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Geothermal in Mine Closure: Visualizing the Hydromechanical Properties of a Geothermally Facilitated Bioreactor

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ABSTRACT

The world of today has the more abandoned mines than ever before. Many of these are located in remote regions, set apart from energy sources, people and infrastructure, rendering the necessary remediation efforts in these areas slow-moving and even nonexistent. The primary demand from the industry for these sites is a passive system that utilizes locally available and cheap material. Often the geothermal gradient available in mines, or the corresponding geothermal reservoir conditions proximal to the mine, is a viable heat energy source that can provide advantageous temperature conditions for established remediation techniques, namely bioremediation, which can run on diverse, inexpensive, and locally available material. Although geothermal direct use and bioremediation are proven technologies when practiced independently, the combination of both is not straight forward. The following paper will address the hydromechanical intricacies of this process and its promise for providing relevant remediation to abandoned metal mines in remote regions.

This study involves the use of COMSOL in simulating the thermally driven convective cells produced in a porous bioreactor apparatus. The simulation's results illustrate the potential benefits of such a system based on the hydraulic residence time and thermally augmented reactivity of chemical species flowing through the reactor. The input parameters are based on the environmentally relevant data gathered through field surveys of Rico, Colorado, an old mining town in the Rocky Mountains of southwest Colorado.

1. INTRODUCTION

The state of Colorado prides itself on its picturesque mountainous beauty, and dedication to preserving natural space. Boasting fourth most national park space in the nation, Colorado also hosts an estimated 23 thousand abandoned mines that leak acidic drainage into its rivers, lakes and streams (Colorado, 2003). Abandoned mines dot the mountain landscape, poisoning the ecosystem and rivers. In many cases, a quiet flow of contamination has spread out continuously for a century, marring public spaces enjoyed by humans and destroying ecosystems (Cooke and Johnson, 2002). So often in the history of Mining Engineering, the primary focus rested in the capital costs of an operation, above safety and certainly above environmental costs, which are the most widely impactful and long lasting. Environmental effects were neglected to such an extent that even simple and slight adjustments to mining operations, which could have significantly mitigated the impact of mining, were overlooked or seen as unnecessarily complicating procedures (Bazin, 2013). However, many people are beginning to realize that mine opening and closing should not be considered completely separate aspects of mining; even the opening of a mine should be done cautiously, with an end in mind.

The Gold King Mine blowout has drawn public attention to the inevitable and mounting problem of untreated acid mine waters in abandoned mines. So-called "active treatment options" such as lime addition, reverse osmosis, and ion exchange have been generally ruled out for the majority of abandoned mines, located in rural or remote areas where the constant maintenance and additions required for those technologies would not be available in man power, energy supply or capital (Johnson and Hallberg, 2002). Therefore, passive treatment options are commonly preferred in these, the majority of, situations (Figueroa, 2005). Engineered wetlands are a commonly employed passive technology that has been proven successful in treating acid mine drainage. However, the wetlands are necessarily large (on the order of square miles), and still their most common failure mode is inadequate volume for the treatment of the incoming waste water. Additionally in high-altitude regions where many abandoned mines are located, freezing conditions often cause these open-air wetlands to stall, when the carefully cultivated microbial populations die.

Researchers are currently testing new adaptations for the trusted passive technologies to produce robust options for cold climates. While many groups are focusing on cultivating a microbial community better adapted to the cold (eg. Auvinen et al., 2009; Cabrera et al., 2006; Neculita et al., 2006; Gadd, 2004; Moosa, 2002), few focus on adjusting the thermo-mechanical design of treatment systems (eg. Khademian et al., 2017; Patsa, 2015). The objective of this paper is in analyzing the application of geothermal, an energy source available from contaminated mine wastewater or nearby springs, to improve the hydrologic and kinetic conditions of an insulated passive bioreactor, another acid mine drainage treatment technology. The added heat to the bioreactor system increases contaminant removal efficiency of the system, reducing the required residence time of wastewater in the system, as well as decreasing the space requirements of the system. Using and regulating a locally available heat source can help operators have better control of the underground reactor environment.

The input parameters are based on the inspiration for this research, Rico Colorado, an old mining town of around 250 people, blessed with geothermal springs and cursed with acid mine drainage. From 1887 to 1958 Rico produced silver, copper, zinc, lead, and sulfuric acid (for the processing of uranium) from its rich mountains. The destruction of the sulfuric acid plant by beloved "eco-outlaws" Johnny and Roy in 1964, began a new era in Rico (Curran, 2011). Today the town is primarily focus is on renewable energy development and environmental sustainability. In the last decade the town has successfully petitioned for the EPA to takeover neglected mine remediation projects in two different sites within the town's borders.

Situated in the Rocky Mountains of southwestern Colorado, Rico experiences an average January low temperature of -15°C and an average July high temperature of 23.5°C. Geothermal spring temperatures average around 40°C. Soil temperatures in the region, read at a depth of 20 inches, range from 17°C to 0°C annually; soil temperatures read at 40 inches, range from 17°C to 2°C (NRCS, 2017). Contaminants found in the acid mine drainage around Rico consist primarily of zinc, copper and sulfate. The reactions to remove acid and metal zinc are the focus of the kinetic study referred to this paper.

2. WASTEWATER TREATMENT MECHANISMS

The implications of geothermal facilitation of a bioreactor for the treatment of mine wastewater is not as straightforward as one might expect. The artificially high temperature gradient imposed on the tank reactor results in convection cells in the water if the inflow rate is adequately low. Convection cells produce a self-stirring system, typically deemed beneficial in treatment technology [Figure 1].

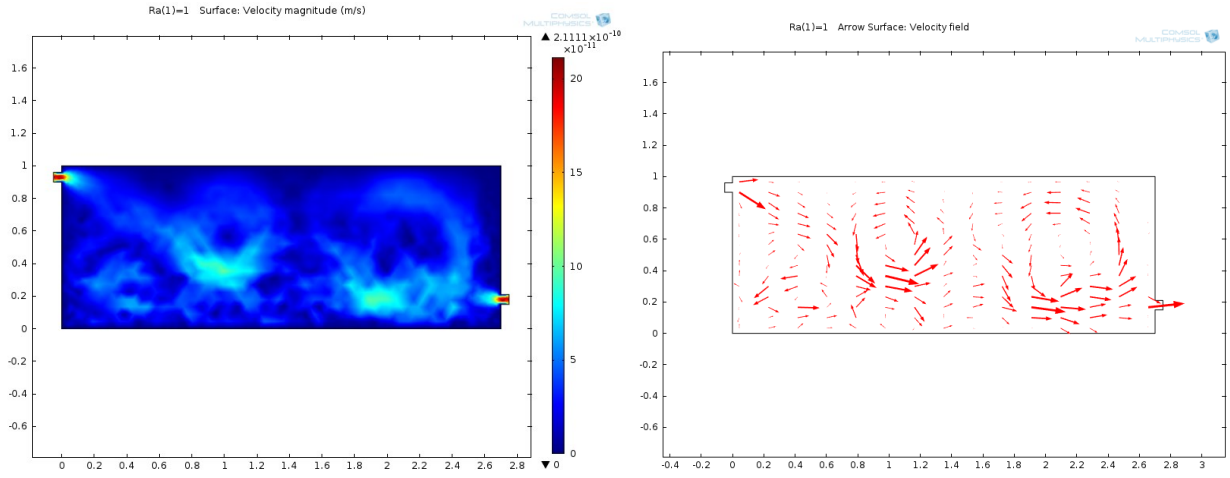


Figure 1 Three distinct convection cells form in preliminary model; above figure is velocity surface plot, where lighter colors represent higher speeds of flow. Bottom figure shows proportional velocity vectors showing direction of flow. The image has a heat source on the bottom edge, a cold heat sink on the top, and a corresponding temperature gradient on the sides, with water flowing from top left to bottom right. No porous matrix in this image.

If a tank is stirred it can improve contact time and distribution of microbes, alkalinity, and a given contaminant in the system. It also helps to prevent "short circuiting" of the system, when streamlines carry contaminated water through the system without allowing the designed hydraulic residence time. Often the two extreme idealized configurations in wastewater treatment theory are "mixed flow" systems and "plug flow" systems [Figure 2].

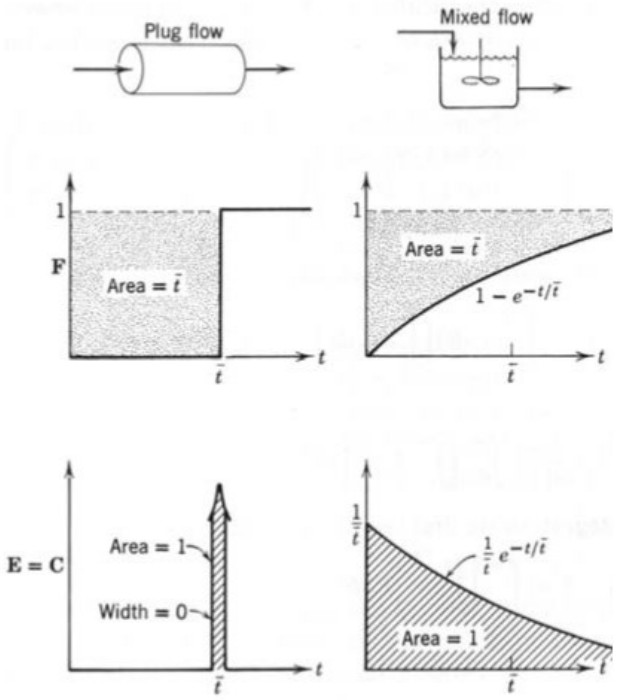


Figure 2 Idealized reactor systems with flow curves of a step injection (from Stenstrom, M.K. and Rosso, D. 2003)

In any given reactor, the contaminated water and treatment chemical are mixed together in a tank, remaining in the constant volume until the required residence time is met. If the given inflow and outflow are zero, a simplified expression for change in concentration in a batch reactor is Equation 1 (Reynolds and Richards, 1996).

$$V\frac{dC}{dt} = V\, r_c \tag{1}$$

Where V is volume, dC/dt is change in concentration over time, and r is the rate of change in concentration. For a first order reaction, r_c is –kC, where k is the rate constant. Thus the integration of this equation yields the expression for concentration after a given time.

$$C = C_0\, e^{-kt} \tag{2}$$

In a plug flow system where a contaminant is piped in slowly, with perfect radial mixing and no lateral dispersion, the "plug's" residence time is perfect for its treatment. The concentration of contaminant in a plug flow reactor is based on hydraulic residence time, or τ, rather than time, t.

$$C = C_0\, e^{-k\tau} \tag{3}$$

Hydraulic residence time is defined as a volume over a flow rate (V/Q).

Plug flow in practice has dispersion. The realistic approximation of plug flow, used in wastewater treatment is "mixed flow" in series. So-called "continuously stirred tank reactors" (CSTR) are typically employed in drinking water and wastewater treatment plants. For a steady state CSTR, the following conservation of mass equation is given:

$$Q\, C_0 + V\, r_c = Q\, C + V\frac{dC}{Dt} \tag{4}$$

Rearranging and integrating this equation yields an expression for expected concentration based on initial concentration and time over hydraulic residence time (t/τ),

$$C = C_0\, (1 - e^{-\frac{t}{\tau}}) \tag{5}$$

In order to overstep dispersion effects, the CSTR in series configuration allow for an approximation of perfect plug flow, by sequentially setting up CSTRs which perfectly distribute the contaminant and reactant in a tank for a given time before expelling that concentration to the next CSTR in the series. The equation for concentration of effluent from CSTR in series is shown in Eq.

$$C = \frac{C_0 \frac{N}{\tau}\left(N\frac{t}{\tau}\right)^{N-1} e^{-\frac{Nt}{\tau}}}{(N-1)!} \tag{6}$$

Where N is the number of CSTR in series. For a steady-state, first order reaction, the final concentration for CSTR in series becomes

$$C = C_0 \left(\frac{1}{1 + k\left(\frac{t}{N}\right)}\right)^N \tag{7}$$

Equation 7 shows that for the same given time, concentration removal can increase significantly by adding CSTR in series.

Designing a tank reactor with convection cells that approximate CSTR in series would lend advantages to a remote passive system of wastewater treatment that were thought to only be available in city-centered municipal waste systems, fully equipped with electrical stirring fans and automated outflow valves. Convective self-stirring abilities of remote bioreactors could reduce treatment time and space requirement.

In order to design a usable geothermal bioreactor, one should optimize space requirement, inflow speed and convection cells produced. The more theoretical cells in series per given volume, the more efficient the reactor set-up. Maximizing inflow speed while minimizing space requirement for treatment is key for constructing a reactor in remote regions. Since temperature gradient varies with the season, it is also important to investigate the effect of seasonal variation on convection cells, residence time and flow rates. The driving forces in producing the convective cells are gravity and temperature, affecting buoyancy. Deterring forces include the flow-through pressure generated by inflowing waters as well as blockages from compaction in a real bioreactor system.

3. MODELING

The purpose of this modelling study is to evaluate the hydromechanical implications of imposing a steeper temperature gradient, by using geothermal heat in a subterraneous bioreactor. In the initial scenario, there is a roughly 2.7x1 tank (length x width) approximating the proportionality of a potential field scale reactor. The temperature at the base of the tank is held constant at 313.15 K, the average temperature of a geothermal spring in Rico, CO. The sides of the reactor have a cooling effect on the fluid, down to a temperature of 278.15 K, an extrapolated steady-state winter ground temperature of about 6 feet below the surface. The initial temperature of the inflowing water is 289.15 K, which is an average outflow temperature of underground mine wastewater. Inflow comes from the upper left side of the tank and outflow goes through the bottom right of the tank. The tank is given a porosity of 0.8 to reflect a typical bioreactor's initial conditions.

COMSOL Multiphysics couples laminar flow and heat transfer in fluids to model the altered flow paths of a heated fluid within a given 2D or 3D geometry. The solutions for laminar flow are based on the Brinkman equations, which are used when modeling a liquid phase within a solid phase porous domain.

$$\begin{aligned} 0 &= \nabla \cdot \left[-p\mathbf{I} + \frac{\mu}{\epsilon_p}\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right) - \frac{2\mu}{3\epsilon_p}(\nabla\cdot\mathbf{u})\mathbf{I}\right] \\ &\quad - \left(\frac{\mu}{\kappa_{br}} + \beta_F|\mathbf{u}| + Q_{br}\right)\mathbf{u} + \mathbf{F} \\ \rho\nabla\cdot\mathbf{u} &= Q_{br} \end{aligned} \tag{8}$$

Where ρ is fluid density, μ is dynamic viscosity, u is velocity, ε is porosity, Q_{br} is a mass source or mass sink (SI unit: kg/(m^3·s)), p is pressure, F is force as a result of gravity and other volume forces, and k_{br} is permeability. The Forchheimer term β_F has SI units of kg/m^4 contributes a viscous drag force.

Heat transfer is modeled based on heat transfer in the liquid phase and in the solid phase.

$$\begin{aligned} \rho C_p \mathbf{u}\cdot\nabla T &= \nabla\cdot(k_{eq}\nabla T) + Q \\ k_{eq} &= \theta_p k_p + (1-\theta_p)k \end{aligned} \tag{9}$$

Using user-defined thermal conductivity k_P, density ρ, and specific heat capacity C_P for each domain, reflecting properties of water in soil. Θ_P is the volume fraction term, given by 1-ε.

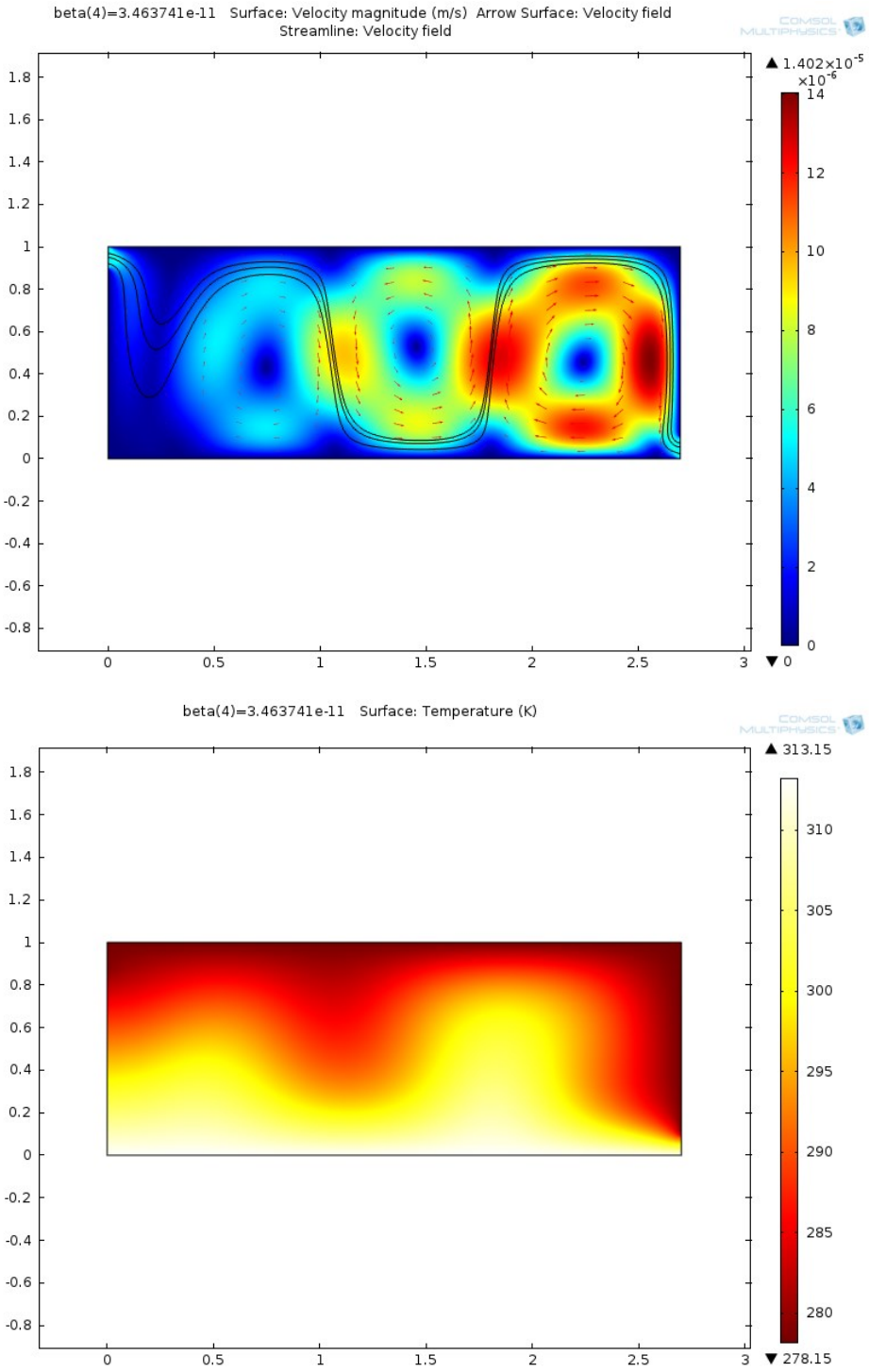


Figure 3 Velocity modeled, arrows show relative magnitude, and black lines show streamlines through the system (top); Heat modeled with light colors representing hotter temperature and dark colors showing cooler temperatures (bottom), with inlet velocity of 5e-6 m/s within a 1x2.7 m^2 tank. The outside temperature is 5°C shown in Kelvin on the color bar.

The parameters that are under the control of the designer for an implemented wastewater treatment system are shape and dimensions of the tank, heat source placement and distribution in and around the tank, outlet and inlet position; these variables can be manipulated to form various convective cell patterns in the tank model. External parameters, out of the designers control include water inflow temperature, outside temperature and seasonal temperature fluctuation (though this fluctuation can be mitigated by burial depth), as well as geothermal spring temperature and contaminant concentration in the waste stream.

Figure 3 shows three distinct convective cells runs an inlet velocity of 5e-6 m/s. The bottom edge of the tank is uniformly heated to 40°C, the top edge is cooled to 5°C, and the sides reflect a corresponding temperature gradient. Using rough analytical models explained above [Equation 7], the contribution of three convective cells on a system alone would decrease the necessary average residence time by 22% to treat the water to the same level, without considering the temperature's effect on reaction rate.

$$k_T = k_{20} * 1.035^{T-20} \tag{10}$$

Equation 10 gives a rudimentary empirical relationship between reaction rate k, and temperature T in degrees Celsius (Reynolds and Richards, 1996). If the average temperature augmentation of the system is 20 degrees, then the rate constant of contaminant removal would double according to this relationship.

3.1 Changing Inlet Velocity

In order to test the effect of increasing inlet velocity, the baseline model was tested at 10e-6 and 15e-6 m/s, shown in Figure 4 (left and right respectively). Water velocity increases as pressure increases on the outflow wall of the tank. The destruction of the convective cells produces a large "dead" (low flow) region at the entrance of the tank. Dead zones are not ideal in a tank design, as they promote accumulation on mass and short-circuiting, when the intended residence time of the designed system is undermined.

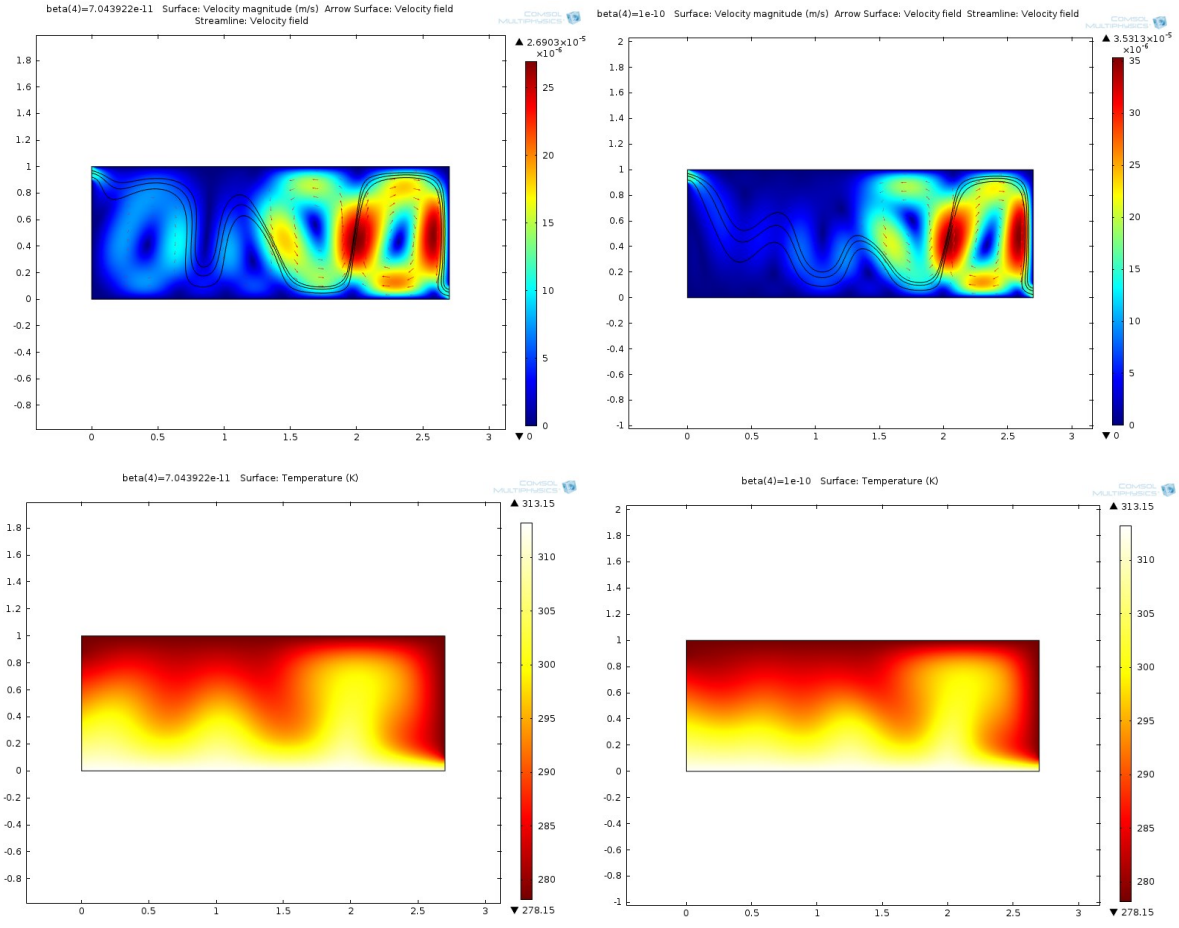


Figure 4 Devolution of the convection cells and subsequent heat transfer when raising the inflow velocity to 1e-5 m/s (left images) and 1.5e-5 m/s (right images). Outside temperature is 5°C

At 10e-6 m/s, the evolution of a weaker fourth convective cell is apparent, with a corresponding distortion of the hot front from the bottom of the tank. At 15e-6 however, the first two convective cells are destroyed and the heat distribution is similarly tempered. The average temperature on the side of the inlet decreases as velocity into the tank increases, limiting the water's exposure time to geothermally augmented temperatures within the duration of the residence time.

3.2 Simulating Seasonal Variation

Typically mine wastewater systems are designed to suit a winter environment, to ensure the mostly dormant microbial populations can react sufficiently to treat the contaminant stream. However, the shallower temperature gradient produced in the summer time should negatively impact the buoyancy driven convective system within a subterraneous tank.

Raising the outside temperature to average summer ground temperatures, of 16°C, decreases the number of well-defined convective cells to just two [Figure 5]. The cells are oriented in a way that prevents streamlining through the tank, creating a tortuous path for the waters to follow.

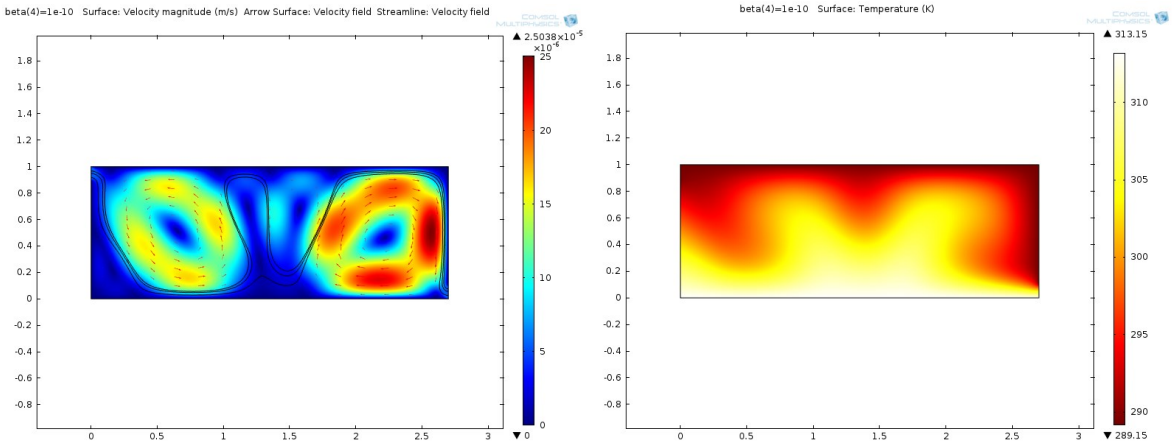


Figure 5 Velocity and heat maps of "summer" outside temperature, at 16°C, and inlet speed at 5e-6 m/s

The "summer" simulation results have two striking features. One is that although the inlet speed is the same as the first model presented [Figure 3], the maximum velocity attained in the tank is 60% higher in the summer simulation than in the winter simulation. The second feature to note is that the left most convection cell is rotating counterclockwise in the summer, rather than clockwise as it did in the winter. The counterclockwise rotation produces a shearing zone between the leftmost convective cell and the "frustrated" partial cell in the middle. The shear zone results in dead space that constricts the flow on either side, perhaps resulting in the increased circular velocities. The two main convective cells occur, rather than three, due to the reduced temperature gradient within the tank.

In order to represent the additional flows experienced in summertime, an additional simulation investigates a summer tank with increased inflow. If water inflow rate is increased by 20%, while maintaining the same thermal conditions, the convective cell geometry changes to three fully formed cells, one still being frustrated in the middle, moving against flow from the leftmost convective cell [Figure 6].

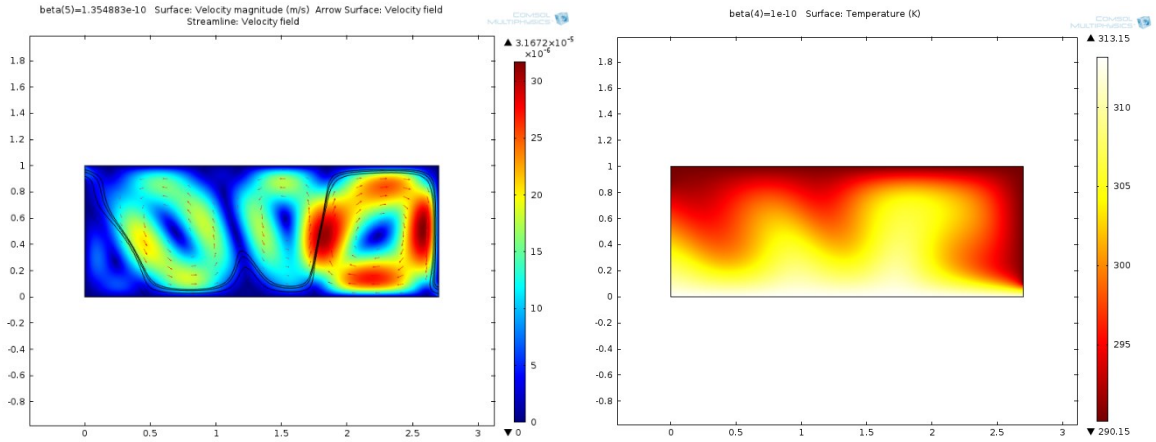
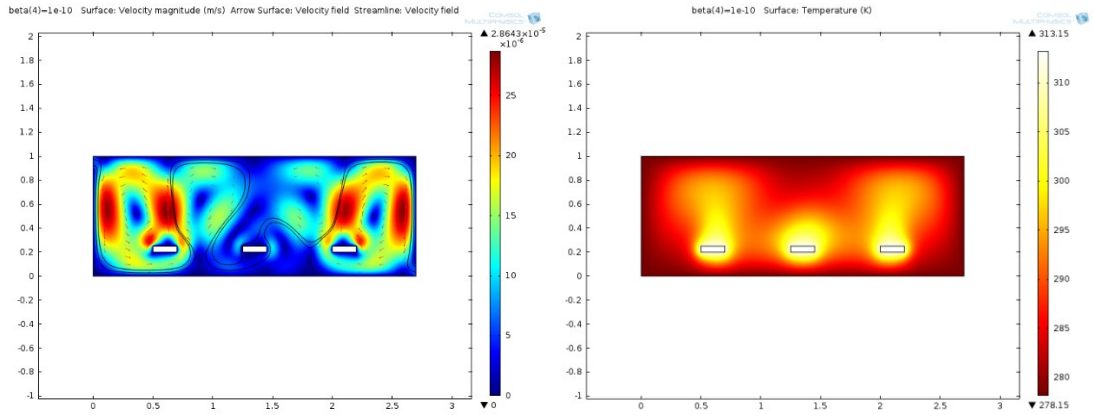


Figure 6 Coolest temperature of 16 °C with inflow rate of 6e-6 m/s

3.3 Configuration of Heat Source

Placement of the heat source is another controlled variable in the design of a geothermally facilitated bioreactor. Geothermal could be piped through the reactor to increase heat distribution to the upper levels of the reactor and perhaps reduce "dead zones" produced in the system. We see by adding three hotspots in the 2D simulation that heat is distributed more symmetrically in the system and there is less area of "dead zone" where velocity is near zero and material can accumulate. Distribution of the heat source also seems to encourage the formation of 1-2 more convective cells at the baseline speed of 5e-6 m/s [Figure 7, top]. The middle heat source though acts against the convection stimulated by the system. Removing the middle heat source allows the four convective cells to fully form in the tank [Figure 8].

Another way of looking at this augmentation of convective cell number is that this heat distribution can support more convection cells at a higher inflow speed. If the inflow is increased by 50%, the convective cell count returns to three, increasing again the dead flow zone, but enhancing the heat distribution from the discrete heat sources [Figure 7].



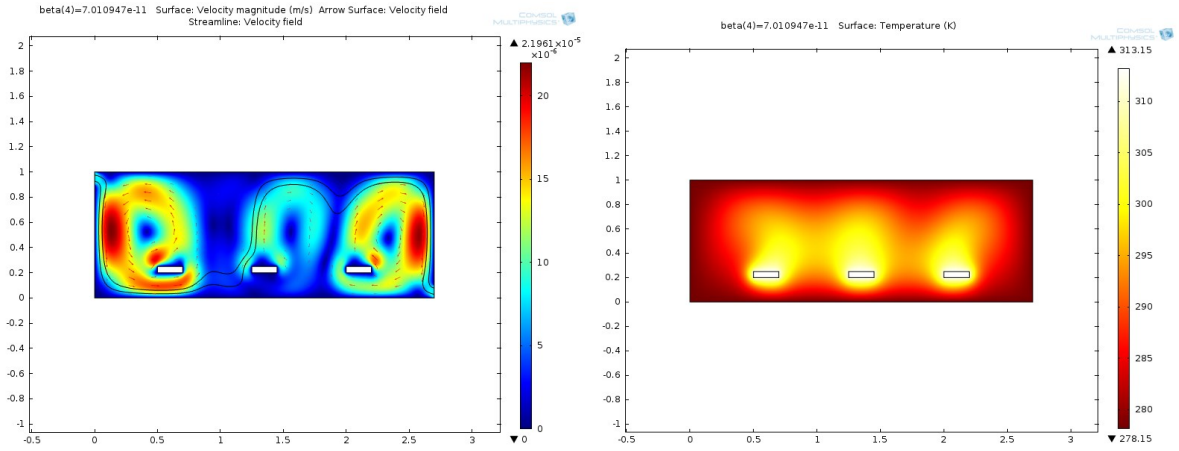


Figure 7 Three point sources of 40°C, walls are at 5°C, at 5e-6 m/s inlet flow (top), and 7.5e-6 m/s inlet flow (bottom)

Upon further study the third convection cell is maintained at double inlet speeds as well, and only begins to dissolve at inlet speeds of 15e-6 m/s (not shown).

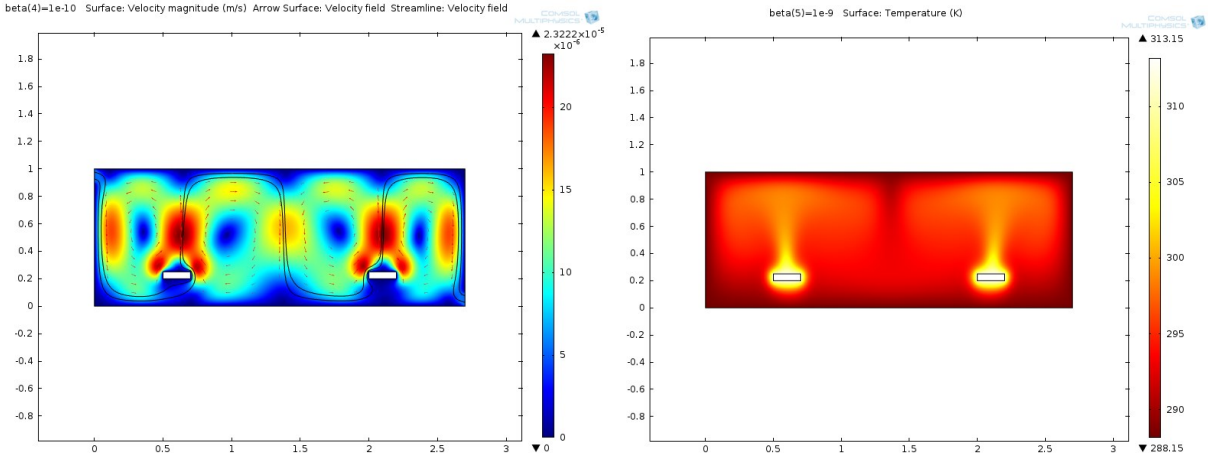


Figure 8 Middle heat source removed, inlet velocity of 5e-6 m/s, 15-40°C temperature difference between wall and source

4. CONCLUSIONS

As the environmental and social impacts of mine wastewater are fully realized by the general public, more pressure will be placed on mine companies and the Environmental Protection Agency to attend contaminated water sources. A feasible solution that can address the scale of water contamination today must be an affordable, low maintenance, long lifetime treatment of mine water. Geothermal waters, often geologically correlated to massive sulfide deposits mines, may provide a local and easily harvested resource for achieving these aims. Heat which drives microbial reaction could increase the efficiency of acid mine drainage treatment bioreactors, and significantly reduce the construction costs for remediation systems. Local geothermal resource could also stabilize the SRB microbial population through inoculation and alkalinity. Either geothermal resource provided from a gravity gradient or artesian spring could be supplied to the remediation system without added pumping or electrical cost. Consistent temperature is an important factor for reducing the monitoring and maintenance costs of mine site remediation technologies.

The findings of this study suggest that increased inflow velocities and reduced average residence time (or space requirement) can be obtained if the heat source is selectively distributed in discrete segments of the reactor tank. Such placements should allow the natural convective cells, which adapt to the imposed temperature gradient, to fully develop in order to reduce dead zones and prevent wasted heating. The designer should be aware of the seasonal ground temperature fluctuations in the target area in order to install a system that copes with predictable convection cell growth and reduction. Additionally, increased inflow speed both distorts convective cells and improves heat distribution throughout the tank. Evaluating the net effect would require adequate temperature based kinetic information from the particular microbial community present.

More work still needs to be done to evaluate the new problems an added heat source could pose to the existing designs of sulfate reducing bioreactors, and other remediation schemes. The rate of carbon source depletion, and the precipitation of solids and interactions of the entire microbial community in a bioreactor are all factors in the success of direct use geothermal in bioremediation systems. Since typical systems draw water out to the surface to settle, they have been dependent on and mercy to the wide fluctuations of outside temperatures experienced on a mine site, having major implications on the efficiency, longevity and reliability of the bioremediation systems. With a temperature stabilizing geothermal draw, the many uncertainties of a passive system and the corresponding extreme over-designing measures disappear.

The perpetual flow of surface and groundwater is an aspect of the water cycle that has reliably sustained humans and all life on earth; but now, as that flow mobilizes toxic metals and generates acidity from mine minerals, controlling an infinite supply of water is a formidable challenge of both mining and environmental engineering (Mittal, 2011; Jarvie-Eggart, 2015)). Using the local geothermal gradient available in or near an abandoned mine may be the key to the success and wide-spread application of passive bioremediation systems, especially in remote, and topographically challenging areas.

In the future of this research, kinetic parameters taken from active bench scale bioreactors will be overlain on the models presented to represent realistic microbial growth patterns, contaminant consumption rates based on temperature, and mineralization of metal sulfides. The result will be a model of an evolving bioreactor which can optimally respond to compaction of carbon source material, biofilms, and precipitation of metals with flow patterns that can redistribute consolidated materials.

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