Convection mechanisms for geothermal heat exchangers in a vertical mine shaft

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Abstract

This paper evaluated using a water-filled abandoned mine (Orphan Boy) as a heat source for a 240-kW closed-loop heat pump with the goal of heating a 2,000-m^2 building. The mine has a 245-m vertical shaft connected to a large stope by three horizontal cross-cut shafts. There is 1,250 x 10^6 L of water at a consistent temperature of 24-26° C that is available mostly in the stope. The only heat exchanger placement option is in the vertical shaft. Therefore, the focus was to model heat exchanger placement in the vertical shaft to determine the extent to which the systems will induce thermal currents between the stope and vertical shaft. Modeling of thermal currents, temperature profiles and heat contribution from the ground was done using finite difference and computational fluid dynamics. An optimal configuration was determined showing sufficient water movement and heat transfer will occur with a low water temperature in the shaft above 20° C. This project supports a U.S. Department of Energy (DOE) grant that will implement the full-scale system.

Key words: Geothermal energy, Geothermal installation, Abandoned mines, Mine shaft, Heat transfer technology

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Introduction

Montana Tech is located in the historic mining town of Butte, MT and is adjacent to the Orphan Boy Mine. This abandoned underground mine will be the heat source for a down-hole heat exchanger (DHE)/heat pump system. The mine was abandoned in the 1950s and has since filled with water to within approximately 30 m of the surface. The shaft is composed of a 245-m vertical shaft connected with horizontal crosscut drifts at 60 m and 150 m below the water level, as depicted in Fig. 1. The drifts connect to a large stope with approximately 1,250 x 10^6 L of water at a consistent 24-26° C. The intent is to build this heating system to augment or fully heat a newly built 2,000-m^2 building on the Montana Tech campus.

As designed, the system uses "off-the-shelf" parts, making the basic configuration straightforward, with the exception of the DHEs, which need to be placed into the vertical shaft. Because there are few or no examples of placing heat exchangers in a vertical shaft, the primary focus of this work was to model the heat exchanger placement and configuration in the vertical shaft to determine the extent to which thermal currents develop between the stope and vertical shaft via the horizontal crosscut drifts. The movement of water is necessary to be able to provide the required energy. Without inducing thermal currents to exchange the shaft water with water from the stope, there is insufficient energy for the heat pump system to work at the desired level. This study includes the modeling of water flow, temperature profiles and the heat contribution from the surrounding rock walls.

Background

Geothermal heating and cooling is an established method of heating commercial and residential buildings. For example, Ball State University in Indiana is building an $80-million system with 3,600 vertical boreholes 120-160 m deep, tied to more than 1,600 km of piping (Fickes, 2012). This system is designed to heat and cool 47 buildings and is expected to be cost effective. The use of coal-produced electricity for the heat pumps is a subject for another time, but it does point to the practicality of using geothermal heat pumps to service large buildings or complexes.

Mine water use for geothermal systems is a concept that is being considered worldwide. Conventional underground mining has been practiced for centuries, and there are many mines that have been abandoned and subsequently flooded. The authors refer the readers to an article by Watzlaf and Ackman (2006), which provides an excellent summary of the status of the use of geothermal systems in abandoned mines in the United States and Canada. Other examples include the flooded lead mines in Park Hills, MO, which serve to heat and cool a 750-m^2 municipal building. The water is only 110 m deep and is at a temperature of 14° C. In Springhill, Nova Scotia, the water in abandoned coal mines is used to heat and cool 14,000 m^2, with the supply water held between 13-20° C during the year. While there have been a number of other examples and reports on using heat pumps in abandoned water-filled mine formations (Culver and Lund, 1999), no example was found in which heat exchangers were placed in a vertical

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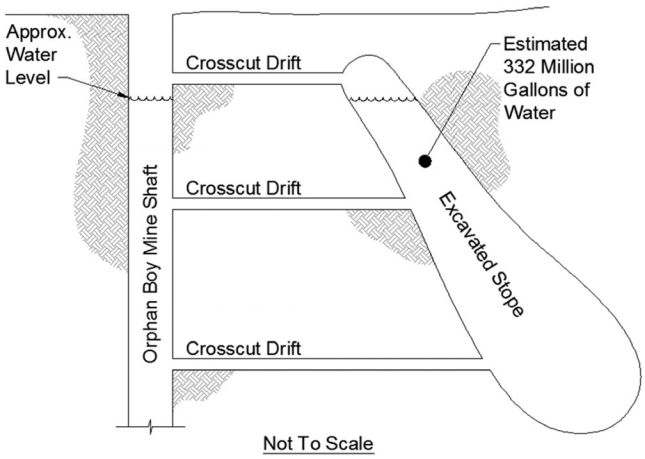

Figure 1 — Basic illustration of Orphan Boy Mine shaft and stope.

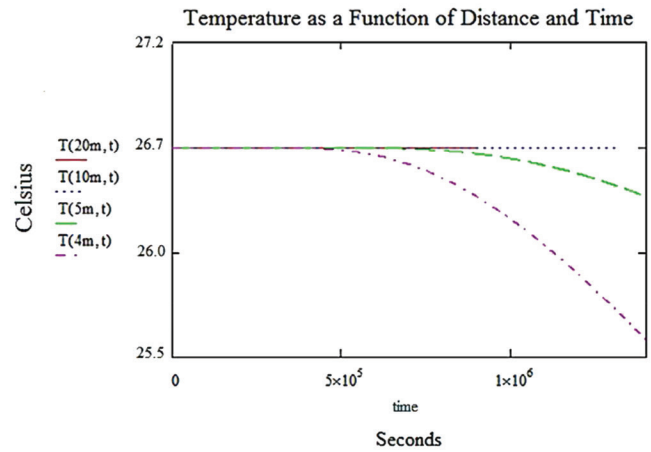

Figure 2 — Transient temperature for a semi-infinite solid with surface convection over time.

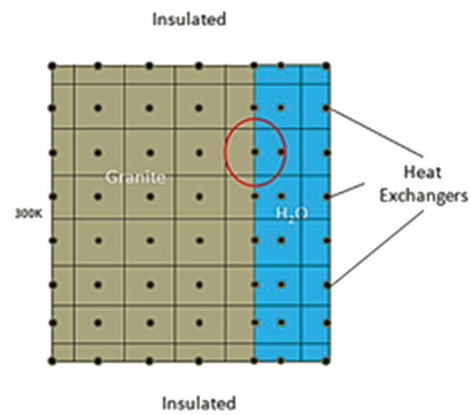

Figure 3 — Nodal grid of mine shaft with formation and energy balance of each node.

mine shaft with the intent to induce thermal currents in order to move water from abandoned workings to the DHEs. In this context, a series of models were constructed to simulate the DHE configuration to determine the extent to which the design would induce thermal currents.

Modeling approach

The overall modeling approach was to first use a simpler 2-D model to inform more complex 3-D models. The 2-D model used a finite difference approach to quantify the heat transfer within the mine shaft from the surrounding walls and to determine the stability of the model when the DHEs were included. The 3-D model of the shaft, including the surrounding rock and stope interaction, was built to simulate the heat transfer and fluid dynamics.

Before the 2-D convection model could be created, the effective distance of the surrounding rock was required. The effective distance is the point at which the far distant rock material temperature is unaffected by the heat extraction. To determine this, it was assumed that the convection in the shaft behaved as a vertical plate, allowing the authors to calculate the distance within the model where the temperature could be assumed to be constant (Eq. (1)) (Fausett, 1999). It was also assumed that the heat extraction was 240 kW, and that the far wall was held at 26° C.

$$\theta(x,t) = erfc\left(\frac{x}{2\cdot\sqrt{\alpha\cdot t}}\right) - \left(\exp\left(\frac{h\cdot x}{k} + \frac{h^2\cdot\alpha\cdot t}{k^2}\right)\right)\cdot \left(erfc\left(\frac{x}{2\cdot\sqrt{\alpha\cdot t}} + \frac{h\cdot\sqrt{\alpha\cdot t}}{k}\right)\right) \quad (1)$$

For Eq. (1) to be valid, it was assumed that natural convection would be the primary means of heat transfer. This would imply little to no forced flow rate within the mine shaft (no leaking in or out). To confirm this, a camera was lowered into the mine shaft with a 30-m tube attached to the line so that visible ink could be injected and any movement of water confirmed. The results showed the water to be essentially stagnated.

The rock surrounding the mine shaft and stope supplies the heat to the water and the assumption is that the rock will hold a constant temperature when energy is extracted at some certain distance within the formation. By knowing this distance, boundary conditions could be set for both the 2-D finite difference model and the 3-D SolidWorks model. Also needed was an average convection coefficient from the surface of the rock and the water. To determine this, a Nusselt number for a flat plate of 21,100 was calculated using a Grashof number of 1.32 x 10^{17}, a Prandtl number of 0.146 and a Rayleigh number of 1.92 x 10^{16} (Hellums and Churchill, 1962). An average convection coefficient could be determined from the Nusselt number, along with the characteristic length and the thermal conductivity of the water (Hellums and Churchill, 1962). This value was found to be 48W/m^2 x K. More detail is provided in the Thornton thesis (2012). Using these values and assumptions, the temperature within the surrounding rock formation around the shaft reached a constant at a distance of approximately 20 m from the shaft as shown in Fig. 2 (along with other distances and times).

The 2-D finite difference model was created assuming symmetry throughout the formation and mine shaft. To include the heat exchangers, the finite difference model was set up on a 2-D grid, as seen in Fig. 3. The partial distance for the *X* and *Y* direction were set equal to each other at 3 m. Each node represents a steady state temperature for that section.

Standard finite difference methods were used, where for each section of the grid, the energy entering and leaving the section were summed in keeping with the first law of thermodynamics. Conservation of energy within the granite was represented by Fourier's Law, meaning that only conduction occurs in the granite, while convection was assumed from the surface of the granite to the water, which was represented by

Newton's law of cooling (NCEES, 2010). The steady-state heat transfer that occurred within the water itself was calculated by Fourier's Law (NCEES, 2010). The 2-D model provides representative parameters of heat transfer within the system. Once the equations were set, the equation for a 42-by-42 matrix was input into MATLAB (Fausett, 1999). The results showed that with the DHE, the temperature profile of the surrounding rock reached a constant temperature at 20 m.

With boundary conditions quantified by the 2-D model, the 3-D model was built using SolidWorks for input into the computational fluid dynamics software FloEFD (2011). However, there were some modeling problems to resolve. First, a cylinder representing the rock surrounding the actual shaft was built in SolidWorks. The cylinder was set to a length of 240 m, a radius of 18.3 m and a square shaft voided in the middle and having a cross-sectional area of 10 m^2 that represented the vertical shaft. However, it was found that by having the rock around the shaft modeled as a cylinder and the shaft modeled as a square section, numerical instabilities were induced at the corners and caused lengthy calculation times. This was resolved by modeling the rock and the shaft as cylinders, with the scaled volume of material for the rock and 10 m^2 for the shaft, as in Fig. 3a. The material assigned to the cylinder representing the surrounding rock was granite. Thermal material properties were defined in this section, including conductivity, specific heat and a thermal expansion coefficient.

The other obstacle to resolve was the required computation time. The time the simulation took to complete its calculation was significant, due to the number of elements of the shaft compared to the surrounding rock. With the focus of the study to determine whether natural convection can be induced within the mine, more elements were needed for the shaft (water) portions. However, with this particular model, there is much more rock than water, and the computer resources available were insufficient. Two steps were taken to reduce model size and computation time. First, the properties of the rock were scaled by a factor of 10. Second, the model was broken into three sections and run separately.

To scale the properties of the rock, the thermal conductivity was changed from 2.79 W/m x K to 0.279 W/m x K, and the heat capacity was changed from 775 J/kg x K to 7,750 J/kg x K. In doing this, the "thickness" of the rock portion of the model could be reduced by a factor of 10 and reduced the number of elements required by a factor of approximately seven times.

Second, the complete model of the Orphan Boy shaft was divided into three sections and modeled in SolidWorks as 61-m-long pieces with a diameter of 4 m, as shown in Fig 4. The cross-sectional area of the shaft was maintained at 10 m^2. The horizontal crosscut drifts that connect the shaft to the stope were included in the model. Boundary conditions were set for each section such that they matched between their respective adjacent sections. Specifically, the hydrostatic pressure was set at each section in respect to its depth, each section was forced to match continuity and the temperature was set equal at boundaries. The specifics of matching boundary conditions between sections can be found in Thornton (2012). By scaling the material properties, dividing the model into three sections, and modeling the shaft as a circular cross-section, the computational time was significantly reduced. The models allowed the visualization of the currents and temperature gradients as will be shown.

The method of heat exchange in the system is via a closed loop plastic pipe system that will be lowered into the shaft. Currently, the design calls for 4,000 m of 2.54-cm-(1-in.-) diameter pipe that is in 200-400-m sections. In this case, each

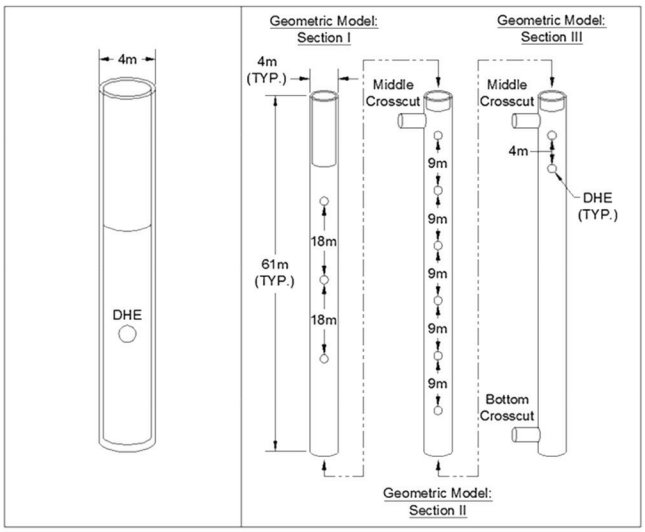

Figure 4 — Geometric models a) initial model with surrounding rock formation (left) and b) model with scaled rock properties and spherically shaped heat exchangers, Section I, Section II and Section III (right).

section is referred to as a DHE. Each DHE, or approximately each 200-400-m loop, will have water circulated from the heat pump via a manifold system that can have varying flow rates for each loop. Therefore, each loop was considered as its own heat exchanger and modeled as such. Consequently, the number and location of the DHEs are important in how the thermal currents are developed relative to the crosscut drifts.

To determine the number of heat exchangers and their locations relative to the crosscut drifts, a number of variations of the model were run to determine what was optimum. The goal of these runs was to determine the basic location and configuration. These variations focused on the placement of heat exchangers within the shaft and relative to the horizontal connector shafts to the stope. The authors have designed the DHEs such that they can be moved up or down in the shaft in order to optimize the system. The DHE will be instrumented and data collected and reported. While several configurations were modeled, only what we determined was the best of several different models will be presented. In this context, generally, it was found that placing 11 DHEs near the top of the shaft was best. Specifically, three heat exchangers were placed in Section I at 18 m apart. Six were placed in Section II with the beginning DHE placed in close proximity to the crosscut, then descending at 9 m apart, and two were placed in Section III in close proximity to the 150-m level crosscut at 4 m apart. This is where the water was believed to be the coolest due to the slight density difference in the water.

The total maximum building load expected is 240 kW and was used as the input value into the model. With the 11-DHE design, there was an energy extraction gradient in each section, with 20% of the required 240 kW being extracted from the Section I section, 70% being extracted from Section II and 10% being extracted from Section III. Section I had a descending extraction gradient, with the beginning heat exchanger being set at 33 kW, the second being set at 9.5 kW and the third being set at 5 kW. Section II also had a descending energy extraction gradient, with first heat exchanger being set at 66 kW, higher because of its location being so close to the inlet flow of the crosscut. The second carried a load of 42 kW, the third set at 25 kW, the fourth set at 17 kW and the deepest two were set at 8

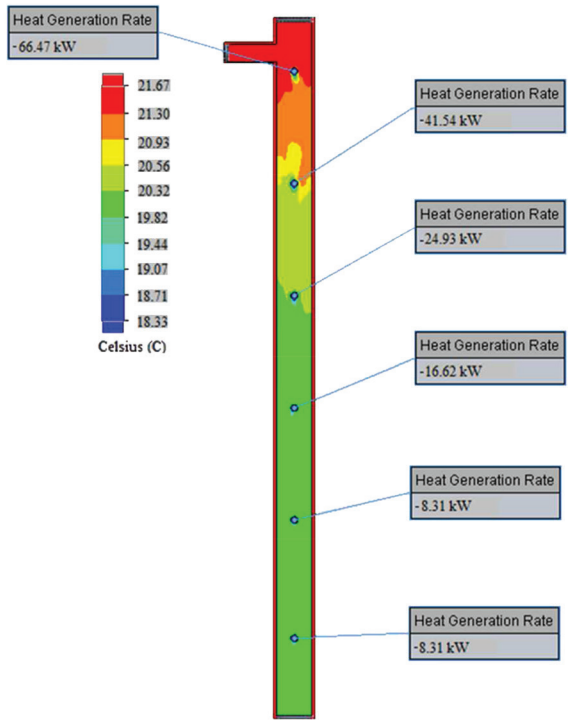

Figure 5 — Section II temperature profile for the case considering the 11-DHE design.

kW. Section III's two heat exchangers were both set at 12 kW.

Results and discussion

Overall, the simulation indicated the system would experience a steady-state temperature in a range of 20-26° C. The largest temperature difference was measured at the bottom of Section II, as shown in Fig. 5. This occurred even though this is the section in which the largest amount of energy is being extracted. This substantiates the prediction that thermal currents were induced and water would be moved from the stope to the vertical shaft. The low temperature of 20° C was measured at the bottom of the middle section.

Looking at specific sections, Section I consisted of the three heat exchangers that carried 20% of the 240 kW load and reflected only a 1° change (23-24° C, Fig. 5). The velocities that were simulated reached a maximum of 0.092 m/s and the flow patterns were consistent with natural convection.

Section II had the most heat exchangers placed in the entire model, consisting of six DHEs placed 9 m apart. The water velocities reached a maximum of 0.1 m/s around the heat exchanger located at the 100-m level near the crosscut. A low temperature of 20° C was calculated at approximately the 150-m level. The flow trajectories did not reflect ideal flow patterns, but some consistency could be seen near the heat exchanger located near the crosscut. The flow pattern around the 100-m heat exchanger and the temperature profile of Section II can be seen in Fig. 6.

Section III is not shown, but had a nearly constant temperature and low flow rates. For more details, see Thornton (2012).

One of the most important results was that the model indicated that natural convection is the primary mechanism of heat transfer from the water and can be induced. Since the temperature reached a steady state, it was concluded that the

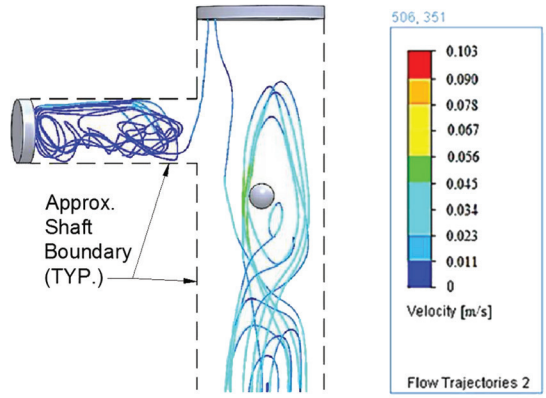

Figure 6 — Flow trajectories around the DHE located at the 100-m level of the shaft.

surrounding formation rock was sufficient in providing the required heat to the water and with the water movement there is sufficient energy within the system to more than heat the building.

Eleven heat exchangers appeared to be the optimum number to place in the three sections of the model. However, additional experimental work is needed to fully optimize the DHE locations. The lowest temperature surrounding a heat exchanger was modeled to be 20° C. Section II, where six of the 11 DHE were located, had the most water movement. The authors determined that the majority of heat exchangers should be placed in Section II to induce thermal currents.

What is clear is that the relative location of the heat exchangers is critical relative to the location of the crosscuts that connect to the stope. This is critical to having "access" to the stope water. The simple model has shown that using heat pumps in vertical mine shafts is feasible. Installation of the system will occur in late 2012 and early 2013 and implementation results will be reported.

Acknowledgments

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