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Sustainable heat extraction from abandoned mine tunnels: A numerical model

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Abandoned mines are often associated with enduring liabilities, which involve significant costs for decades after the decommissioning of the mine. Using a decommissioned mine as a geothermal resource can offset the environmental costs by supplying green heat to the communities living in and around the mine area. In this paper, a numerical assessment of geothermal heat extraction from underground mine workings using an open loop geothermal system is carried out. In this study, our focus is on fully flooded mines where the heat flow from the rock mass to the mine cavities is dominantly controlled by conduction in the rock mass. The sustainable heat flux into the mine workings is assessed using a transient two-dimensional axisymmetric heat transfer model. Finite volume method is applied to solve the model and simulate the transient temperature fields in the rock mass and within the water (flowing through cavities). The model is capable of controlling the rate of heat extraction through continuous adjustment of the rate of water flow through the mine. Sustainable rate of heat extraction is calculated for seasonally varied heat loads and for different project life cycles. It is shown that, with proper resource management, each kilometre of a typical deep underground mine tunnel, can produce about 150 kW of usable heat in a sustainable manner. The model is validated by comparing its results with other published models and realistic data available from Springhill mine, Nova Scotia, Canada. It is found that the sustainable heat extraction is controlled dominantly by virgin rock temperature, thermal conductivity of the rock mass, and seasonal heat load variations. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4712055]

I. INTRODUCTION

Capturing usable heat from mine water can help with improving the sustainability of mining activities by using postmining infrastructure as an energy resource for communities living in areas close to the mine site.[1,2] Underground mines consist of a network of shafts, tunnels, and drifts which are commonly flooded after closure. These mines are considered potentially viable geothermal resources as they have all three required components of a geothermal resource, namely, heat, water, and permeability.[3] In deep underground mines, the heat component is geothermal and independent from solar radiation. Considering general continental geothermal gradient of 0.03 °C/m, a temperature of 25–35 °C can be reached in a 1000-m-deep underground mine which can be an excellent geothermal resource.[4]

After an underground mine is decommissioned and flooded, millions of cubic meters of water will be stored within the mine cavities. This water infiltrates into the mine from three sources. The first source is water from precipitation that finds its way into the mine network

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due to gravity. The second source is the water from underground aquifers that penetrates into mine openings due to hydro-geological pressure. A third source may be artificial flooding, through diverting surface waters (such as lakes) into the mine workings.

The infiltration of water into underground mine openings is obviously dependent on the permeability of the underground rock formation. As for the permeability, there are two types of permeability in the mine: (1) The natural permeability of the rock mass caused by geological/tectonic processes in time and (2) the man-made permeability related to the mine openings in which water can flow with little hydraulic resistance. The combination of heat, water, and permeability makes underground mines an excellent open loop geothermal resource. Also, since the flooded mine has a great water storage capacity, it can be used as a geothermal reservoir to manage the heat loads during the peak-demand-periods. Thus, short-term energy storability in underground mine cavities, which is not easily available in conventional open loop systems, provides a great opportunity for peak shaving.[5]

Geothermal heating/cooling systems are categorized into two distinct types.[6] The first is the open loop in which underground water is chilled using a heat pump to extract some of its heat energy and is then returned to the underground aquifer. Open loop systems require the availability of underground water aquifers. The second type is the closed loop system in which geothermal energy is extracted by circulating water (or a mixture of water and antifreeze) in a closed network of heat exchange tubes embedded in the ground.

Conventional open loop geothermal systems are based on tapping into an aquifer in which water flows slowly from the injection point towards the production point. Similar situation is present in abandoned mines where a mine tunnel acts as a conduit for water flow between the injection and production points with the exception of having very little hydrological resistance (compared to an aquifer). Therefore, an underground mine is similar to an open loop geothermal system where the water flow is controlled mainly from above the ground (by adjusting the rate of production and injection). The present paper studies heat extraction from medium temperature resources in underground mines for the purpose of heating with heat pump systems. Compared to shallow geothermal resources, this paper is dealing with higher temperature resource (available in deep mines) leading to higher coefficient of performance (COP) (i.e., less dependence on electricity).

A major cost associated with conventional open loop systems is drilling and well maintenance. These costs play very important roles in the economic feasibility of an underground open loop system. Thus, the application of underground openings of a mine as an open loop geothermal system provides the opportunity of decreasing these costs (as fewer wells are needed, compared to conventional open loop systems).

Using geothermal energy from mines in Canada started in the 1980s.[7] One of the pioneering studies in the field of geothermal heat mining is the Springhill project, in Nova Scotia, Canada which has been extensively discussed in a number of publications.[7,8] In this project, a coal mine is used to heat a plastic factory with an approximate surface area of 14 000 m^2. The production well is located 140 m deep and a flow rate of 240 l/min of mine water is fed to the heat pump system which includes 11 heat pumps used for heating in winter and cooling in summer.[8] The mine water at the production well has a temperature of 18 °C and leaves the system at a temperature of about 13 °C (equivalent to 84 kW of heating load) in winter and 25 °C (equivalent to 120 kW of cooling load) in summer and then the water is re-injected to the mine 30 m below the surface.[9] The average COP for the system is 3.6 in the winter.[8] The company's saving, using the geothermal system, is estimated to be $160 000 per year in energy costs over a conventional oil furnace system.[7]

The Springhill heat mining is a small scale project which does not raise any resource sustainability issues. However, if a mine is intended to be used at large scale (providing heat to a large community), the resource assessment and sustainability issue would be of great importance. There are other small scale and large scale examples worldwide that successfully use mine water in open loop geothermal systems. For instance, in Germany, Wismut mine in Marienberg provides 690 kW of heat capacity[10] and in Freiburg, a mine gallery is used to provide heating and cooling for a castle.[11] The Heerlen project in Netherlands is one of the greatest heat mining projects, using mine water from a flooded abandoned coal mine. In this project a combination of 350 dwellings, 3800 m^2 of commercial space, and 16200 m^2 of community buildings are cooled and heated using mine waters.[12] In the winter, the water is pumped out from the 700 m level at 30–35 °C and in summer, it is extracted from 250 m level at 16–19 °C.[12]

With successful application of low temperature open loop geothermal systems in some flooded mines, more attention is drawn towards systematic works to find criteria for viability of different mines for large-scale heat extraction. In Canada, a preliminary study was carried on Con mine, Yellowknife, North West territories.[13] Con mine is a decommissioned gold mine just beside the city of Yellowknife (in North West Territories) in which water temperature is above 35 °C in the deeper levels of the mine. Considering the high dependency of this Nordic Canadian city on fossil fuels for heating, extraction of geothermal energy is expected to significantly reduce the city's energy costs and carbon footprint.[13] It is estimated that Con mine can contribute up to 10 MW of usable heat to the city.[13]

Another study carried out on Gaspe mines in Quebec shows that more than 700 kW can be produced from flooded copper mines near Murdochville.[14] Other studies in Canada include the Britannia Mine (British Colombia) in which up to 5 MW of usable heat was estimated to be available in the mine.[15]

Using abandoned mines as open loop geothermal resources is constrained by implementation costs, and high risks associated with thermal behaviour of these resources. The risk is mostly related to the fact that much of the available information about the underground mine workings cannot be incorporated as firsthand information into the geothermal models, due to the complexity (or even in some cases the uncertainty) of the basic geometry information of the underground openings and in-mine water movement.

The risk issue is also associated with the resource sustainability. Since the heat capacity of a mine is limited and should be matched with the demand, the total rate of sustainable heat extraction from the mine should be carefully assessed. Otherwise, if over-exploited, the mine will not be able to provide sustainable heat in long-term and its capacity to provide heat will be diminished in a relatively short period of time. One way to assess the resource sustainability is to employ a numerical simulation model which takes into account the most important and better known factors and deals confidently with the uncertainty or absence of data on some less important parameters.

During the last decade, investigators have developed numerical tools for assessing the deliverable heating/cooling capacity of underground mines. Rodriguez and Diaz[16] proposed a semi-empirical method for assessing the geothermal heat capacity of underground mine galleries. Their study is based on 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 (rate of heat extraction) and the outlet water temperature. However, the speculative nature of their model limits the practicality of their model in cases where transient heat transfer in the rock mass is significant.

Studies conducted by Raymond and Therrien[14] and Renz *et al.*[17] investigate the possibility of using the fractured rock masses of underground mines to extract mine water as geothermal heat source. The present study deals with the cases where the hydraulic conductivity of the rock formation is negligible, compared to that of the underground mine tunnel (i.e., conduction is the main heat transfer mechanism inside the rock mass).

Hamm and Bazargan Sabet,[18] used FLUENT and MARTHE computer codes to simulate heat transfer in the 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 in the assessment of geothermal application of abandoned underground mines. However, this approach gives extremely case sensitive results (which highly depend on having, usually not available, reliable and specific data) and can hardly propose any universal guidelines for the resource heat content management.

The present paper is intended to provide the general computational tools for engineers to assess the heat transfer in underground mine components (tunnels), where mine reliable data is scarce. Here, the total volume of rock mass involved in the heat transfer phenomenon is calculated. The first order parameters affecting the heat transfer mechanism are singled out and their effect on heat extraction scenarios studied. This research will help providing useful engineering rules to reliably estimate the total sustainable geothermal heat capacity of a mine, for different resource extraction scenarios.

The sustainability of the resource is very important because of both heat and fluid components of the mine. First, the accessible heat of the mine resource is limited despite the total volume of the mine rock mass being enormously large (considering that only a small portion of the rock is involved in the heat exchange phenomenon). For this reason, it is important to extract the heat at a sustainable rate so that the resource would not be thermally degraded during the project life cycle. Second, to avoid fluid depletion, it is of prime importance to re-inject the fluid into the mine after heat extraction. Note that water should be returned to the underground resource not only because of the sustainability issue but also due to the equally important environmental concerns.

Seasonal variations in the heat demand often raise a major problem in the management of a resource with limited heat capacity. For example, in Canadian communities, the heat demand is dominant during the cold winter when the resource limitation may pose difficulties in coping with peak demand. In order to investigate the effect of this issue on the performance of the geothermal system, a numerical method is proposed which takes into account the seasonal heat load variations in different exploitation scenarios.

The findings of this study help to engineer a heat reservoir in accordance to the dimensions of the selected mine component, water flow and inlet/outlet temperature into the mine component. So, it would provide a tool in the hands of engineers which enables them to design a suitable open loop geothermal system based on realistic parameters and constraints imposed by the demand (e.g., temperature of the injected water, flow of water, and seasonal variations of heat load). The proposed method would also provide an effective communication between the underground resource and the above-ground heat extraction/distribution technology. For example, we can set the chilling temperature of the heat pumps to a lower level during the cold season which would improve the heat production from the mine component (considering that any increase in the temperature difference between the injected water and the resource temperature will increase the rate of the heat exchanged between rock mass and water). Off-the-shelf software (such as FLUENT) was not used in this work, because of their lack of the versatility and adjustability. For example, in order to investigate the seasonal heat load variations, the heat load should be adjusted in each time step of the numerical simulation. This is made possible by adjusting the flow rate of the water pumped through the mine component in accordance to the load demand.

II. MODEL DESCRIPTION

A flooded underground mine tunnel is considered in constructing the bulk geometry of the model. Water infiltration through the rock mass into the tunnel is negligible, because the water will move through the lowest hydraulic resistant path which is the mine gallery. Also, water movement inside the rock mass is considered as a second order effect after the mine is fully flooded assuming that there is no hydrological gradient in the deep flooded mine (except the hydraulic gradient induced by production and injection). Using the same argument, the issue of natural convection inside the rock mass is deemed to be negligible in comparison to the forced convective flow inside the tunnel. Fig. 1(a) shows the schematics of tunnels in an underground mine. The geometry of the model is shown in Fig. 1(b). Since the proposed geometry is axisymmetric, the numerical domain, shown in Fig. 1(c), is a 2D representative of Fig. 1(b).

As can be seen in Fig. 1, the model is composed of two distinct media, namely water and rock. It is assumed that water flows only through the mine component with a uniform flow. Thus, the only component of the flow field will be the velocity of water inside and along the tunnel. The transient energy balance equation is expressed

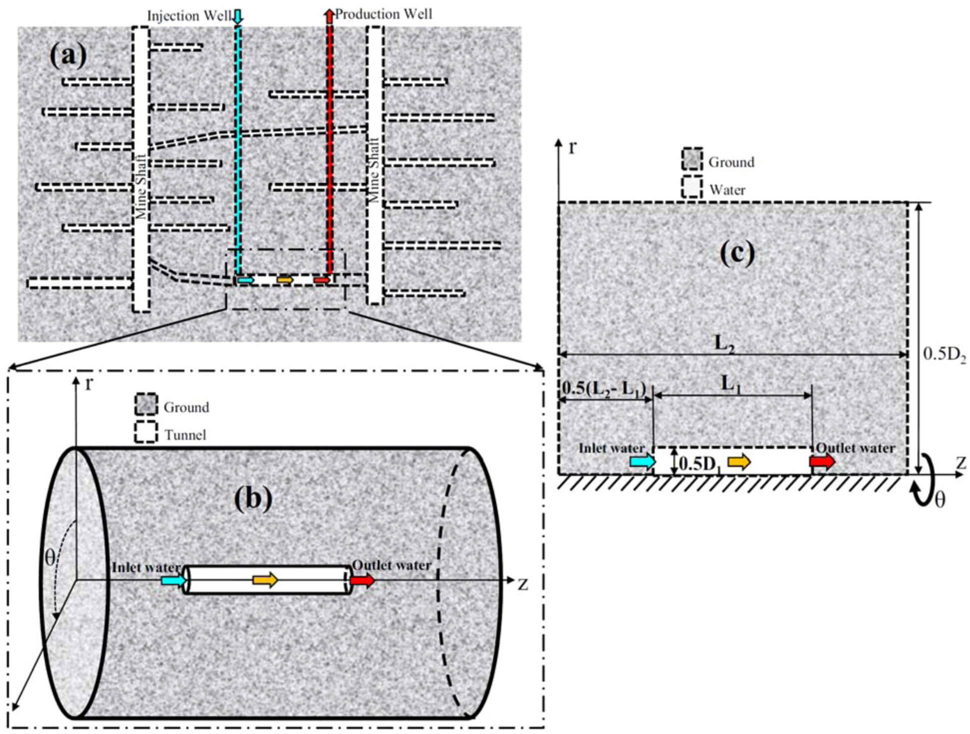

FIG. 1. (a) Underground mine schematics, (b) 3D demonstration of the model, and (c) 2D demonstration of the numerical domain.

$$\rho C_p\left(\frac{\partial T}{\partial t}+\left(w\frac{\partial T}{\partial z}\right)\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{1a}$$

or

$$\frac{\partial T}{\partial t}+w\frac{\partial T}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}\left(\alpha r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\alpha\frac{\partial T}{\partial z}\right), \tag{1b}$$

where ρ, C_p, k, and $\alpha = k/\rho C_p$ are density, specific heat capacity, thermal conductivity, and thermal diffusivity of the medium, respectively. It should be noted that the thermal properties are medium-dependent, meaning that in the tunnel, they will be the thermal properties of water and in the ground, and they will be the thermal properties of the rock mass. Also, T is the temperature and w is the z-component (longitudinal component) of underground water velocity (which is assumed to be zero in the rock and non-zero inside the flooded tunnel. Equation (1) mathematically demonstrates the following heat transfer mechanisms:

1. Forced convection inside the tunnel:
   This heat transfer mechanism is the result of the laminar forced flow of water inside the mine tunnel. If properties of water are substituted into Eq. (1), the resulting equation would be the equation of unsteady convective heat transfer in water where, w is the key parameter that conveys the heat along the z axis of the tunnel.
2. Conduction in the rock mass:
   There will be no significant water movement in the rock mass. So, if thermal properties of rock and $w = 0$ are substituted into Eq. (1), the resulting equation would be the equation of unsteady conductive heat transfer in the rock mass.

Since Eq. (1) represents heat transfer in both water flowing through the mine tunnel and the underground rock mass, this single expression will be the governing heat transfer equation. As Eq. (1) states the energy balance in the entire medium, the equality of heat exchange between the water flowing through the tunnel and the rock mass will be automatically satisfied. Using the "harmonic mean method" developed by Patankar,[19] the value of thermal conductivity at each point is calculated in a way that the heat flux exchanged between the water and the ground regions is balanced. Since the temperature of water is lower around the tunnel inlet, compared to its temperature around the tunnel outlet, the rock mass around the inlet of the tunnel is colder than the body of rock around the outlet. This longitudinal temperature gradient creates a conduction heat flux along the z-axis in the rock mass (in addition to the radial heat flux component across the rock zone). It should be noted that most of the existing mine thermal models (e.g., Rodriguez and Diaz[16]) have not included this effect into their equations.

Isothermal condition is assumed for the boundaries except for $r=0$ axis where adiabatic boundary condition is assumed. Also, temperature of water at the inlet of the tunnel is T_{in}. As for the initial condition, the rock mass and the underground water are in thermal equilibrium at temperature of T_g (where T_g is the ground temperature). So, the boundary and initial conditions will be as follows:

$$\left.\frac{\partial T}{\partial t}\right|_{r=0} = 0, \tag{2a}$$

$$T|_{r=0.5D_2} = T|_{z=0} = T|_{z=L_2} = T_g, \tag{2b}$$

$$T|_{r<0.5D_2, z=0.5(L_2-L_1)} = T_{in}, \tag{2c}$$

$$T|_{z=0} = T|_{t=0} = T_g. \tag{2d}$$

III. NUMERICAL METHOD

In order to solve the governing equation (Eq. (1)), finite volume method is used. Fig. 2 shows the configuration of a finite volume cell and its associated control volume and control surfaces.

The discretized form of Eq. (1) is generated by multiplying this equation by r and then integrating the governing equation over the finite volume surrounded by west wall (w), east wall (e), south wall (s), and north wall (n),

$$\int_S^n \int_W^e r\left(\frac{\partial T}{\partial t} + W\frac{\partial T}{\partial z}\right) drdz = \int_S^n \int_W^e r\left(\frac{1}{r}\frac{\partial}{\partial r}\left(\alpha r\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\alpha\frac{\partial T}{\partial z}\right)\right) drdz. \tag{3}$$

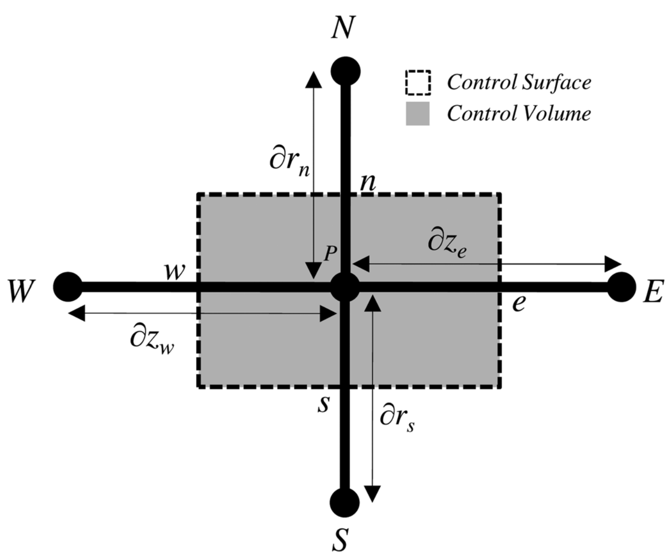

FIG. 2. Demonstration of a finite volume cell and its associated control volume and control surfaces.

The resulting discretized equation would be as follows:

$$\frac{r_n^2 - r_S^2}{2}\left\{\frac{T_P^n - T_P}{\Delta t}\Delta z + w_P(T_e - T_w)\right\} = \frac{r_n^2 - r_S^2}{2}\left\{\frac{\alpha_e}{\delta z_e}(T_E - T_P) - \frac{\alpha_W}{\delta z_W}(T_P - T_W)\right\} + \left\{\frac{\alpha_n r_n}{\delta r_n}(T_N - T_P) - \frac{\alpha_S r_S}{\delta r_S}(T_P - T_S)\right\}\Delta z. \tag{4}$$

According to Eq. (4), in each time step, the updated value of temperature of each control volume cell is expressed by

$$T_P^n = T_P + \frac{\Delta t}{\Delta z}\left\{\frac{\alpha_e}{\delta z_e}(T_E - T_P) - \frac{\alpha_W}{\delta z_W}(T_P - T_W) + \frac{\alpha_n}{\delta r_n}\left(\frac{2r_n\Delta_z}{r_n^2 - r_S^2}\right)(T_N - T_P) - \frac{\alpha_S}{\delta r_S}\left(\frac{2r_S\Delta z}{r_n^2 - r_S^2}\right)(T_P - T_S) - W_P(T_e - T_W)\right\} = T_P + \left\{a_1(T_E - T_P) + a_2(T_P - T_W) + a_3(T_N - T_P) + a_4(T_P - T_S) + a_5(T_e - T_W)\right\}, \tag{5}$$

where the coefficients of Eq. (5) are expressed by

$$a_1 = \frac{\Delta t}{\Delta z}\frac{\alpha_e}{\delta z_e}, a_2 = -\frac{\Delta t}{\Delta z}\frac{\alpha_w}{\delta z_w}, a_3 = \frac{\Delta t}{\Delta z}\frac{\alpha_n}{\delta r_n}\left(\frac{2r_n\Delta z}{r_n^2 - r_S^2}\right), a_4 = -\frac{\Delta t}{\Delta z}\frac{\alpha_S}{\delta r_S}\left(\frac{2r_S\Delta z}{r_n^2 - r_S^2}\right), a_5 = -\frac{\Delta t}{\Delta z}W_P. \tag{6}$$

In order to model seasonal heat load variations, a control scheme was proposed to adjust the pumping flow rate through the mine tunnel. Using the concept of proportional differential integral (PID), w was dynamically adjusted in each time step so that the extracted heat power matched the demanded heat load at each time step. Fig. 3 shows the block diagram of the proposed numerical method including the flow control scheme in which K_P, K_D and K_I are proportional, differential and integral coefficients, respectively.[20] In each time step of the numerical procedure, the resulting temperature difference between the tunnel outlet and inlet $(T_{out} - T_{out})$ was used to calculate the value of the generated heat power using $P^n = \dot{m}Cp(T_{out} - T_{out})$, where $\dot{m}$ is the mass flow rate of water in the tunnel.

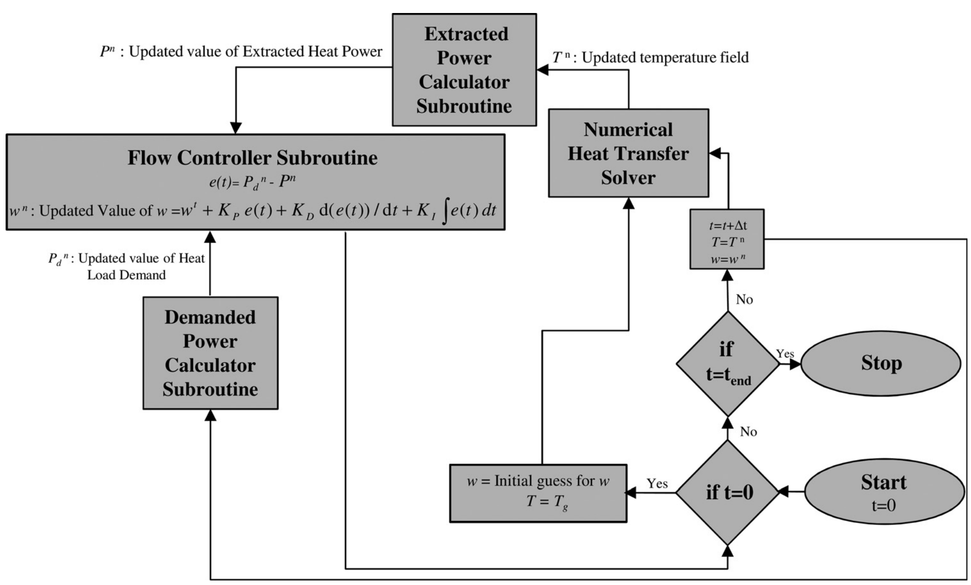

FIG. 3. Block diagram of the numerical method.

A computer FORTRAN program code, named transient heat extraction model for underground tunnel (THEMUT), was developed to solve the discretized form of governing equation (Eq. (5)). The sensitivity of results relative to mesh size and domain dimensions (D_2 and L_2) was analyzed by conducting a series of model evaluation tests described below.

IV. RESULTS AND DISCUSSION

The present numerical model computes the temperature field in rock mass and water for each time step. The obtained temperature field is then used to calculate the value of heat power extraction, gained heat energy, and the average temperature of rock mass. The computational region is chosen such that extending its size does not have any significant effect on the resulting temperature field (less than 10^{-5} relative difference). Thus, the opted size of the computational region is the size for which the infinite boundary requirement is satisfied. Similarly, the number of grid nodes of the structured mesh is chosen such that increasing the number of nodes does not change the resulting temperature field (i.e., the mesh size is made finer as long as the relative difference between the results of two consecutive grid size values is less than 10^{-5}). Table I presents the size of the computational region and the grid size along with other thermophysical properties of a typical test case. Also to make sure that the tunnel flow stays laminar, Reynolds number for the flow inside the tunnel was calculated and it was found to be in the order of 10^2, implying that the flow is well below the turbulence regime and can be assumed laminar. A similar Reynolds number check was carried out for all the test cases reported in the paper to make sure of the laminar flow in the tunnel.

Fig. 4 shows the evolution of temperature field in water and rock mass over time (up to 24 years) of operation of the system (given in Table I). A significant change in the temperature field inside rock mass is observed in Fig. 4, which proves the necessity of transient modeling of temperature field in the rock mass (as opposed to Rodriguez and Diaz[16]).

In order to validate the method, its results are compared with the results of Rodriguez and Diaz[16] for the published data which have been obtained for the geothermal system installed in Springhill, Nova Scotia, Canada. Fig. 5 shows the results in which 4 l/s of water at an inlet temperature of 13 °C is pumped through the underground mine galleries with a rock mass temperature of 21 °C. As can be seen in Fig. 5, the results of the proposed method agree with the results of Rodriguez and Diaz;[16] meaning that water will reach the temperature of 18 °C after traveling 4260 m along the underground mine tunnels. Fig. 5 also implies that due to the "pseudo-steady state" nature of Rodriguez and Diaz's model,[16] their results are slightly (about 5%) above the results of the proposed method. In other words, the fact that Rodriguez and Diaz[16] ignored the transient heat transfer inside the rock mass has led to minor overestimation of water temperature.

Validation of the proposed method is also undertaken by comparing its results with the analytical solutions available for a simplified one dimensional (1D) representative model of heat extraction from an underground mine tunnel. In this 1D radial heat transfer problem, temperature gradient in the rock along the tunnel length is assumed to be zero. The extraction of heat from the rock mass is modeled assuming a constant heat flux (transferred from the tunnel's rock wall to the water) at the tunnel wall. The resulting heat transfer model is the unsteady heat conduction in a hollow cylinder rock mass. The inner diameter of the hollow cylinder is equal to the tunnel diameter

TABLE I. Properties of the test case.

Density of rock = 2500 kg/m^3	T_{in} = 10 °C
Specific heat capacity of rock = 1100 J/kg °C	Cross sectional area of tunnel = 15 m^{-2}
Thermal conductivity of rock = 2.27 W/m °C	D_1 = 4.37 m, D_2 = 80 m
Density of water = 998 kg/m^3	L_1 = 500 m
Specific heat capacity of water = 4180 J/kg °C	L_2 = 600 m
Thermal conductivity of water = 0.58 W/m °C	Number of grid points in r-direction = 160
T_g = 30 °C	Number of grid points in z-direction = 120

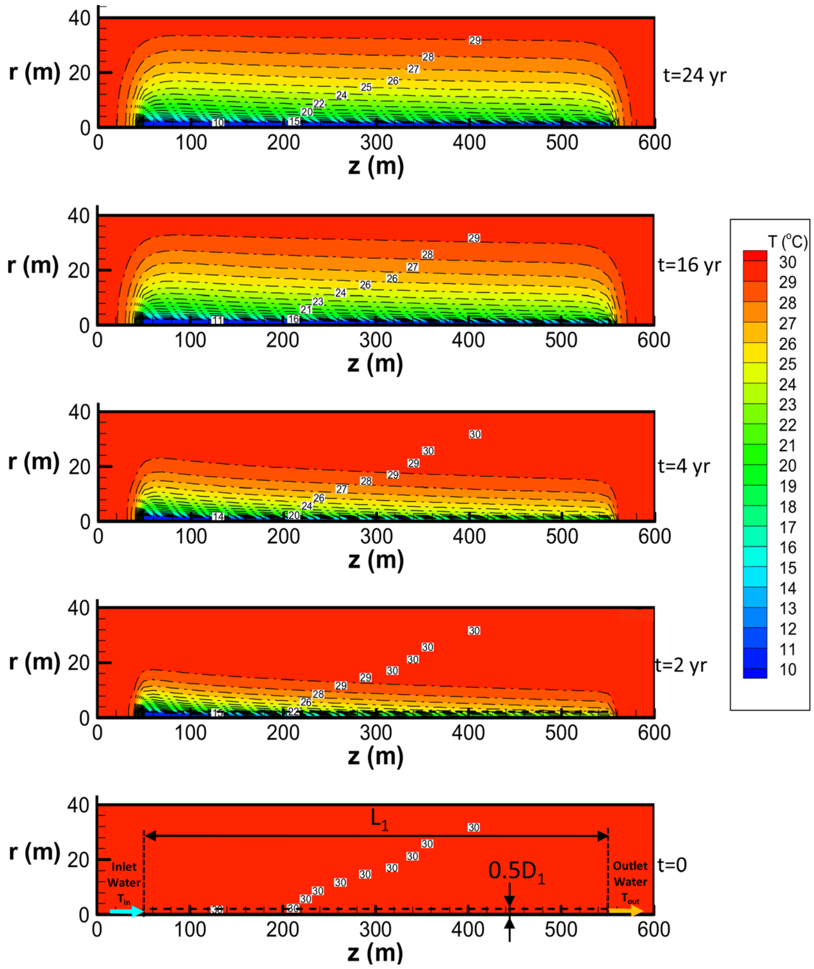

FIG. 4. Evolution of temperature field in rock mass and water (numbers in the white boxes show the value of temperature at the isothermal lines).

(D_1) and its outer diameter is the diameter of the far isothermal boundary (D_2). The heat transfer equation and its initial and boundary conditions are given in Eq. (7).

$$\rho C_p\left(\frac{\partial T}{\partial t}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right),\quad 0.5D_1\le r\le 0.5D_2, \tag{7a}$$

$$-k\frac{\partial T}{\partial r}\bigg|_{r=0.5D_1}=q_w, \tag{7b}$$

$$T|_{r=0.5D_2}=T_g, \tag{7c}$$

$$T|_{t=0}=T_g, \tag{7d}$$

where q_w is the heat flux transferred from the tunnel's wall to the water (negative for heat extraction from the mine rock mass).

Based on Özişik's[21] analytical solution, tunnel wall temperature is calculated at different times. The properties of the mine are the same as the properties given in Table I, except for $L_1 = 4000$ m, $L_2 = 4200$ m, $q_w = 21$ W/m (rate of heat extraction is 84 kW). Table II contains the analytical solution for tunnel wall temperature and the average tunnel wall temperature obtained from numerical solution of the proposed model. According to Table II, the analytical solution

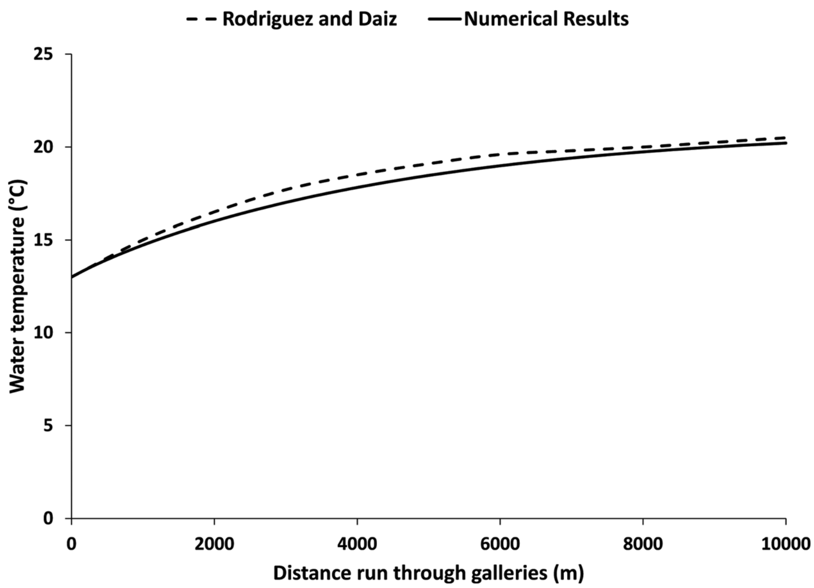

FIG. 5. Comparison of the numerical results for the case of geothermal system of Springhill (Nova Scotia, Canada) with the results of Rodriguez and Diaz.[16]

leads to 3.1% to 3.3% underestimation of the tunnel wall temperature. This shows the importance of full scale modeling of the unsteady heat transfer in the rock mass.

To apply the model to various climate conditions, three different cases of heat load scenario (HLS) are assumed as shown in Table III.

To show the effect of HLS on the performance of the open loop geothermal system, two distinct approaches are compared here. In the first approach, total gained energy (E_{tot}) is constant for all three different cases of HLS (HLS = 1, 2, and 3). Fig. 6 shows the resulted heat power values of this approach while Fig. 7 depicts the average rock temperature and the temperature increase in water (ΔT). T_{out}, ΔT, and average rock temperature are calculated according to the following relations:

$$T_{out} = \frac{1}{0.25\pi D_1^2}\int_0^{0.5D_1} T(r, L_1)2\pi r dr = \frac{8}{D_1^2}\int_0^{0.5D_1} T(r, L_1) r dr, \tag{8a}$$

TABLE II. Comparison between analytical and numerical solutions.

	Average tunnel wall temperature (°C)	
Time (yr)	Analytical solution-1D model	Numerical result-3D model
1	27.387	28.285
2	26.924	27.765
3	26.648	27.474
4	26.451	27.273
5	26.296	27.120
6	26.170	26.996
7	26.063	26.892
8	25.971	26.802
9	25.889	26.724
10	25.817	26.656
15	25.551	26.407
20	25.389	26.260

TABLE III. Description of different HLS (E_{tot} is the total amount of energy gained in one year and P_{max} is the Max rate of heat extracted).

		Month											
Heat load scenario (HLS)		1	2	3	4	5	6	7	8	9	10	11	12
HLS = 1	*Energy*	100% of E_{tot}											
	Power	$P = P_{max}$											
HLS = 2	*Energy*	57.14% of E_{tot}				No extraction					42.86% of E_{tot}		
	Power	$P = P_{max}$				$P = 0$					$P = P_{max}$		
HLS = 3	*Energy*	30% of E_{tot}		12.5% of E_{tot}		15% of E_{tot}				12.5% of E_{tot}		30% of E_{tot}	
	Power	$P = P_{max}$		$P = 0.417\,P_{max}$		$P = 0.25\,Pmax$				$P = 0.417\,P_{max}$		$P = P_{max}$	

$$\Delta T = T_{out} - T_{in}, \tag{8b}$$

$$T_{out} = \frac{1}{0.25\pi D_2^2 - 0.25\pi D_1^2}\int_{0.5D_1}^{0.5D_2} T(r, L_1)2\pi r dr = \frac{8}{D_2^2 - D_1^2}\int_{0.5D_1}^{0.5D_2} T(r, L_1) r dr. \tag{8c}$$

Fig. 7 shows that different heat load scenarios (HLS = 1, 2, and 3) have led to the same value of average rock temperature but the minimum value of ΔT is achieved for the case of HLS = 2. Also it is observed that, compared to the case of HLS = 2, the case of HLS = 3 will lead to a higher temperature raise. This means that we can exploit the same amount of mine energy over a 25-year period while responding to different demand scheduling. The second approach investigates the effect of the three different heat load scenarios (HLS = 1, 2, and 3) when the maximum value of heat power remains the same ($P_{max} = 47$ kW). According to Fig. 8, for the same amount of maximum extracted power ($P_{max} = 47$ kW), the average rock temperature for HLS = 1 would be considerably lower while for HLS = 2 and HLS = 3 will lead to the same average rock temperature. This means that HLS = 1 leads to a higher value of resource temperature degradation compared to HLS = 2 and 3, which depress the resource temperature at the same rate. Fig. 8 also reveals that ΔT for the case of HLS = 1 is significantly lower than that of

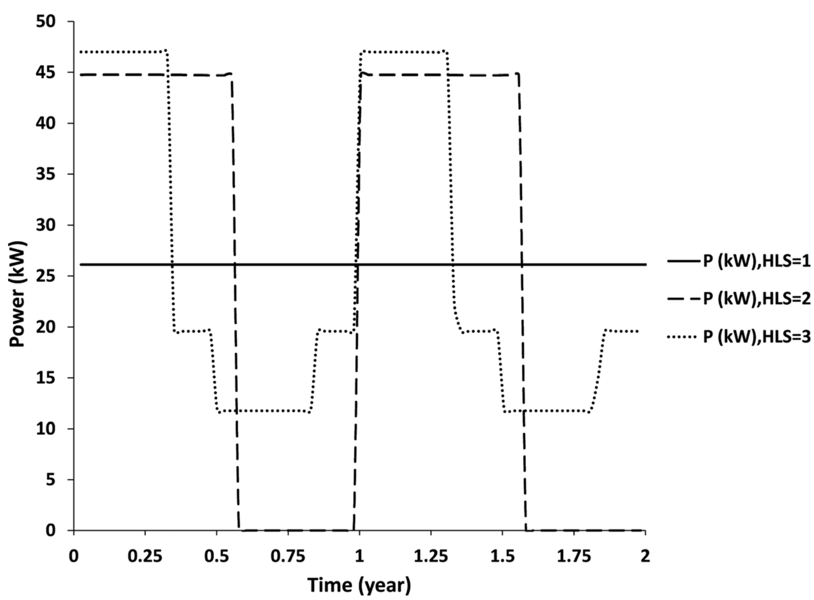

FIG. 6. Rate of heat extraction for different heat load scenarios for a constant E_{tot}.

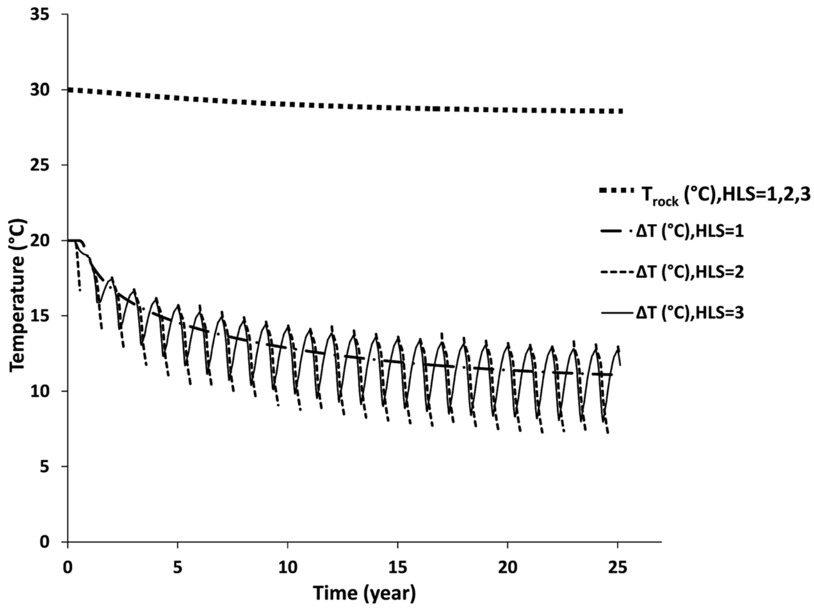

FIG. 7. Effect of heat load scenarios on ΔT (inlet/outlet water temperature difference) and T_{rock} (rock mass temperature) for a constant E_{tot}.

the other scenarios. Thus, Figs. 7 and 8 suggest that HLS = 3, which is the most realistic among the three heat load scenarios, will provide the opportunity to respond adequately to peak loads without degrading the resource.

In order to find the parameters which contribute to the sustainable rate of heat extraction, this term (sustainable rate) should be defined first. For practical reasons, sustainability is defined as the maximum rate at which heat can be extracted from the resource, provided that ΔT does not fall below a certain value (here, it is assumed 8 °C). Note that keeping $\Delta T = 8\,°C$ is a condition from the demand side for keeping the COP of the heat pump(s) in an economically viable range. For the same amount of heat provided to the end users, a higher COP means less

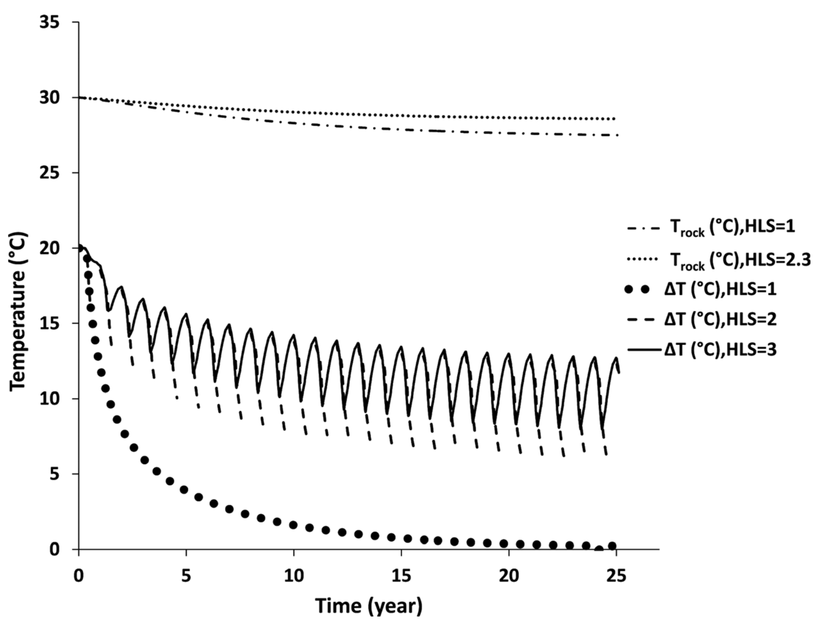

FIG. 8. Effect of heat load scenario on ΔT (inlet/outlet water temperature difference) and T_{rock} (rock mass temperature) for a constant $P_{max} = 47\,kW$.

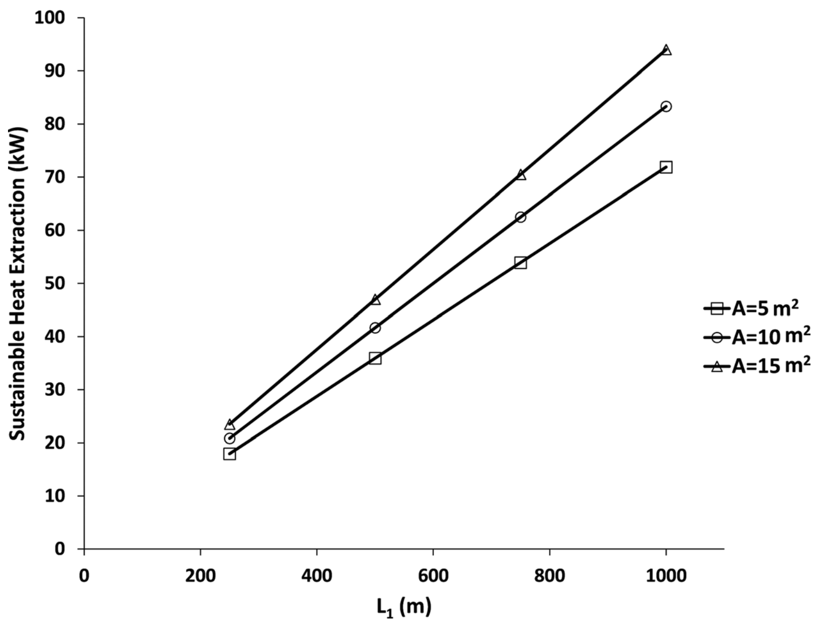

FIG. 9. Effect of length and cross sectional area of mine tunnel on the sustainable rate of heat extraction.

electric consumption by the heat pumps. Thus, being able to maintain a reasonable COP (usually above 3.5) is the key factor in the economic feasibility of the whole geothermal system. Since the COP of heat pumps depend on the resource and the chill temperatures, a $\Delta T = 8\,^{\circ}\mathrm{C}$ is chosen to ensure an adequate rate of heat extraction, without compromising the COP of the heat pump.

Fig. 9 illustrates the effect of the length of the mine tunnel, L_1, on the sustainable rate of heat extraction for three different tunnel cross-section areas at HLS = 3. The sustainable rate of heat extraction is calculated for a mine with properties given in Table I, except for L_1 (which is chosen to be 250 m, 500 m, 750 m, and 1000 m) and L_2 (which is assumed to be 100 m longer than L_1). According to Fig. 9, for a constant tunnel cross sectional area, sustainable heat extraction rate increases linearly with tunnel length.

Effect of thermal properties of rock mass on the sustainable rate of heat extraction is shown in Fig. 10. The thermal properties of the rock are representative of different rock materials found in Northern Canadian mines ($k = 3.45\,\mathrm{W/m\,^{\circ}C}$ for granite, $2.27\,\mathrm{W/m\,^{\circ}C}$ for

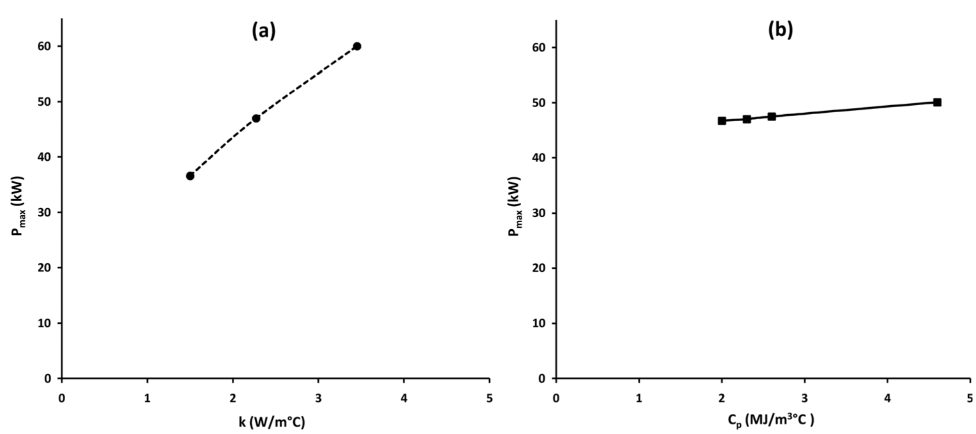

FIG. 10. Effect of (a) thermal conductivity and (b) volumetric heat capacity of rock mass on sustainable rate of heat extraction (P_{max}).

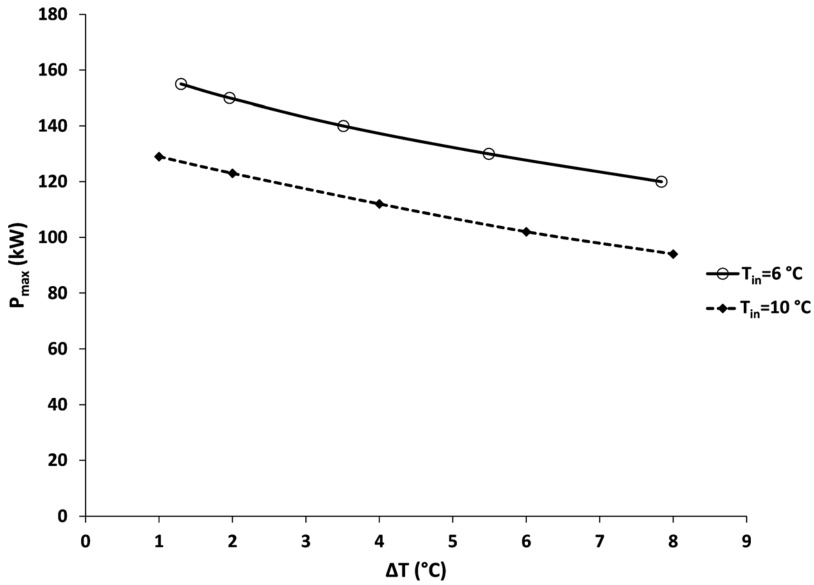

FIG. 11. Effect of ΔT on the deliverable rate of heat extraction for $T_{in} = 6\,°C$ and $10\,°C$.

Granodiorite and 1. 5 W/m °C for basalt). As can be seen in Fig. 10(a), for a constant volumetric heat capacity of $C_p = 2.3\,MJ/m^3\,°C$, sustainable rate of heat extraction is directly related to the thermal conductivity of the rock mass, while Fig. 10(b) illustrates that a similar direct dependency exists between the volumetric heat capacity (of the rock) and the sustainable rate of heat extraction for a rock with thermal conductivity of k = 2.27 w/m °C. By comparing Figs. 10(a) and 10(b), however, it is observed that the effect of thermal conductivity of the rock is much more significant than that of its volumetric heat capacity (or specific heat).

Figs. 11 and 12 show the effect of operating parameters of heat pump (ΔT and T_{in}) on the deliverable geothermal energy for a 1000 m long underground mine tunnel. The mine tunnel has the properties of Table I (except for $L_1 = 1000\,m$ and $L_2 = 1100\,m$) and it is assumed to operate under HLS = 3 for 25 years. According to Fig. 11, by lowering the inlet temperature (T_{in})

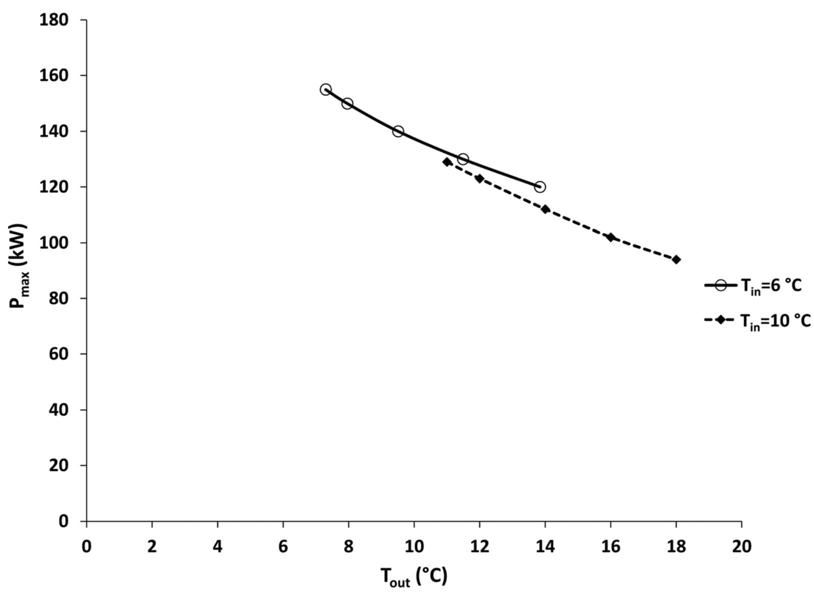

FIG. 12. Effect of T_{out} on the deliverable rate of heat extraction for $T_{in} = 6\,°C$ and $10\,°C$.

from 10 °C to 6 °C, the rate of heat extraction from the resource can be significantly improved. Fig. 12 shows that P_{max} will decrease with an almost similar trend for both $T_{in} = 6\,°C$ and 10 °C. From the physical point of view, the system is operating in a way that when more power is demanded, heat is extracted from the reservoir at a higher rate and therefore, the energy content of the reservoir is drawn at a rate faster than the heat influx. Thus, as Fig. 11 shows, faster depletion of the reservoir heat content will lead to a decrease in reservoir temperature which itself will results in a lower T_{out} and therefore a lower ΔT (since $\Delta T = T_{out} - T_{in}$). It is important to note that the model is capable of extracting heat according to the demanded heat power, by adjusting the flow rate. Also, as Fig. 12 shows T_{out} will depend on the rate of heat extraction, and not much on the inlet temperature (T_{in}).

V. CONCLUSION

A numerical simulation of a mine tunnel thermal response to different heat extraction scenarios is developed to provide simple rules for design engineers to use the mine heat resource in the most efficient and sustainable manner.

It is shown that thermal conductivity of the mine rocks plays the most important role in determining the sustainable rate of heat extraction from mines in long term. Other parameters such as permeability and specific heat capacity of the mine rocks have less important effect on long-term geothermal heat extraction from flooded mine with large openings. As the geometry of the underground mine workings is very complex (especially after mine decommissioning), design engineers are recommended to consider long mine tunnels for an open loop system to properly predict the resource reaction to different heat extraction scenarios. In such simple geometries, length and the cross section of the mine tunnel(s) have the most important effect on the total recoverable heat from the mine.

It is shown that deep mine tunnels can be a significant source of heat energy which can be extracted in a sustainable manner, if the resource limitations and the demand variations are synergistically linked through a versatile resource model. It is found that for a typical underground mine (with ground temperature of 30 °C), each kilometre of a mine tunnel can potentially deliver about 150 kW of geothermal heat, in a sustainable manner, with a proper resource management. It is also found that the key parameter that defines T_{out} is the resource temperature which itself depends on the rate of heat extraction from the resource; the higher the rate of heat extraction, the lower the resource temperature.

Based on the numerical results, an area of up to 40 m immediately around the mine tunnel is affected by the heat extraction during the life time of the project. Thus, if two mine tunnels are within this critical distance, there would be conductive heat leak between them. However, in most underground mines, main tunnels are at a distance more than 40 m from each other. So, the effect of conductive heat communication between the main tunnels of the underground mines can be ignored.

The model presented in this paper provides design engineers with simple tools to predict the thermal behaviour of the underground mine workings in response to different heat extraction scenarios. Intermittent heat extraction from the mine (as may be prompted by seasonal climate conditions) would better sustain the resource in long term and would guarantee availability of higher rate of energy extraction during short term periods of peak demand. The model also allows engineers to design the resource development plan (by deciding on the location of the production and injection wells) and to maximize the resource's potential through optimization of the operating parameters (i.e., flow rate and heat pump operating temperatures).

The study shows that underground mines can be a significant source of green heat for Canadian mining communities, where decommissioned mines have so far been liabilities rather than assets.

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