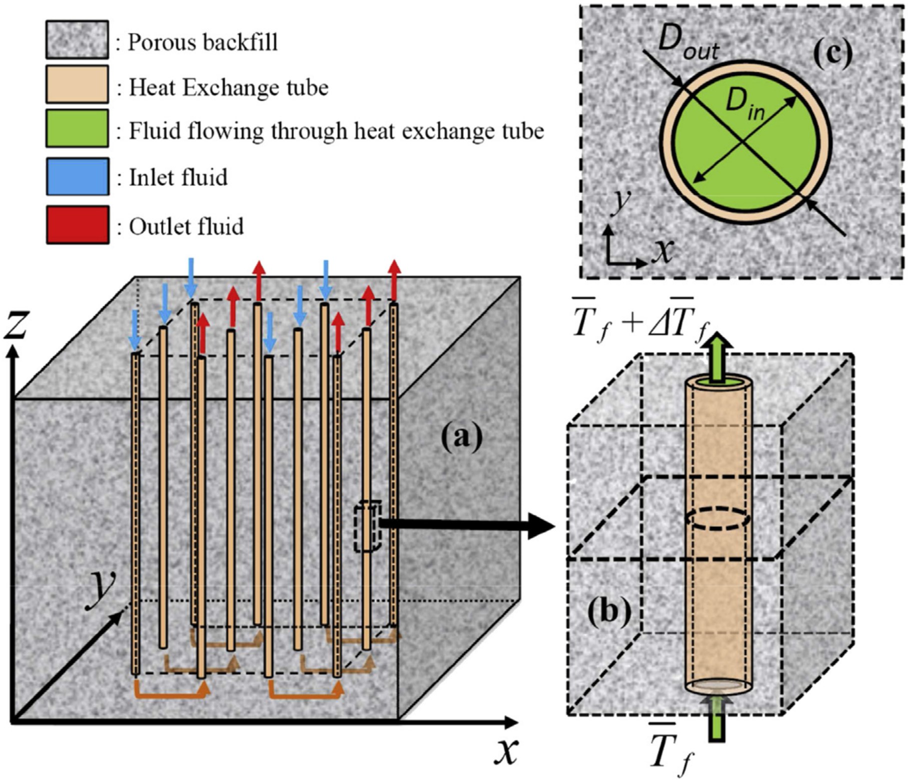

Fig. 3. Demonstration of a tube cell on a heat exchange tube, b) isometric view tube cell and its surrounding control volume, and c) top view of the tube cell.

axis of the tube (at $r = 0$). Consequently, the equation of forced convection for the fluid flow inside the heat exchange tube will be as follows.

$$\rho_f C_f W_f \frac{\partial T_f}{\partial z} = k_f \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_f}{\partial r} \right) + \frac{\partial^2 T_f}{\partial z^2} \right) \tag{6}$$

Using finite volume method, a FORTRAN computer code was developed to solve the governing Equations (2)–(4) and (6). A detailed description of the descritization method and the

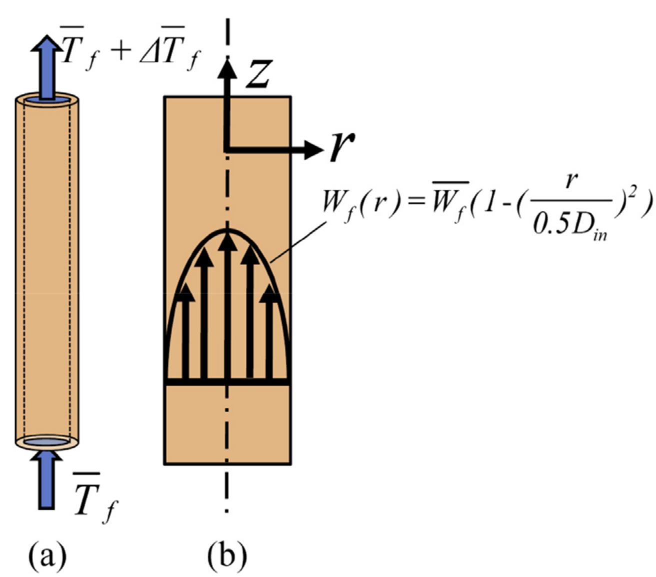

Fig. 4. The model proposed for heat transfer inside the heat exchange tube; (a) 3D, and (b) 2D.

numerical method used to solve the descritized equations are given in Ghreishi-Madiseh et al. [28].

3. Experimental model

To further evaluate the result of the numerical model, a physical model was designed and built to simulate an underground back-filled stopes in which heat exchanger tubes were installed. It is a representative physical model of a stope coupled heat exchanger (SCHE). Since in situ evaluation of the performance of a real scale SCHE is cost- and time-intensive, the experiments were conducted in laboratory scale. A cylindrical container made from aluminum (for uniform heat transfer) and filled with mine fill material was constructed to represent the backfilled stope. The cylinder was sealed tightly to prevent water loss and maintain the moisture content of the mine fill material. To measure the temperature, TC-PVC-T-24-180 thermocouples manufactured by OMEGA were used. This type T thermocouple is capable of measuring the temperature with an accuracy of 0.1 °C. The readings of these thermocouples were compared against the readings of a standard thermometer to calibrate thermocouples. To satisfy the isothermal boundaries of the numerical model, the aluminum wall of the cylinder was equipped with band heaters to keep the temperature of the boundary at any desired set points. This was made possible by using a Proportional Integral Derivative (PID) control loop that was devised in the user interface software developed to control the system and store the temperature of the walls. To minimize heat loss from the system, glass wool industrial insulation sheets (with thickness of 10 cm) were placed around the cylinder after band heater installment. Eleven copper tubes (1.55 mm inner diameter, 1 mm wall thickness) were installed inside the cylinder resembling the tube network in an SCHE to investigate the effect of tube network arrangement. The tubes were designed in a way that they could be easily connected in series or parallel. To have a steady flow of liquid inside the tubes, a controllable peristaltic pump was used. Any part of heat exchanger tubes outside the cylinder was insulated thoroughly with un-slit foam rubber pipe insulation to minimize any thermal disturbances from outside ambient. To control the temperature of the inlet water and to evaluate the influence of water on SCHE performance, a PID controlled electric heating system was devised to adjust the water inlet temperature. Thermocouples were installed at the inlet and outlet points of each tube to analyze the heat gain of the system. The exploded view of experimental setup is shown in Fig. 5. Thermocouples were installed in different locations of the cylinder to monitor the performance of the experimental setup. To monitor the thermal properties of the mine fill material, KD2 Pro probes were installed inside the cylinder at different locations. To evaluate the quality of heat transfer inside the cylinder, numerous thermocouples were installed inside the cylinder. To have orderly comparative readings, thermocouples were installed on two levels along the height of cylinder at different pre-determined points and on the surface of each tube. Fig. 6 shows the thermocouple locations and tube arrangement on each level inside the cylinder.

Control and data acquisition system includes a National Instrument Compact Field Point (CFP) computer, with multiple racks on which standard National Instrument input/output cards were placed to allow for measurement and control. A total of 24 channels were read using CFP with 2 readings per second which were used for high accuracy control and reading e.g. inlet and outlet water temperature. Data acquisition of the remaining (80) thermocouples was done by using a multiplexer unit (Agilent Technologies Inc., Santa Clara, CA) with the frequency of one sample per 15 s. To control the inlet source temperature and boundary of cylinder a combination of Pulse-Width Module (PWM) output card and Solid State Relay (SSR) were used.

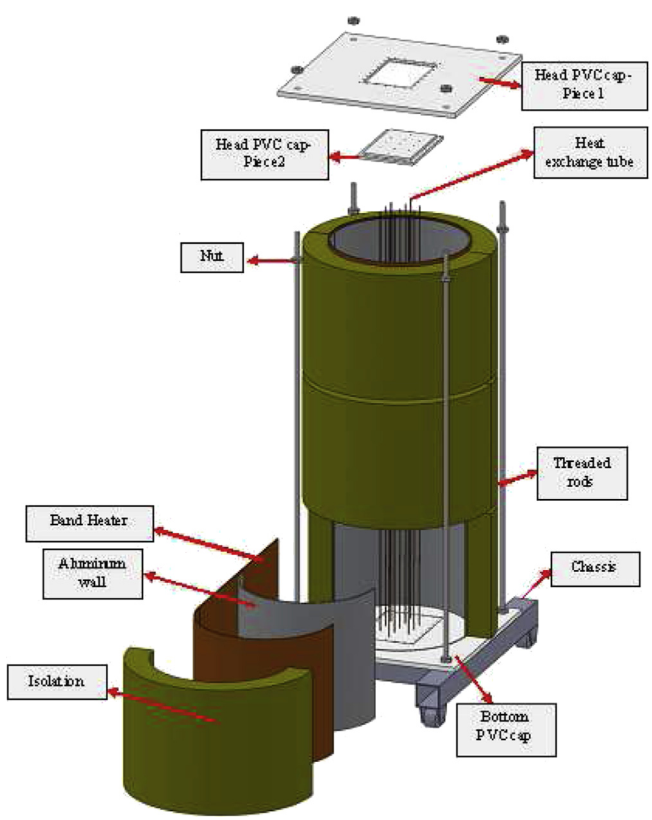

Fig. 5. Exploded view of the experimental setup.

Using LabView computer software, an interface was developed to control the PWM channels and to record the temperature of each thermocouple. The software is capable of showing the temperature values and the PWM percentage in real time. Inputting the tube paths, their associated thermocouple numbers and water flow rate of each path, the user is able to monitor the temperature at the inlet and the outlet of each tube/path, as well as the temperature difference and the rate of heat extraction of each tube.

The cylinder was filled with mineral processing tailings from Clarabelle plant, Canada. Particle size distribution of this tailing is shown in Fig. 7. The mineral composition of this tailing is shown in. Table 1. Specific Gravity of this tailings material was measured at 2.85 using ASTM C188 − 09 test method. Knowing the density of the dried material, the total weight of the dry tailings added into cylindrical test setup, and the total volume occupied by the mixture, the average porosity of the mixture was calculated at %35 with the average wet density of 2.20 gr/cm^3.

Hydraulic conductivity test were done on the used mine fill materials using ASTM D2434-68 method which resulted in a range of 1.05×10^{-5}–3.21×10^{-4} m/s for the very loose to densely consolidated tailings. Using KD2 Pro thermal properties measurement method and based on the procedure introduced for measurement of thermal properties of backfill [22], It was found that this tailings material has an average thermal conductivity of 1.48 W/m°C and an average specific heat capacity of 1.14 kJ/kg°C. Thermo-physical properties of the experimental setup and the filled material is shown in Table 2.

Each experiment started with a preconditioning procedure in which the inlet water temperature and the cylinder boundary temperatures were stabilized at the user-defined value. Afterward, the water was pumped through heat exchanger tubes with the user-defined flow rate. At this stage, temperature reading and recording would start and continue till the end of each test. The tests were stopped when the user ensured that the steady state heat transfer was achieved. The key parameters to show agreement between the experimental and modeled results are the temperature at the outlet of the SCHE as well as the temperature difference between the inlet and the outlet of the SCHE.

4. Results and discussion

4.1. Experimental vs. numerical

A reliable model must be able to predict the rate of heat extraction/injection with an acceptable accuracy. Assuming a constant flow rate of water, the rate of heat extraction is defined by measuring the temperature difference between the inlet and outlet of the geothermal heat exchanger. As a result, the validity of an SCHE numerical model can be called amenable only if it can estimate the temperature of the inlet/outlet fluid with an acceptable accuracy. In this study, the temperature of water leaving the geothermal heat exchanger and its difference with inlet water temperature were compared between modeled and experimental data. For each of the experiments, the mathematical fit of the inlet temperature was worked out as a function of time. This time dependent inlet temperature was input into the numerical model and the results of numerical model were then compared with the experiments.

4.1.1. Single tube

In the first series of experiments, heat transfer in a simple SCHE comprising a single heat exchange tube (tube#6 in Fig. 6) was studied. Fig. 8 shows the inlet temperature and its fit function along with the resulting experimental and modeled outlet water temperature. Water was pumped at 1.92 mL/s with wall temperature of

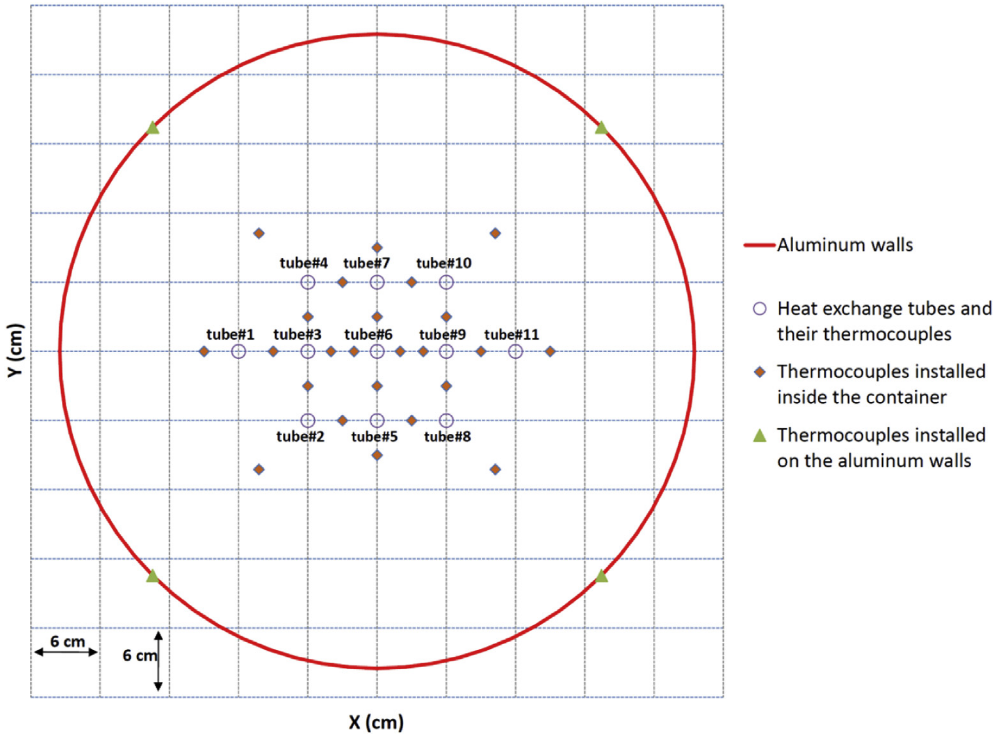

Fig. 6. Distribution pattern of heat exchange tubes and thermocouples.

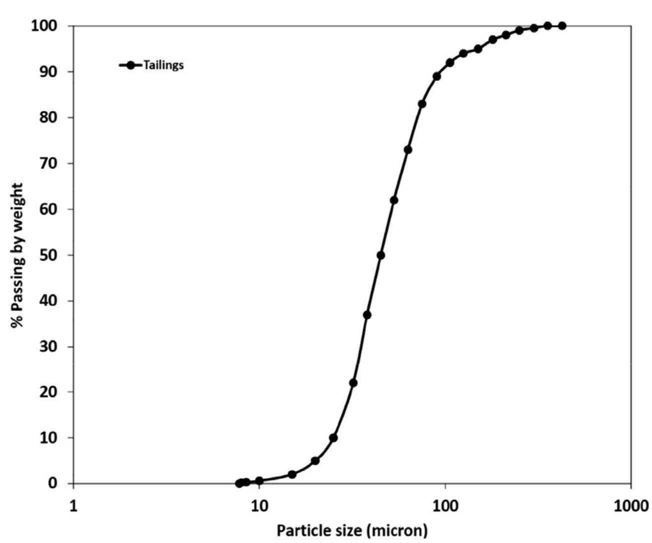

Fig. 7. Particle size distribution of tailings.

28 °C. Steady state heat transfer was reached after 14 h. The maximum relative difference between the numerical and the experimental results was about 2% for the outlet temperature and about 11% for the temperature difference. An interesting feature of this test was the almost constant temperature difference between the inlet and outlet of the heat exchange tube. Thus, it can be said that the numerical model is capable of modeling the constant rate of heat extraction scenario.

4.1.2. Two connected tubes

This section studies heat transfer in a heat exchanger comprising two heat exchange tubes connected in series, tube#7 and #5 from Fig. 6. In this test, the water entered tube#7, exited tube#7, entered tube#5 and exited tube#5. In this test the wall temperature was 28 °C and the pumping rate was 1.36 mL/s. It is equivalent to a constant inlet temperature test. As Fig. 9 shows, the maximum relative difference between the numerical and the experimental results was about 2% for the outlet temperature and about 4% for the temperature difference. Note that the inlet temperature of tube#5 is equal to the outlet of tube#7 and the rate of heat extraction of tube#7 was higher than tube#5.

In another double tube test, the ability of the heat transfer model in simulation of heat transfer in a heat exchanger with a tube spacing which was different from that of last test was examined. In this test, water was pumped through tube#1 and #11 (shown in Fig. 6), sequentially connected in series. Water was pumped at mL/s and the wall temperature was fixed at 28 °C. This experiment represents a constant inlet temperature experiment (Fig. 10). The maximum relative difference between the numerical and the experimental results was about 1% for the outlet temperature and about 2% for the temperature difference.

4.1.3. Parallel arrangement of two double tubes

This section describes studies of heat transfer in a heat exchanger comprising four heat exchange tubes, with every two tubes connected in series. In other words, the geothermal heat exchanger of this experiment comprises two parallel paths; tube#2 connected in series to tube#5 and tube #4 connected in series to

Table 1
Mineral composition of tailings.

Quartz	Albite	Calcite	Muscovite	Actinolite	Anorthite	Biotite	Pyrrhotite	Chlorite
20.69%	18.87%	5.96%	5.96%	10.19%	22.06%	8.45%	2.31%	4.07%

Table 2
Characteristics of physical model and the filled material.

Diameter of the container	0.55 m
Heat exchange tube length	1.65 m
Inner diameter of the heat exchange tube	1.6 mm
Tube thickness	1 mm
Porosity of the material	0.35
Specific heat capacity of material	1.14 kJ/kg°C
Density of the material	2.2 gr/cm^3
Thermal conductivity of material	1.48 W/m°C

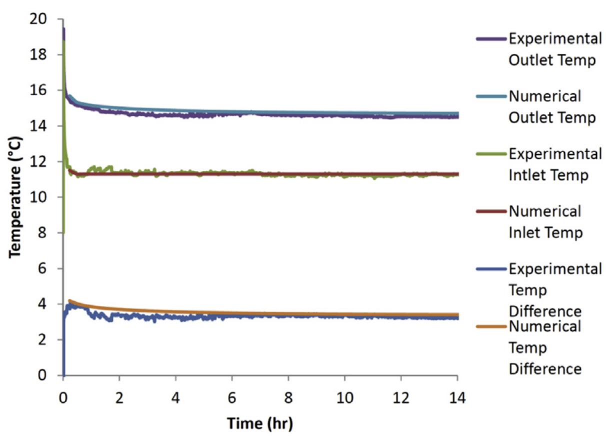

Fig. 8. Modeled and experimental water temperature at the SCHE inlet and outlet and the difference between the water temperature at the inlet and outlet for a single heat exchange tube.

tube#10 (tube numbers shown in Fig. 6). Water was pumped at 1.00 mL/S and the wall temperature was at 28 °C. Fig. 11 shows the inlet and the outlet temperature profiles of the heat exchange tubes of the experiment; note that the inlet temperatures of tube#2 and #4 are equal. Similarly, the inlet temperatures of tube#8 and #10 are equal to the outlet temperatures of tube#2 and #4, respectively. The inlet/outlet temperatures of the identical heat exchange tubes of the two parallel paths were similar. The maximum relative difference between the numerical and the experimental results is about 1% for the outlet temperature and about 2% for the temperature difference (Fig. 11).

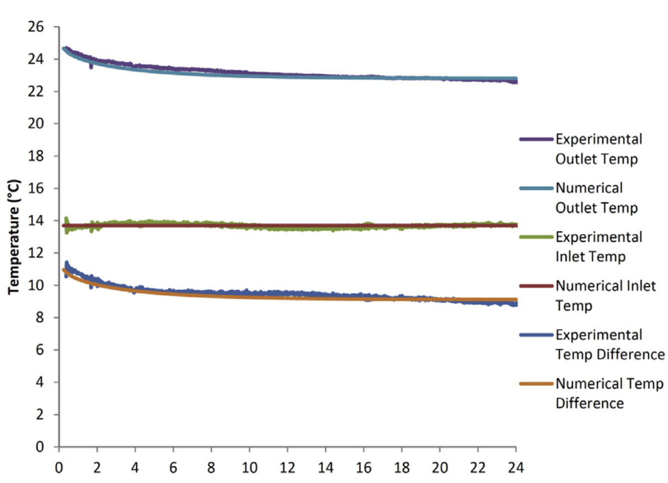

Fig. 9. Modeled and experimental water temperature at the SCHE inlet and outlet and the difference between the water temperature at the inlet and outlet for two connected tubes.

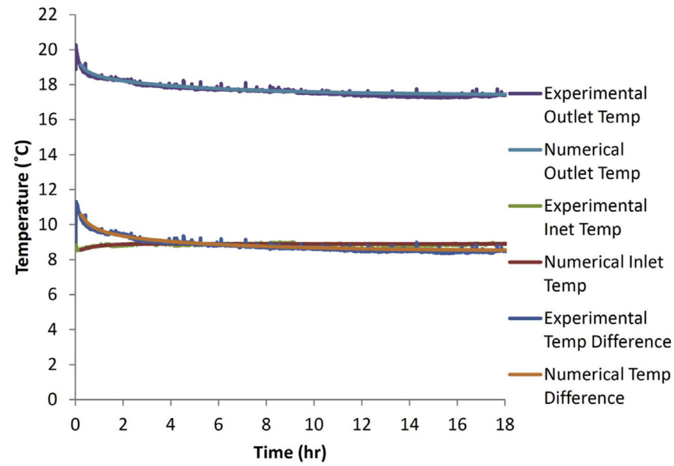

Fig. 10. Modeled and experimental water temperature at the SCHE inlet and outlet and the difference between the water temperature at the inlet and outlet for double tube at increased spacing.

4.2. *Numerical model implementation*

To identify the parameters that have the most significant effect on the performance of SCHEs, the proposed numerical model was used to study heat transfer in a typical SCHE, with the properties in. Table 3 and Table 4 excluding the variable parameters for each test. Using the developed numerical model, effects of various parameters (such as thermal conductivity, hydraulic conductivity, geothermal gradient, rate of heat extraction and tube arrangement) on the performance of the SHCE are studied in the following sections.

4.2.1. *Effect of hydraulic conductivity of backfill*

To investigate the effect of natural convection on heat transfer in SCHEs, the performance of heat extraction from SCHEs were studied, using a wide range of ground hydraulic conductivity values that represent various possible backfill materials. The SCHE consists of 36 heat exchange tubes, 4 m apart in a matrix formation shown in Fig. 2. The rate of heat extraction is assumed to be 5.4 kW.

Fig. 12 shows the temperature field for the SCHE with a hydraulic conductivity of 10^{-4} m/s after 5, 10, 20 and 30 years of operation. Heat extraction from the backfilled stope results in temperature drop inside the backfill. As time passes, the extension

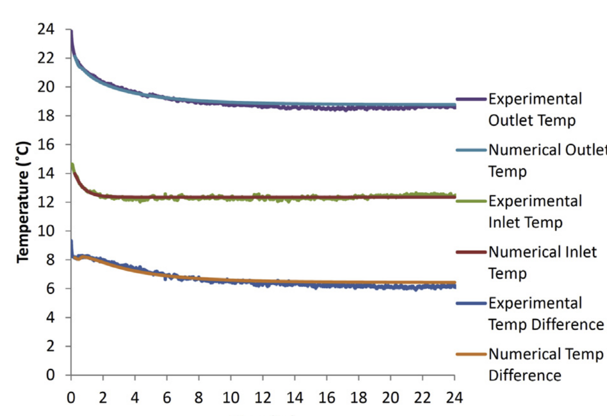

Fig. 11. Modeled and experimental water temperature at the SCHE inlet and outlet and the difference between the water temperature at the inlet and outlet for parallel arrangement.

Table 3
Thermal properties of backfill, tube, and water.

	Backfill	Tube	Water
Density (kg/m^3)	2200	–	998
Heat capacity (J/kg °C)	1136	–	4180
Thermal conductivity (W/m°C)	1.5	4	0.58
Hydraulic conductivity (m/s)	10^{-4}	–	–

Table 4
Properties of the SCHE.

Domain size	60 m × 60 m × 70 m
Heat exchange tube length	30 m
Inner diameter of the tube, D_1	25.4 mm
Tube thickness	6.3 mm
Ground temperature	22 °C
water flow rate through SCHE	0.257 kg/s
Number of U-tubes	6 × 6
Porosity of ground, φ	0.4

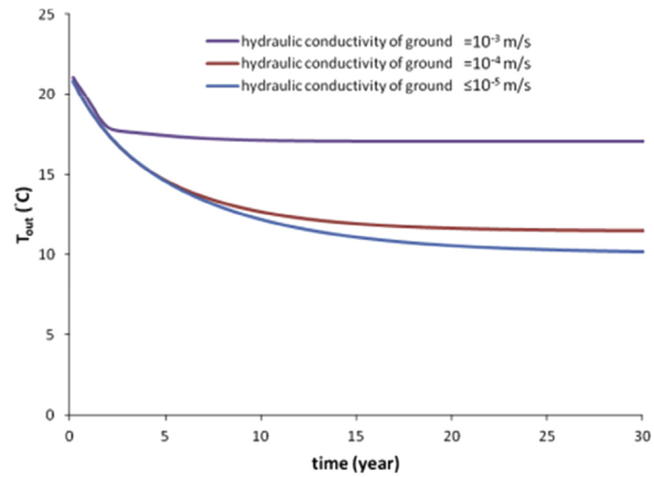

Fig. 13. Outlet temperature of three SCHEs with different hydraulic conductivity of ground, modeled over a 30-year time period.

of this cold zone results in a lower resource temperature, which will decrease the outlet temperature of the SCHE, as shown in Fig. 13.

To investigate the effect of hydraulic conductivity, outlet temperatures of the SCHEs with various hydraulic conductivity values are shown in Fig. 13. The results associated with $k_h \leq 10^{-5}$ m/s are the same. In other words, the effect of natural convection for $k_h \leq 10^{-5}$ m/s is negligible. However, as hydraulic conductivity increases, natural convection leads to a higher outlet temperature. For example, after 20 years of operation, the outlet temperature for $k_h = 10^{-4}$ m/s is almost 1 °C higher than the outlet temperature for $k_h = 10^{-5}$ m/s, while the resulting outlet temperature for $k_h = 10^{-6}$ m/s is only 0.01 °C higher than the outlet temperature associated with $k_h = 10^{-5}$ m/s. Fig. 13 indicates that an SCHE exhibiting natural convection can provide heat at a higher outlet temperature compared to an identical, impervious SCHE. This

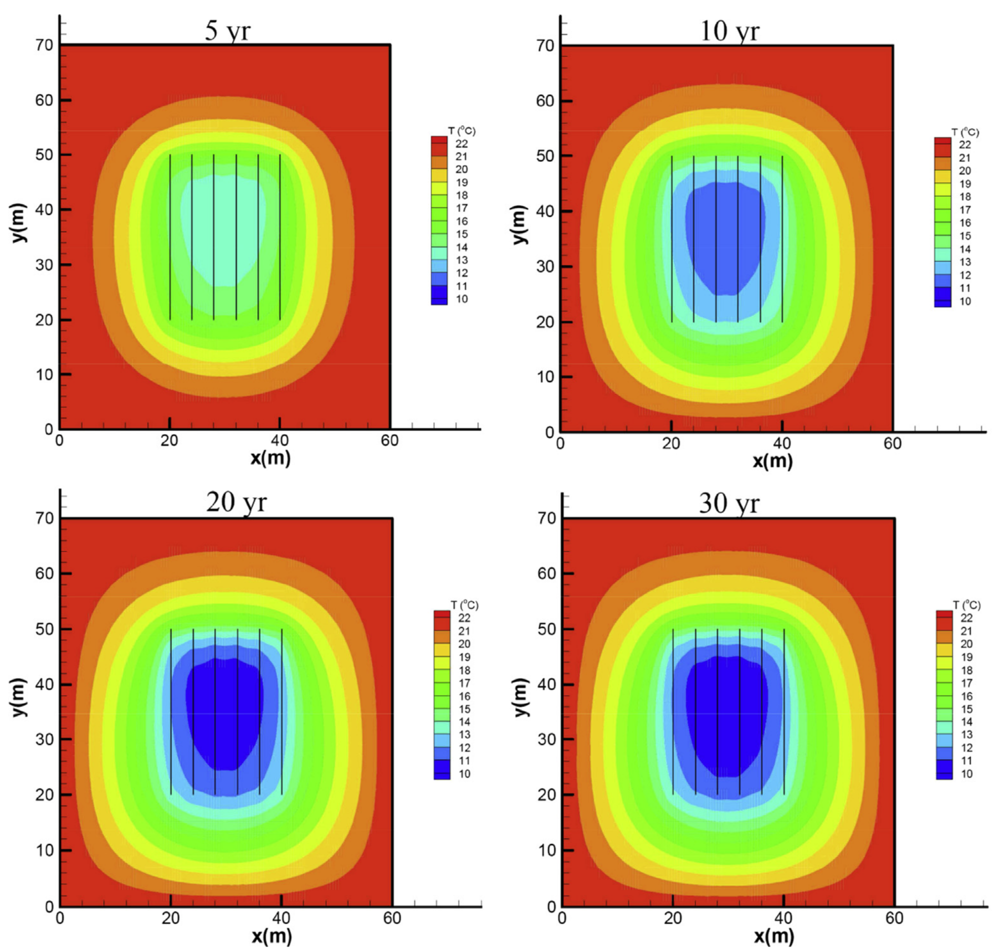

Fig. 12. Temperature field in the mid-plane ($y = 0.5$ H$_1$) of an SCHE with a hydraulic conductivity 10^{-4} m/s after 5, 10, 20 and 30 years of operation.

suggests that the rate of heat extraction can be enhanced in long-term operation of a GCHE by taking advantage of natural convection. Considering the low hydraulic conductivity of paste and hydraulic backfill ($k_h \leq 10^{-5}$ m/s), it can be said that natural convection has little or no effect on the performance of geothermal energy extraction from backfilled mine stopes.

4.2.2. Effect of thermal conductivity of rock mass and backfill

The effect of thermal conductivity of rock mass surrounding the stope was studied by comparing four cases in which an SCHE is surrounded by a rock body with thermal conductivity of 1–2.5 W/m°C. The resulting outlet temperature is shown in Fig. 14. Increasing the thermal conductivity of rock mass strongly affected the outlet temperature. In other words, as the thermal conductivity of rock mass increases, conduction of heat energy from heat from the far boundaries to the SCHE improves. However, this improvement is not endless and a hypothetical SCHE surround by a rock mass with zero thermal resistance is equivalent to a backfilled SCHE surrounded by isothermal rock walls.

To investigate the effect of thermal conductivity of backfill on the performance of SCHEs, four SCHEs with backfill thermal conductivity of 1–2.5 W/m°C were assumed. Fig. 15 shows the resulting outlet temperature for four different values of thermal conductivity of backfill. Increasing thermal conductivity of backfill will greatly improve the outlet temperature. However, there is a limit to this improvement: if the thermal conductivity of backfill is considerably higher than of the rock mass, heat transfer into the SCHE is ruled by the resistivity of rock mass. Comparison of Figs. 14 and 15, suggests that thermal conductivity of backfill plays a more important role on the performance of geothermal energy extraction from backfilled mine stopes. This is because backfill is the medium that is immediately responsible for transferring the geothermal heat into the heat exchange tubes.

4.2.3. Effect of tube arrangement

Cost of drilling and excavation is a sizeable portion of the overall costs of conventional GCHEs. Therefore, the number of boreholes of a conventional GCHE is usually defined by economic as well as technical considerations. Contrary to conventional borehole heat exchanger, the heat exchange tubes of an SCHE are installed in an empty stope. This means that the number of tubes installed can be defined to achieve optimum performance. To study the effect of number of heat exchange tubes, three SCHE systems with 16, 36 and 64 heat exchange tubes. The geothermal extracted heat power was assumed to be the same for all three systems. The results of the effect of number of tubes on the outlet temperature of the SCHE are shown in Fig. 16. Increasing the number of tubes from 16 to 36 increases the outlet temperature significantly, but the increase in outlet temperature is smaller when the tube number is increased from 36 to 64.

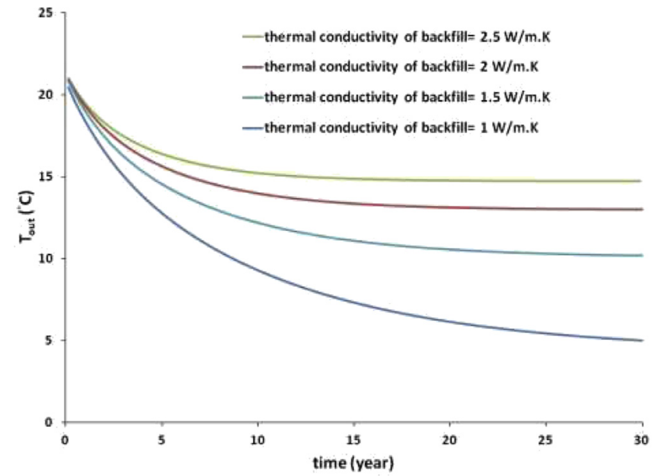

Fig. 15. Outlet temperature of four SCHEs with different thermal conductivity of backfill, modeled over a 30-year time period.

4.2.4. Effect of ground temperature

Ground temperature at the location of an SCHE is dependent to the geothermal gradient of the mine reservoir. The correlation between the temperature of the resource and the performance of a geothermal heat pump is of extreme importance. The Coefficient of Performance (COP) of the geothermal heat pump connected to the SCHE is strongly affected by the temperature at which the geothermal heat is produced; for the same rate of heat extraction, a higher ground temperature will lead to a higher outlet temperature. Fig. 17 shows the effect of ground temperature on the

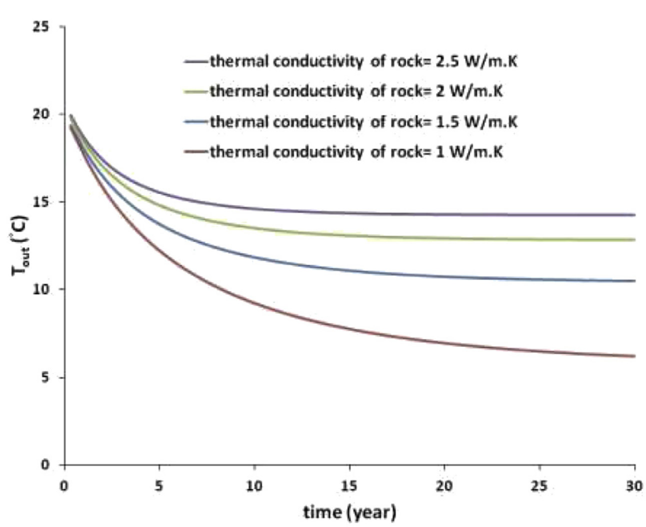

Fig. 14. Outlet temperature of four SCHEs with different thermal conductivity of rock, modeled over a 30-year time period.

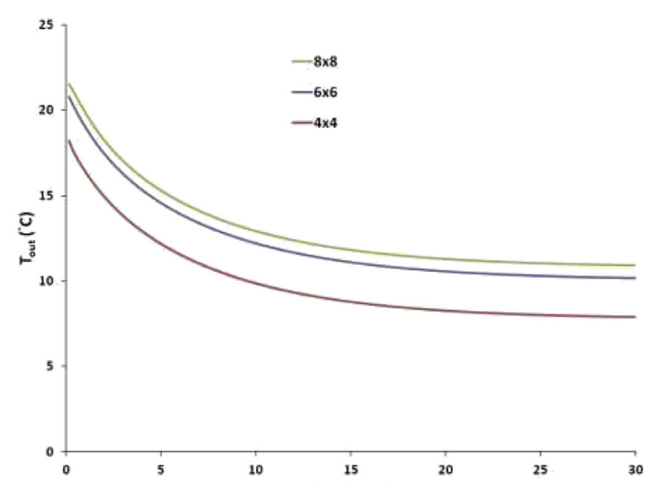

Fig. 16. Outlet temperature of three SCHEs with different number of tubes, modeled over a 30-year time period.

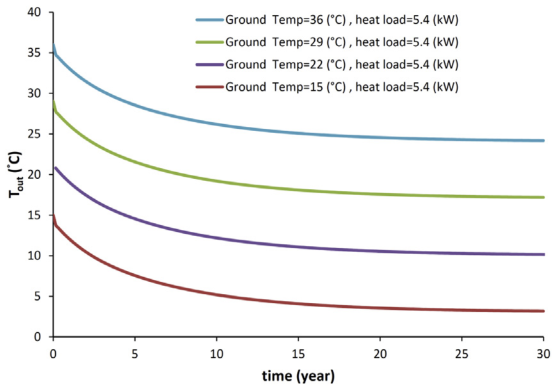

Fig. 17. Outlet temperature of four SCHEs with a constant rate of heat extraction of 5.4 kW and different ground temperature values, modeled over a 30-year time period.

performance of an SCHE. For the same amount of heat extraction, increasing the ground temperature by a given amount will increase the outlet temperature by the same amount. This is because the coupled energy equations for ground and water (Equations (4) and (6)) are both linear with regards to temperature. Therefore, an increase in the ground temperature will augment the outlet water temperature by the same amount. Fig. 17 also shows that the higher the ground temperature, the higher the rate of heat extraction can be. Thus, a deeper mine provides the opportunity to have access to higher ground temperatures and therefore higher rate of heat extraction.

4.2.5. Effect of rate of heat extraction

One of the most important steps in the design of a geothermal heat exchanger is to define the rate at which the SCHE can sustainably produce geothermal heat. If a resource is subjected to overproduction of heat, its temperature will drop relatively soon and it will no longer be able to provide heat at a reasonable temperature. This temperature drop will decrease the COP of geothermal heat pump, which may endanger the economic feasibility of the geothermal system. To study the effect of rate of heat extraction on the outlet temperature, heat transfer in an SCHE subjected to various rates of heat extraction is simulated. Ground temperature of 36 °C is assumed in this part of study. Fig. 18 illustrates the effect of rate of rate of heat extraction on the outlet temperature of the SCHE. As an example, the sustainable rate of

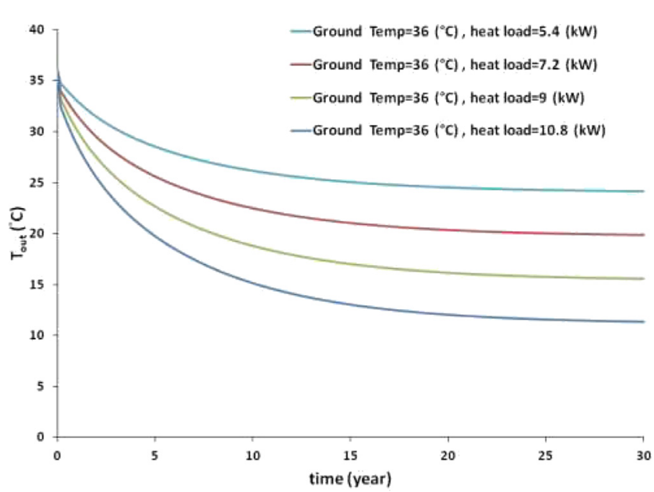

Fig. 18. Outlet temperature of four SCHEs with a ground temperature of 36 °C and different rates of heat extraction, modeled over a 30-year time period.

heat extraction for the SCHE of this study should be selected in accordance to Fig. 18. Let us assume that an outlet temperature above 12 °C is required for the operation of the geothermal heat pump to be economically viable. In this case, after 20 years of extracting at the rate of 10.8 kW, the outlet temperature will be below 12 °C. Therefore, 10.8 kW is not a suitable rate of heat extraction.

5. Conclusion

Backfilled stopes of an underground mine have a considerable capacity for sustainable geothermal heat production, not only during the operational life of the mine, but also after the mine has been closed. Determining the sustainable rate of heat extraction, which is the maximum rate of heat extraction at which a desirable outlet temperature (i.e. COP) is maintained, is one of most important factors for the economic feasibility of a geothermal system. The most significant heat exchange mechanism in backfill is conduction. Therefore, the thermal conductivity of the backfill material plays a significant role in the geothermal heat production. A typical Canadian underground mine, with its numerous vast backfilled stopes, is capable of producing 20 MW of usable heat, which is equivalent to an annual savings of 3.5 million dollars (assuming that the geothermal system replaces natural gas heating), or 11 million dollars (assuming that the geothermal system replaces electric heating). Thus, applying the novel idea of harvesting geothermal energy from underground mine stopes could create "sustainable mining communities" that can produce inexpensive, clean and renewable energy not only during the mining operation, but also long after ore depletion.

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