

**POSSIBILITY OF HARVESTING HEAT FROM BACKFILLED MINE STOPES**

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### **ABSTRACT**

Underground mines, with their relatively high ground temperature and their extensive backfilled stopes provide a great opportunity for producing geothermal heat. The novel idea of installing a network of heat exchange tubes into stopes prior to backfill placement converts each mine stope into a heat producing battery. In this system, backfill plays the role of the heat exchange medium conducting heat from the surrounding rockwalls to the heat exchange tubes. This geothermal heat can be used for heating: mine facilities and buildings, the intake air, a close-by mineral processing plant, or even nearby communities. This paper investigates the possibility of extracting renewable geothermal energy from backfilled mine stopes by means of closed-loop geothermal cycles. To simulate realistic operational conditions a heat transfer model is developed and solved numerically. To evaluate the numerical results, a small scale physical model is constructed and the experimental results are compared with the simulation results. The study estimates the sustainable rate at which heat can be extracted from a typical underground mine stope, the resulting outlet temperature and performance of the geothermal system. The results show that mine stopes are capable of sustainably producing geothermal heat not only when the mine is active, but also after the depletion of the ore body. Therefore, an underground mine will no longer be perceived as an enduring economic liability, but as a long-lasting source of clean, renewable, and inexpensive low-grade geothermal heat.

### **KEYWORDS**

Geothermal energy, underground mine, ground-coupled heat exchanger, backfilled stope, geothermal stope

### **INTRODUCTION**

The pending scarcity of fossil fuel resources and the environmental issues associated with burning these fuels have motivated scientists to look for alternative and renewable sources of energy. Geothermal energy is recognized as one of the most promising and cleanest options for heat production and electricity generation. 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. 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.

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 underground water displacement. Also, an open-loop geothermal system is only applicable when an underground water aquifer is available (Kavanaugh & Rafferty, 1997). 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. 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.

The second type of the geothermal heating/cooling system is the 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 result in environmental underground water displacement issues, 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. 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.

The present paper investigates the novel idea of employing closed-loop geothermal cycles in underground mines. In the closed-loop type of geothermal cycle, extraction of energy from the geothermal source is carried out by circulating a “working fluid” in a closed network of tubes implanted into the geothermal source, and is 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 for open-loop geothermal systems. Also, because the underground water is not pumped to the surface, there will be no risk of exposure of the chemical content of the underground water to air.

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.

## MATHEMATICAL MODEL

The geometry of the model comprises a cubic control volume of backfill, shown in Figure 1a. GHCE tubes are installed vertically inside the stope. The proposed geometry of the GHCE tube network in Figure 1 incorporates U-tubes as well as single 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 GCHE tubes may be interconnected in series to increase the outlet temperature of the circulating fluid, which is assumed to be water.

Backfill is a porous medium, so the governing equation for heat transfer in the GCHE 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 (Nield & Bejan, 1992). Therefore, the governing heat transfer equation is expressed by:

$$\rho_m C_m \frac{\partial T}{\partial t} + \rho_f C_f (u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z}) = \frac{\partial}{\partial x} (k_m \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k_m \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k_m \frac{\partial T}{\partial z}) + q \quad (1)$$

where  $\rho_m$ ,  $C_m$ ,  $k_m$ ,  $\rho_f$ ,  $C_f$ , 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 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, respectively, the  $x$ ,  $y$ , and  $z$  components of the volume-averaged velocity of water in a porous medium. It is 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.

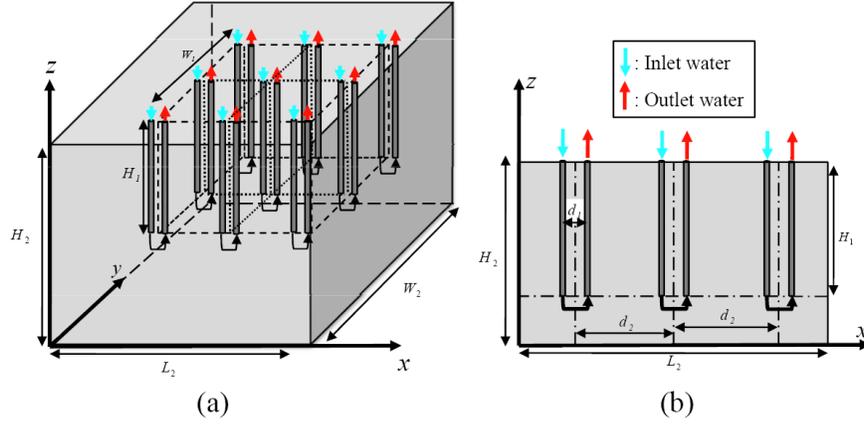


Figure 1- (a) 3D representation of the model, and (b) mid-plane cross section

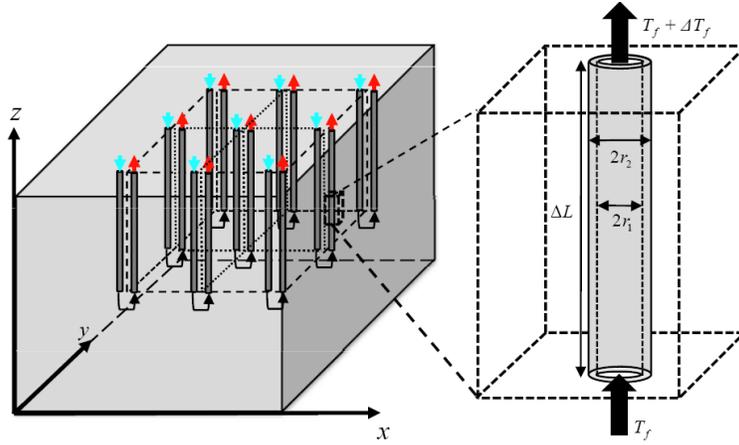


Figure 2- Tube cell and its surrounding control volume

Also  $\dot{q}$  in equation (1), is the rate of heat transferred from the backfill to the water through the tube wall per volume of the porous media (Li & Zheng, 2009; Nam, Ooka, & Hwang, 2008). Thus,  $\dot{q}$  is nonzero only when water resides in a tube cell, and is zero elsewhere. For a tube cell and its associated control volume, shown in Figure 2,  $\dot{q}$  is expressed by:

$$\dot{q} = -\dot{m} C_f (T_{out} - T_{in}) \times \frac{1}{\Delta V} \quad (2)$$

where  $T_{in}$ ,  $T_{out}$ ,  $\dot{m}$ , and  $\Delta V$  are respectively, the temperature of water at the inlet of the tube cell, the temperature of water at the outlet of the tube cell, the mass flow rate of water through the tube cell, and the volume of the tube cell. In equation (2),  $T_{out}$ , is defined by using the energy balance in the control volume; the rate of heat gained by the water is equal to the convective heat flux through the tube wall. Thus, the energy balance equation is expressed in the following differential form:

$$\dot{m} C_f dT_f = U_o (\pi D) (T_{wall} - T_f) dL \quad (3)$$

where  $T_{wall}$ ,  $U_o$ ,  $T_f$ ,  $D$ , and  $L$  are respectively, the wall temperature, the overall heat transfer coefficient, the fluid bulk temperature, the inner diameter of the tube cell, and the length of the tube. Integrating equation (3) over the length of a tube cell leads to the following:

$$\dot{m} C_f \int_{in}^{out} \frac{dT_f}{T_{wall} - T_f} = (\pi D U_o) \int_0^{\Delta L} dL \quad (4)$$

where  $\Delta L$  is the length of the tube cell, and  $\dot{m} = 0.25\pi D^2 V_w$ , where  $V_w$  is the velocity of water in the tube. The overall heat transfer coefficient in equation (4) comprises two heat transfer resistivity values; the convective resistivity of flow inside the tube and the conductive resistivity of the tube thickness. Thus,  $U_o$  is formulated as follows:

$$\frac{1}{U_o} = \frac{r_2}{r_1} \times \frac{1}{h} + \frac{r_2 \ln(r_2/r_1)}{k_{tube}} \quad (5)$$

where  $h$ ,  $r_1$ ,  $r_2$ , and  $k_{tube}$  are respectively, the coefficient of convection of flow of water inside the tube, the inner radius of the tube, the outer radius of the tube, and the thermal conductivity of the tube. The first term on the right-hand side of equation (5) corresponds to the convective thermal resistance between the fluid and the inner tube wall, while the second term on the right-hand side refers to the thermal resistivity of the tube thickness. The convection coefficient,  $h$ , is calculated from (Dittus & Boelter, 1930):

$$Nu_D = hD/k_f = 0.023 Re_D^{0.8} Pr^{0.3} \quad (6)$$

where  $Nu_D$ ,  $Re_D$ ,  $Pr$ , and  $k_f$  are, respectively, the Nusselt number, the Reynolds number, the Prandtl number, and the thermal conductivity of water. A finite-volume method is employed for discretization of equation (1) (Patankar, 1980). An optimized FORTRAN code with a structured Cartesian mesh was developed to conduct the numerical calculations. To simulate a constant rate of heat extraction, an inlet temperature adjuster subroutine was devised in the computational code that takes advantage of the Newton-Raphson method to adjust the inlet temperature of the heat exchanger so that the extracted heat power matches the demanded heat load power.

### Thermal properties of backfill

Knowledge of the thermal properties of backfill is key to a proper simulation of heat extraction from underground mine stopes. An unsteady-state measurement technique employing a needle probe (ASTM D5334 – 08) was used to measure the thermo-physical properties of backfill in this research. The KD2 pro needle probe from Decagon Devices Company was used to simultaneously measure the thermal conductivity and resistivity, the volumetric heat capacity and the thermal diffusivity of a body. For improved accuracy, each data point is the result of five measurements, and for a given five-measurement set, if the difference between them exceeded 5% of their average value, that set of the data points was rejected to avoid excessive error. Briefly, each data point is composed of five measurements with less than 5% deviation from their average value.

Sample homogeneity and the effect of sample size, as well as effective parameters in backfill design, such as curing time, pulp density and binder content were studied. It was found that a novel aspect for interpreting the thermal conductivity of backfill is needed - by introducing backfill as a porous material, effects of physical parameters including the degree of saturation, the porosity and different solid particles could be investigated.

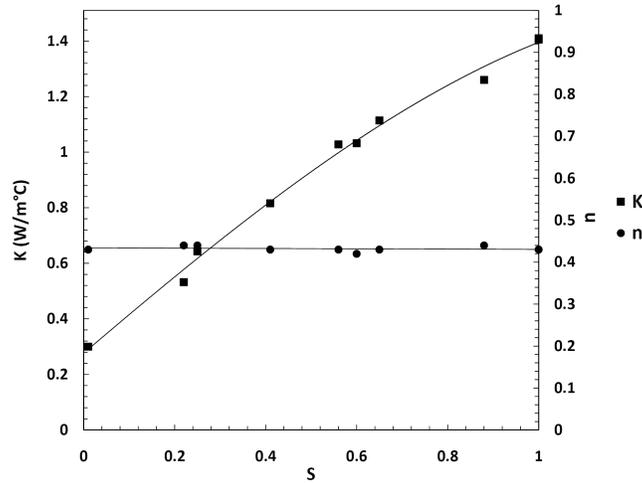


Figure 3- Effect of the degree of saturation on thermal conductivity of backfill

Saturation is the most effective factor among the above mentioned set of physical parameters. For example, in Figure 3 the thermal conductivity of a fully saturated backfill sample with a porosity of 0.42 is 1.4 W/m<sup>2</sup>C, whereas the thermal conductivity of the same fully-dried sample is 0.23 W/m<sup>2</sup>C. Therefore, if a backfill with high thermal conductivity is needed, saturation will be the key element to be monitored and controlled.

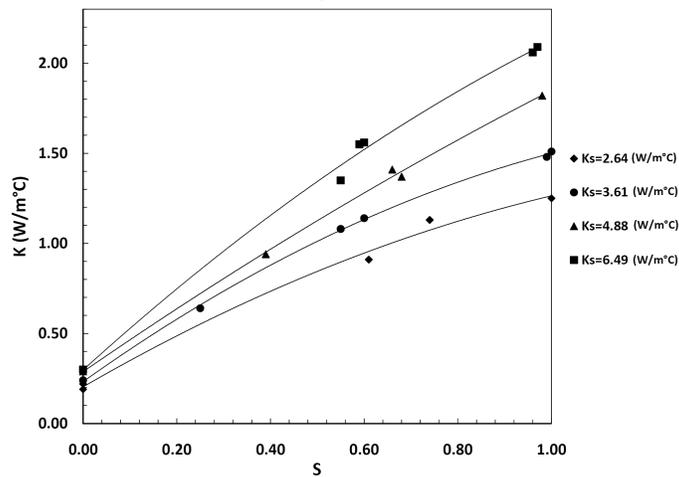


Figure 4- Mixed effect on solid particles and saturation on thermal conductivity of backfill

In Figure 4, the effects of the thermal conductivity of the solid particles of the backfill and the degree of saturation on the thermal conductivity of backfill are shown. Regardless of the degree of saturation of the porous backfill, a solid particle with a higher thermal conductivity results in a backfill composition with a higher thermal conductivity.

## RESULTS AND DISCUSSION

To show the potential for geothermal heat production from backfilled mine stopes, a sample mine stope is considered with properties shown in Tables 1 and 2. The results include the temperature field in the backfill mass and the temperature of the water flowing through heat exchange tubes. Figure 5 shows the temperature field inside the body of backfill after 5, 10 and 15 years of continuous energy extraction at a constant rate of 64 kW. For ease of assessment, the thermal properties of backfill and the rock mass are assumed to be equal. As can be seen in Figure 5, heat is extracted from the core of the filling mass causing its temperature to drop. However, after approximately 15 years, a steady state is reached in which the conductive heat transferred to the tube network matches the heat absorbed by the tube network; the sole source of heat is the heat conducted through the boundaries and not the sensible heat of the filling material.

	Backfill	Water	Tube
Density (kg/m <sup>3</sup> )	2,000	998	-
Heat capacity (J/kg°C)	1,250	4,180	-
Thermal conductivity (W/m°C)	1.5	0.58	4

Tube length	60 m
Outer diameter of the tube	0.0254 m
Tube thickness	0.005 m
Number of U-tubes	8×8
Center-to-Center distance of the tubes	5.714 m
Mass flow rate of water	5.714 m
Stope size	40 m×40 m×70 m
Thickness of surrounding rock mass	10 m
Rockwall temperature	30 °C

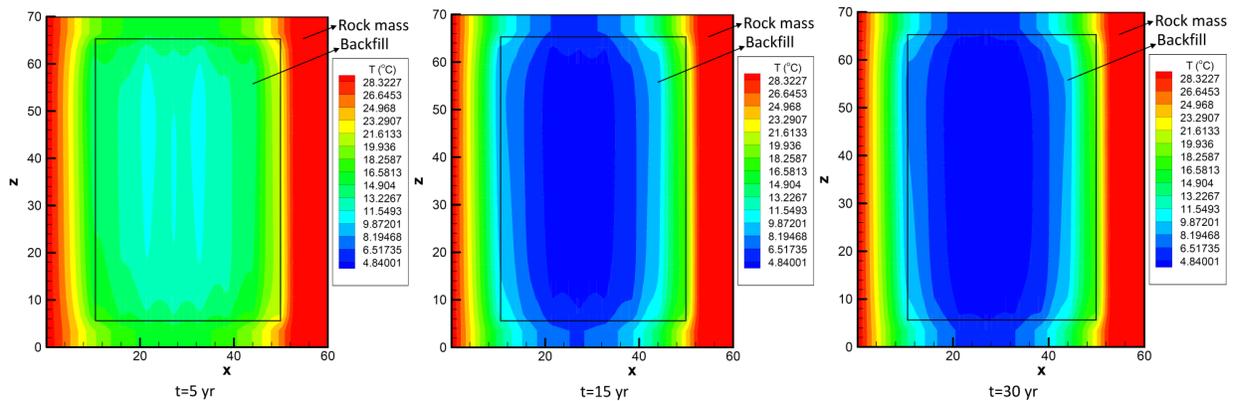


Figure 5- Temperature field at the mid plane of a backfilled mine stope with properties of Table 1 and Table 2, after 5, 15 and 30 years of heat extraction at a constant rate of 64 kW

Figure 6 shows the outlet temperature versus the time of extraction. According to Figure 6, as heat extraction continues and the temperature of the backfill mass drops, the outlet temperature gradually decreases. However, the rate of decrease becomes smooth until a steady state is reached (after approximately 15 years).

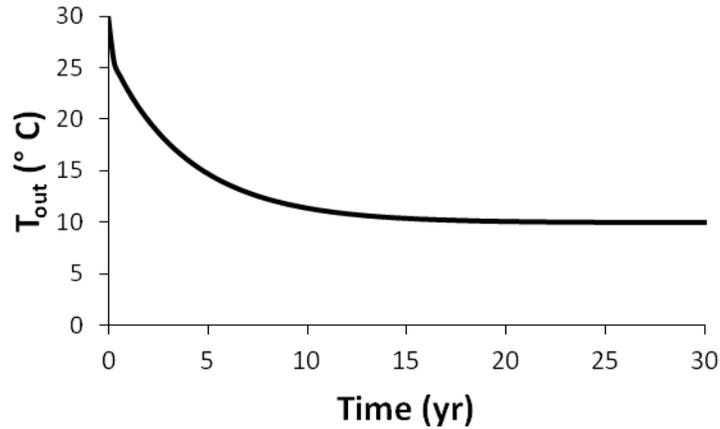


Figure 6- Outlet temperature corresponding to heat extraction at a constant rate of 64 kW from a backfilled stope with properties of Table 1 and Table 2

It is important to note that the Coefficient of Performance (COP) of the geothermal heat pump is significantly dependent on the outlet temperature; the higher the outlet temperature of the water, the higher the COP (and therefore, less electricity is consumed by the geothermal heat pump). Thus, the economic feasibility of the geothermal system depends on the temperature of the produced water. Therefore, in this study, an outlet temperature value of 12°C or higher is assumed to be desirable. Figure 7 shows the effect of the heat extraction rate on the outlet temperature corresponding to the heat extraction from a backfilled stope with properties of Table 1 and Table 2. As shown in Figure 7, the maximum rate of heat extraction for a desirable outlet temperature is about 64 kW.

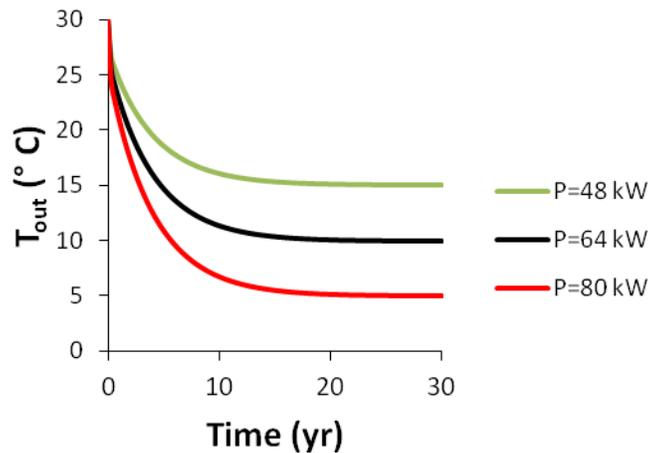


Figure 7- Effect of the extraction rate on the outlet temperature corresponding to the heat extraction from a backfilled stope with the properties of Table 1 and Table 2

One of the key factors in geothermal heat extraction is thermal conductivity of the resource (in this case backfill). Figure 8 shows the effect of thermal conductivity on the outlet temperature corresponding to heat extraction from a backfilled stope with the properties of Table 1 and Table 2. According to Figure 8, higher values of thermal conductivity of backfill will lead to higher outlet temperature values. Considering the fact that the thermal conductivity of backfill is significantly dependent on its moisture content, it is greatly desirable from the geothermal point of view to keep the backfill mass as moist as possible.

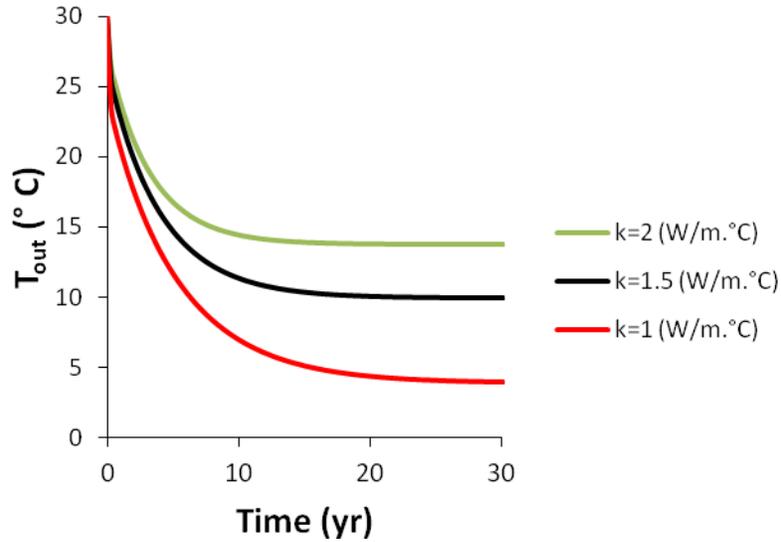


Figure 8- Effect of thermal conductivity on the outlet temperature corresponding to the heat extraction from a backfilled stope with the properties of Table 1 and Table 2

One way to increase the outlet temperature of water is to connect the geothermal tubes in series. However, this technique will lead to a higher fluid bulk temperature and therefore, decrease the rate of heat extraction. Figure 9 shows the effect of the tube network arrangement on the outlet temperature corresponding to the heat extraction from a backfilled stope with the properties of Table 1 and Table 2. Two identical tube networks are considered; in one of them all the tubes are operating parallel, but in the second one every two tubes are connected in series. As Figure 9 shows, a tube network with no tubes in series leads to a higher outlet temperature. In other words, having no tubes in series will increase the temperature difference between the resource and the bulk fluid and therefore, improve the heat transfer rate; meaning that a higher inlet temperature will lead to the same extracted power compared to the case when every two tubes are connected in series.

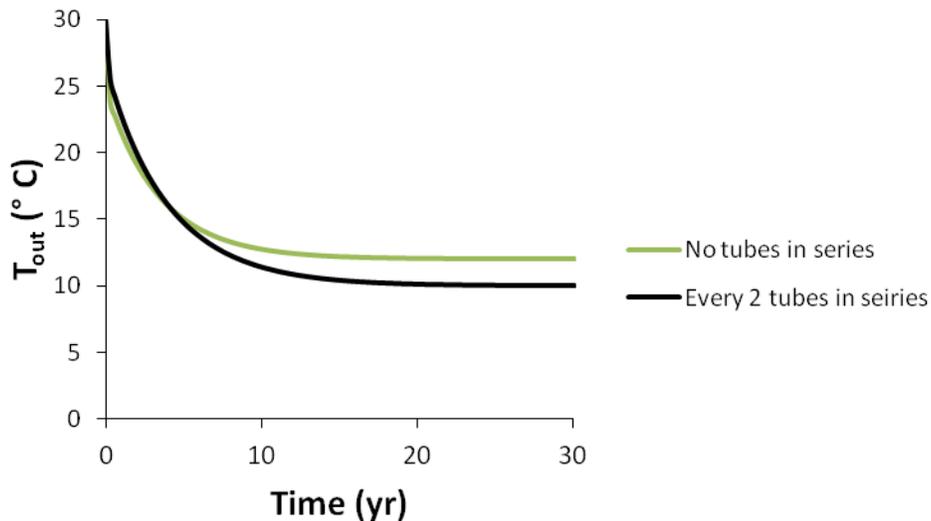


Figure 9- Effect of the tube network arrangement on the outlet temperature corresponding to the heat extraction from a backfilled stope with the properties of Table 1 and Table

## 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 inside the 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 megawatts 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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