

Geothermal in a Bioreactor System

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ABSTRACT

All Abandoned mines across the world leak contaminated waters into precious water resources, threatening human populations and natural environments alike. The primary demand from the industry for addressing the contamination is a passive system that utilizes locally available and cheap material, with little energy or maintenance requirement. Passive treatment systems can operate in remote regions, using diverse, inexpensive, and locally available material with low waste production, but are subject to ambient conditions and often space intensive. The geothermal gradient available at abandoned mines, or the corresponding geothermal reservoir proximal to the mine, is a viable heat energy source that can provide advantageous temperature conditions for established remediation techniques, namely bioremediation. The following paper presents a model based on data from a column experiment to show the effect of an imposed temperature gradient on the permeability and microbial kinetics of a bioreactor. The model reflects evolving thermal and mass transfer in the multiphase system. The addition of geothermal energy to a bioreactor is shown to improve long-term permeability, enhance reaction and precipitation kinetics, and decrease spatial expanse of designed bioreactor systems.

1. INTRODUCTION

The potential of geothermal direct use has been limited to a few tried and true applications thus far. Residential or commercial space heating and cooling, spas, aquaculture and greenhouses are some of the more common examples. The potential to use geothermal, as a readily available heat source has not been applied to more complex systems, due to location (Khademian et al., 2018) or due to complexity of adding such a heat source to industrial processes. One such process is the remediation of mine influenced water at remote, abandoned mining sites.

There are 23,000 abandoned mines in Colorado alone often in remote, freezing climates, and mostly related to magmatism in the Colorado Mineral Belt. The same young magmatic processes have blessed many of the post mining towns with geothermal resources, which local communities wish to exploit.

Most mining companies charged with the remediation of disused mine sites prefer a cheaper, self-sustaining water treatment option, often referred to as a “passive system.” One of the more robust and affordable passive systems is a sulfate reducing bioreactor or SRBR. Sulfate reducing bioreactors have been shown to remove 98-99% of initial copper, 85-90% of initial iron, and 95-99% of initial aluminum from acid mine drainage, but a decrease in efficiency is observable in the winter months, though anaerobic sulfate reducers are notably resilient in above-freezing, cold temperatures (Janin and Harrington, 2015). One drawback of passive systems, including SRBRs is that in order to allow for the required residence time, a large expanse of flat land must be carved from the mountains, and still there most common failure mode is insufficient space.

One potential adjustment to the passive system is adding a geothermal element that could not only prevent freezing of the reactor, but also increase efficiency of the SRBR cell, reducing the space necessary to perform treatment. A heating element could also induce convection to improve contact and chemical distribution in the subsurface cell. This paper develops a model to evaluate the design and performance of a geothermally facilitated bioreactor.

2. THERMAL AND MECHANICAL ASPECTS OF BIOREACTOR

The substrate in a typical bioreactor is mixed. Various organic material is used as a carbon source and electron donor, rocks are used to improve permeability and provide scaffolding for the biomass which becomes an additional material in the reactor. Water flowing through the reactor and the precipitated minerals are also a part of the reactor composition. The reactor thus has 4 categories of materials, more or less: liquid (wastewater), solid (rock and mineral precipitates), a spongy material (wood and hay) and gel-like material (biomass). Each piece has its own thermal and mechanical properties contributing to the reactor’s bulk thermal and mechanical reality.

Bacterial growth and substrate utilization are governed by Monod microbial kinetics

$$r_x = Y q \frac{S}{K + S} X_a - b X_a \quad (1)$$

$$r_s = q \frac{S}{K + S} X_a \quad (2)$$

Where r_s is the rate of substrate utilization, q is the maximum rate of substrate utilization, K is the half saturation constant, X_a is the concentration of active bacteria, and S is the concentration of limiting substrate, in this case it is taken to be sulfate. In Equation 16, Y is the yield, defined as g cells grown per g substrate, and b is the decay rate for the microbial population. While empirical and commonly used in microbial studies, the Monod equation bases the microbial growth on the concentration of a single limiting substrate and the microbial population, so it is merely a rudimentary way of looking at microbial reactions (Rittmann, 2001).

The substrate utilization rate changes with temperature according to experimentally derived kinetics retrieved from inoculated columns using mine water from an abandoned mine site in Rico, CO [Table 1]. The half saturation constant and microbial decay constants are also shown to change significantly with temperature (yield less so).

Table 1 Microbial growth parameters that change with temperature

Parameter	Unit	25°C	35°C
Sulfate utilization	mgSO ₄ ²⁻ /day	0.007	0.013
Half saturation	mg/cm ³	0.293	0.016
Microbial decay	1/day	0.528	0.912

Microbial growth leads to reduction in mobile fraction porosity up to 24%, according to experimental NMR results. The growth of bacteria also leads to the reduction of matrix strength and increased fluidity of the matrix.

Several simplifications are usually made when modeling this system. Among the simplifications are the materials within the bioreactor system are completely mixed, and the porous substrate is solid and fixed. While simplifications are necessary for complex systems, such simplifications result in failure of the passive system due to clogging after a few years of bacterial maturation, and system bypass, when the water does not reside in the system for the anticipated time period. Partly simplifying the mechanics of a reactor substrate is a result from inadequate models of organic material deformation. Terzaghi's one dimensional consolidation theory is primarily for mineral soils. Large deformation, settlement after loading, evolving permeability are all features observed in peat, and are unique to porous matrix with high organic content.

A combination of compression and microbial digestion has been shown to significantly reduce the permeability of high organic content matrices. As straw decays in a soil, the soil density increases 1.2 to 1.4 Mg/m³ and the elasticity decreases to half its rebound ratio (Soane, 1990). Studies on bulk peat material shows that fibrous peat holds water in a macropore network and has high compressibility, while amorphous (highly humified) peat holds water in an absorbed viscous condition and shows a plastic resistance to compression (Soane, 1990). The visco-plastic material develops where digestion is taking place. This alteration can conceivably reduce wall permeability and give way to the predominant fluid flow path. This behavior has led to models that present diffusion as the dominant substrate transfer mechanism in biofilm systems (Rittman, 2001).

3. METHODS

In this analysis the model will begin by coupling microbial growth, substrate utilization, fluid flow and thermodynamics, using Comsol Multiphysics platform.

3.1 Fluid dynamics model:

$$0 = \nabla \cdot \left[-p\mathbf{I} + \frac{\mu}{\varepsilon}(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - \frac{2\mu}{3\varepsilon}(\nabla \cdot \mathbf{u})\mathbf{I} \right] - \left(\frac{\mu}{k_{br}} + \beta_F |\mathbf{u}| + Q_{br} \right) \mathbf{u} + \mathbf{F} \quad (3)$$

$$\rho \nabla \cdot \mathbf{u} = Q_{br}$$

where ρ is fluid density, μ is dynamic viscosity, \mathbf{u} is velocity, ε is porosity, Q_{br} is a mass source or mass sink (SI unit: kg/(m³·s)), p is pressure, \mathbf{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/m⁴ contributes a viscous drag force. ε is porosity. Uppercase \mathbf{I} is the moment tensor and T is temperature. Lowercase \mathbf{u} is a velocity vector.

3.2 Thermodynamics model:

Heat transfer is modeled in the liquid phase and in the solid phase.

$$\rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k_{eq} \nabla T) + Q \quad (4)$$

$$k_{eq} = \theta_p k_p + (1 - \theta_p) k \quad (5)$$

Using user-defined thermal conductivity k_{eq} , 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 $1 - \varepsilon$.

3.3 Temperature based microbial model:

Based on empirical evidence of laboratory experiments performed by the author, the changes in the Monod terms can be collected into a temperature dependent empirical term q^* which can substitute for q in the Monod equations.

$$q^* = 0.007 \times 1.07^{T-295} \quad (6)$$

Then by tracking the microbial growth rate in the reactor, changes in permeability will be applied to observe the reactor's response, checking for short circuits in the system, as well as monitoring heat distribution and outlet concentrations.

4. RESULTS

The results of the study were reviewed after the model simulated 1500 days of system function. The model shows the result of mixed convection in the system: thermally driven free convection from the bottom heat plates as well as inflow from the top left and outflow from the bottom right at a velocity of $5e-6$ m/s.

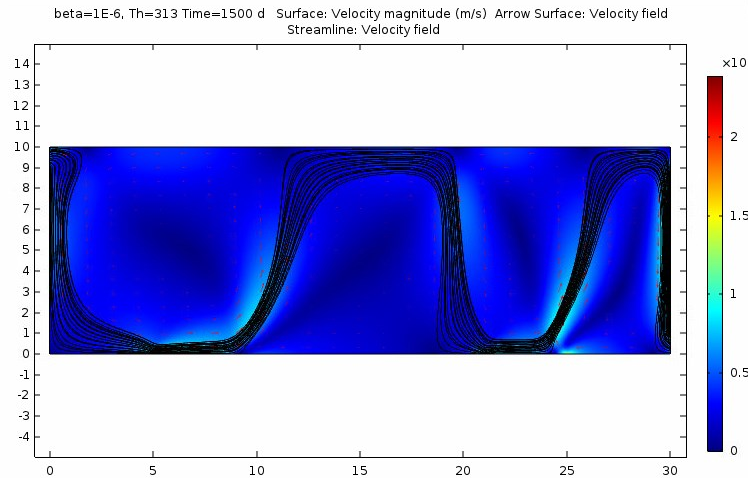


Figure 1 Velocity surface plot of the heated reactor design. Warmer colors represent faster flow, the black lines show flow streamlines and the red arrows show flow direction

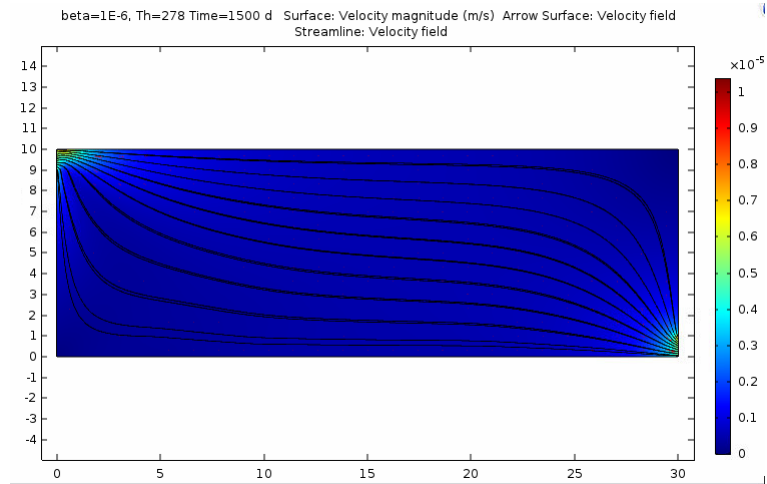


Figure 2 Velocity surface plot of non-heated reactor design, streamlines spread through system

Immediately it is apparent that the thermally driven flow provides more regular flow path for the water. The black lines are streams lines from the inlet to the outlet of the tank, the red arrows are velocity vectors that show the direction of water travel. Rather than taking many flow paths with disparate residence times, the water in the heat treated system is subjected to a single, tortuous flow path through the tank. The centers of the convection cells may be shown to accumulate larger particles if investigated further.

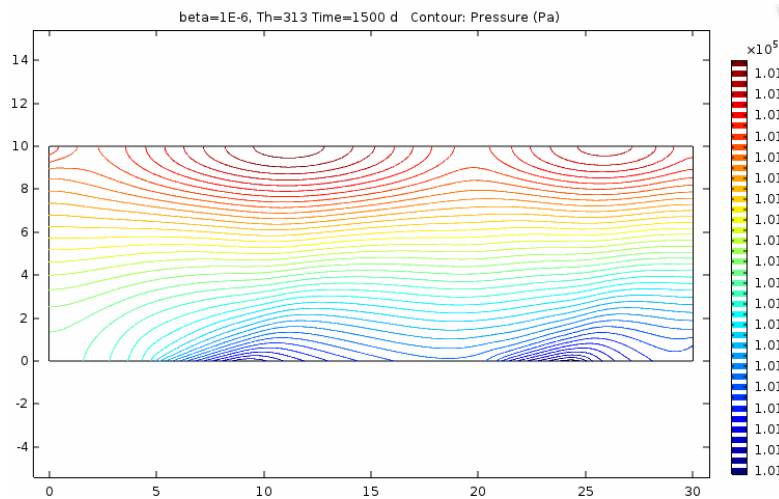


Figure 3 Pressure contours of heated system. Warmer colors represent higher pressure. Prominent pressure gradient oriented parallel to inlet and outlet

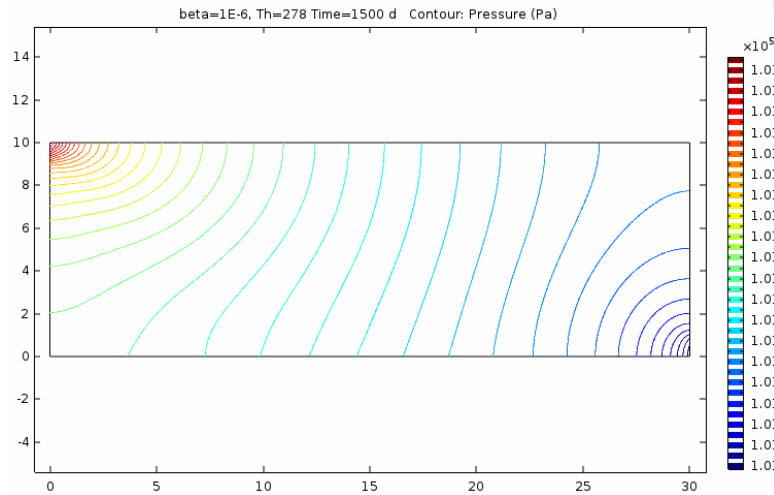


Figure 4 Pressure contours of non-heated system simulation. Prominent pressure gradient oriented perpendicular to inlet and outlet

In the pressure contour figures, the prominent temperature gradient is visible. With the heated system, the prominent pressure gradient is vertically oriented, rather than horizontally oriented as in the non-heated system. The orientation of the pressure gradient indicates where compression of the substrate may occur. Rather than accumulate at the outflow, producing clogging, the heated system will compress material perpendicular to the predominant flow of the system. This facet may increase the longevity of passive treatment systems in the field, and prevent clogging of crucial flow paths.

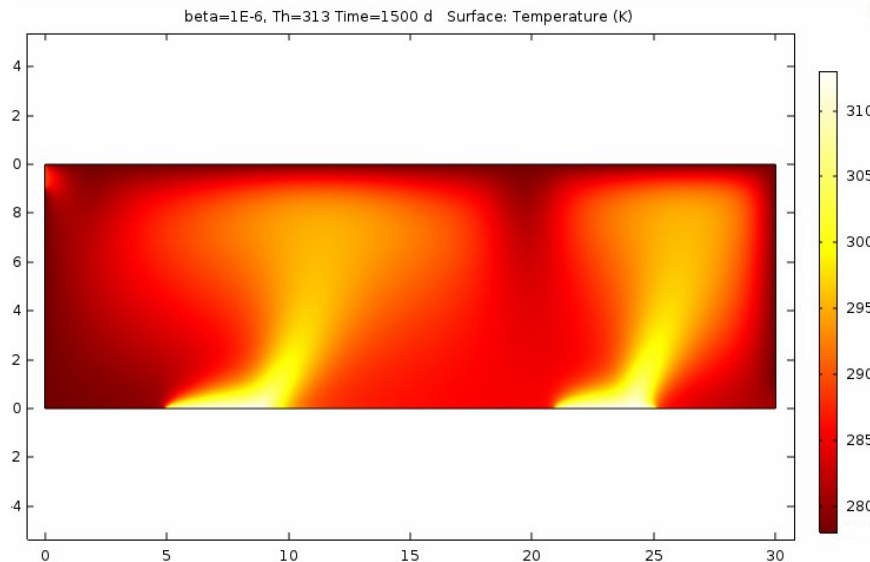


Figure 5 Temperature plot of heated system showing heat distribution in the mixed convection system (Non-heated system not shown)

Figure 5 shows the result of a coupled fluid and thermodynamic model. Whereas in a traditional system the natural available heat from mine groundwater is quickly dissipated to the cold outside environment, a heated system can use the local heat sources to passively dissipate heat in the tank reactor. The convective flow also helps distribute heat in the system so that the beneficial temperature is available to more of the reactor.

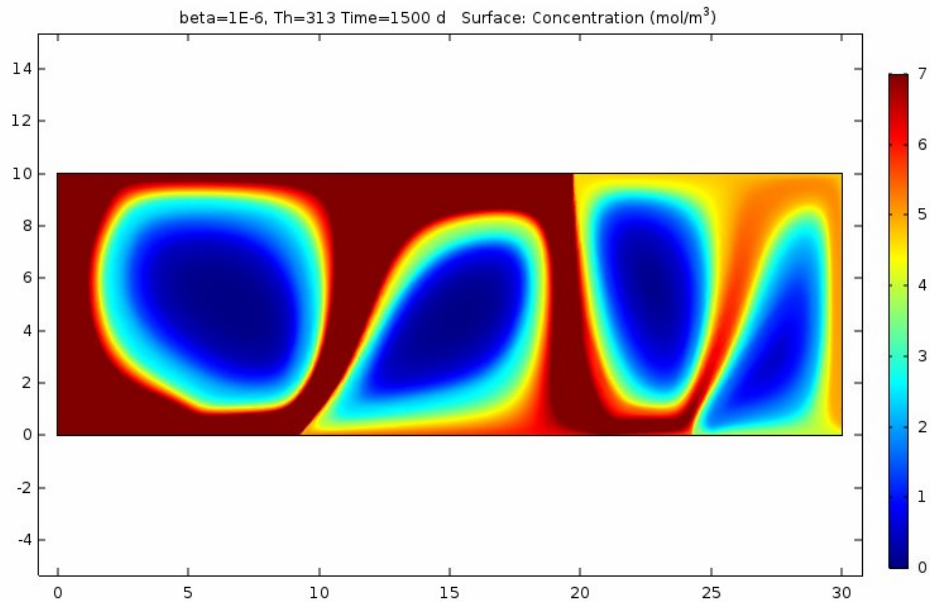


Figure 6 Concentration surface of heated system at day 1500 of simulation

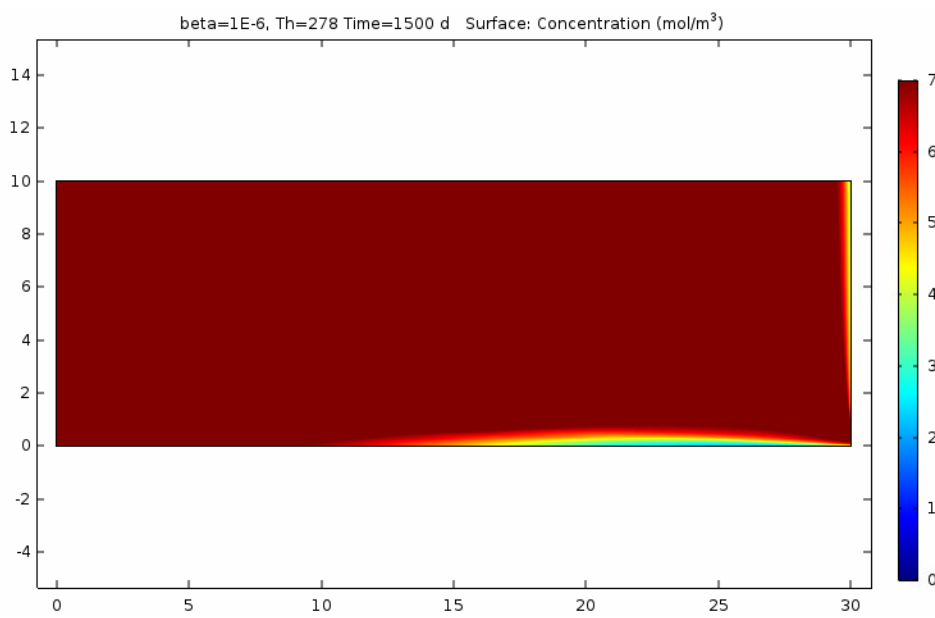


Figure 7 Concentration surface plot of non-heated system at day 1500 of simulation

The surface concentration plots show the distribution of contaminant in the tank reactor. By the simulated 1500th day, contaminant is fully dispersed in the non-heated tank.

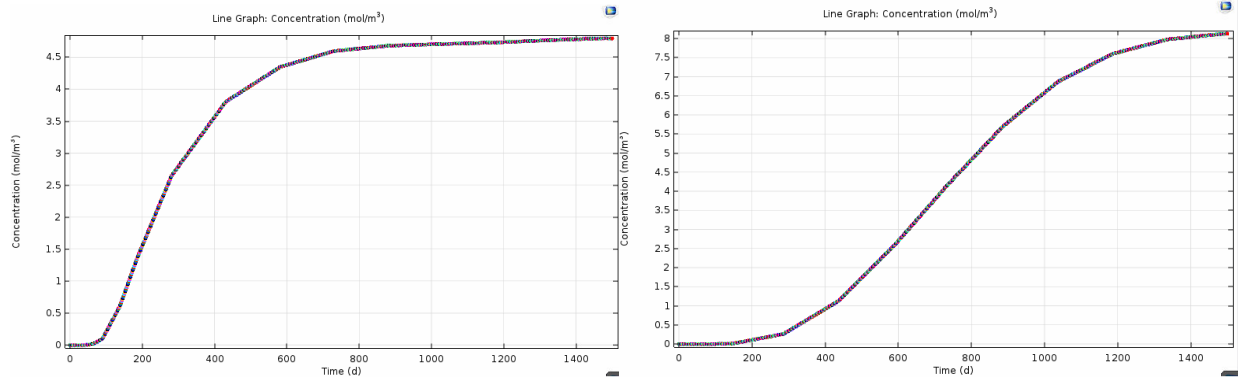


Figure 8 Graphs on the average outlet concentration of the simulated contaminant. The left is the heated system and the right is the non-heated system

The average concentration at the outlet is shown in Figure 8. The first graph shows the result of the outlet with a heating element and the second graph shows the outlet without a heating element. From an initial inflow of 15 mol/m³, the heated tank reduced the concentration of the contaminant to about 5 mol/m³ while the cold tank reduced it to about 8.5 mol/m³. The 40% decrease in contaminant outlet can also be translated to a 40% decrease in the space required for treatment, from a construction or financial standpoint. While diffusion to the center of convection cells essentially limits space utilized by the system, the overall benefit from reduced dispersion and added heat significantly improves the efficiency of the system- not only improving treatment per area, but also improving the pressure gradient which affects eventual compression and clogging.

4.1 Seasonal Stability

In order to study the seasonal stability of the cells, the simulation was run to approximate a summer temperature outside of the convection tank, or 15°C, the recorded ground temperature of high altitude sites tested in Colorado.

The convection cells remain intact in this temperature gradient as well.

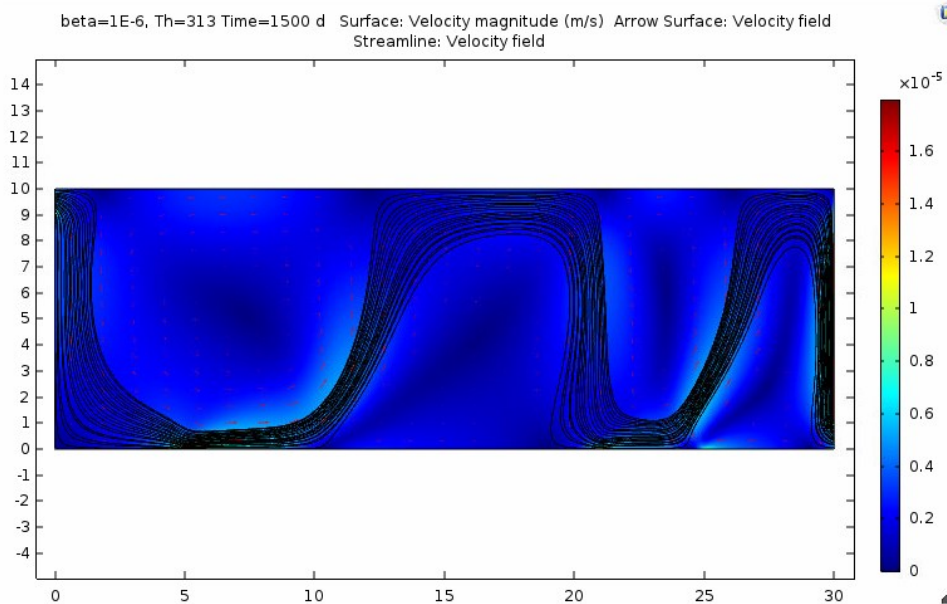


Figure 9 Outside temperature is changed from 5°C (278 K) to 15°C (288 K) to investigate the effect of seasonal temperature variability impacts flow in heated system. Free convection cells in mixed convection system still partially intact

And the warm tank outflow average concentration is further reduced to 2.2 mol/m³.

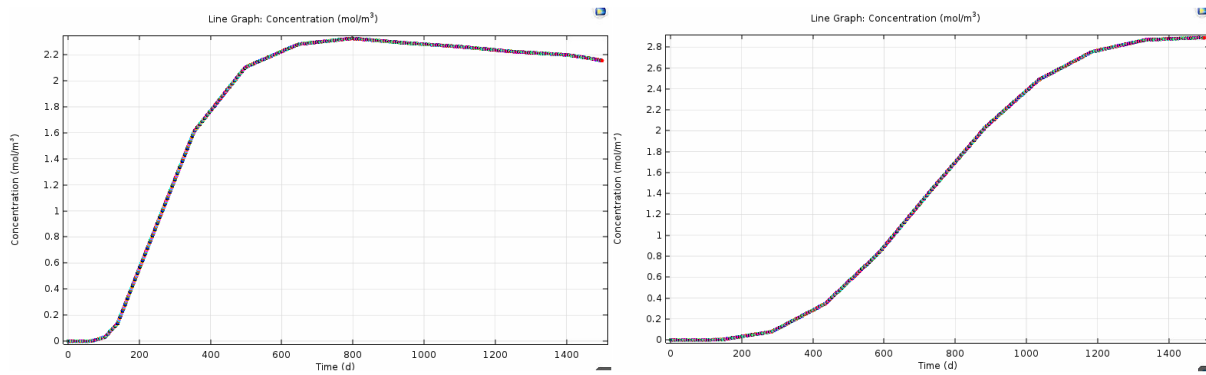


Figure 10 Graphs on the average outlet concentration of the simulated contaminant for the summer condition. The left is the heated system and the right is the non-heated system

The difference between the summer heated and cool tanks is predictably less considerable with only about a 0.8 mol/m³, or 27% difference in average outlet concentration (Figure 10).

Even in summertime ground conditions, improvement of treatment efficiency can be seen when the heating element brings part of the tank to the bacteria’s optimal temperature. The overall impact of the heated system is still beneficial to the remediation efficiency with the reduced temperature difference, showing the system is robust within a 10 degree range of temperature difference.

4.2 Successive bacterial growth

The bacteria concentration plot appears in Figure 11:

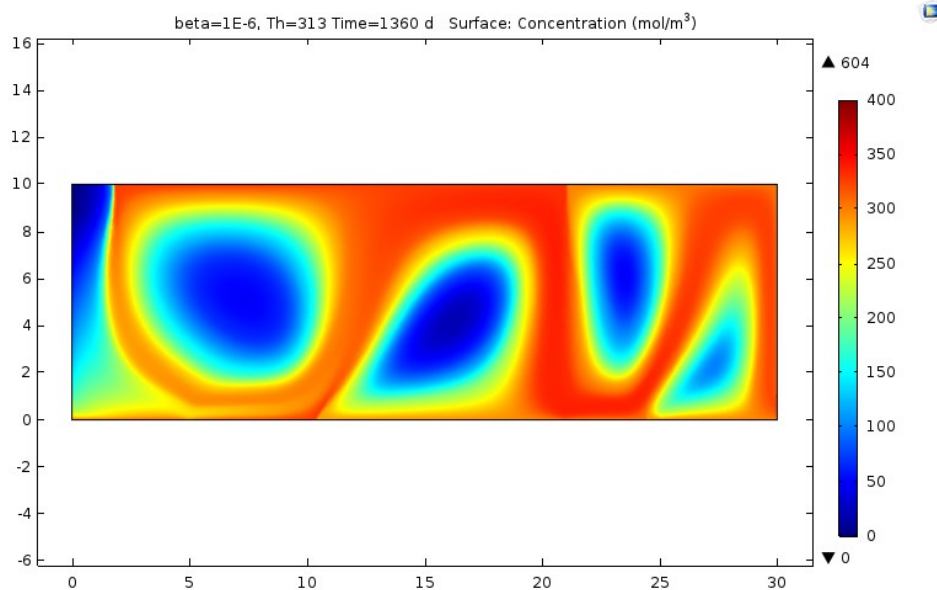


Figure 11 Sulfate reducing bacteria growth in tank reactor at day 1360. Warmer colors representing higher concentrations.

Higher concentrations of bacteria tend to form on the periphery of dominant flow in the first half of the reactor, and then in the dominant flow path in the second half of the reactor. The growth of biofilms has been shown to decrease the local porosity in a system significantly, up to 50%, in this anaerobic system, according to NMR data analyzed in an associated study. The local growth in bacteria corresponds with increased flow velocity in the same space. The collocation of higher velocities and increased bacterial growth could have implications for the tank design. A decrease in permeability at a rapid flow channel could stress the laminar flow conditions of the system, increasing local turbulence and dispersion.

5. CONCLUSION

The removal rate of the regular tank in the winter condition removed 43.3% of the influent contaminant, while the heated tank effectively removed 66.7% of the influent contaminant. In the summer condition, the heated tank could remove 85.3% of the influent contaminant and the cool tank removed about 80%. The use of computational flow modeling in this case study allowed an insight into the added potential mechanical benefits of a heated system as well. Where the traditional systems allow for dispersion and unidirectional flow, the heated system provides a stricter streamline for flow to follow through the tank, with circular flow. The convection observed in this model however reduces the effective reactor volume by constricting flow to the convection cells. Overall the benefit of the heat and dispersion reduction outweighed the reduction in effective volume, making the heated system more efficient.

By integrating computational flow modeling into bioreactor system design, the types of reactors possible will not be limited to basic settling designs. Environmental treatments that fit the landscape or utilize locally available materials and energy sources may be possible to create more efficient systems in remote areas. Future work should focus on showing the effects of evolving permeability, related to substrate decomposition and microbial growth, on the systems hydraulics and heat transfer.

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