Modeling of Stockton University Geothermal System Using COMSOL Subsurface Flow Module

Gerad Villaluna, Sipra Pal, Monir Sharobeam*
Applied Physics Program, Stockton University
*Corresponding author: School of Natural Sciences and Mathematics, Stockton University, 101 Vera King Farris Drive, Galloway, NJ 08205

Abstract: COMSOL is used to solve the steady state heat transfer equation for a stratified medium and in the presence of convective heat transfer due to ground water flow. This initial piece of work is to determine the extent of computational domain necessary for the given geological conditions with heat source that is representative of that of Stockton's geothermal well field. Also, the effects of air flow at the surface of the well field, as well as a constant surface temperature, are investigated.

Keywords: Geothermal heat transfer, convection, conduction, temperature profile

1. Introduction

Approximately two decades ago, the Stockton Geothermal unit was the largest closed-loop ground source heating and cooling system in North America. It comprises of four hundred wells bored to a depth of about 400 feet spanning lateral dimensions of roughly 617 by 194 feet with an average separation between the wells of about 16 feet.[1] Water circulating through U-shaped plastic tubing inserted into the wells act as the heat exchanger fluid carrying thermal energy in or out of the well field depending on the seasonal need. The wells are distributed somewhat symmetrically; therefore, in the absence of convective heat transfer, the temperature distribution at any given depth can be considered the same. The Stockton well field design was based on the Superposition Bore Hole Computer Simulation Model (SBM).[2] Though a very extensive model, it does not incorporate the stratified media nor groundwater flow. The ground geology around Stockton consists of three aquifers, the Upper Cohansey, Lower Cohansey, and the Rio Grande, where there is groundwater flow through sand, with flow speeds averaging several inches per day. In between the aquifers are confining beds of a mixture of clay and sand as seen in Figure 1.

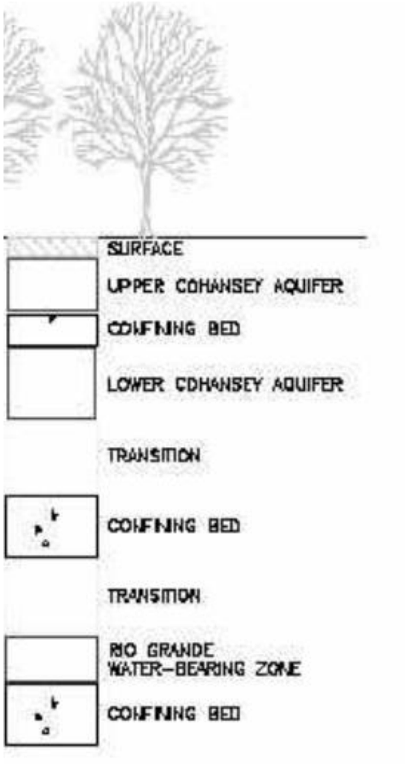

Figure 1: Stratified ground layers

Groundwater flow can cause a tremendous departure from symmetry in the temperature distribution at a given layer in and around the well field.

Well field designers rely heavily on the expected temperature profile of the ground under a given projected heat loads, therefore any assistance they may get from simulation models can be helpful. We would like to use COMSOL subsurface module to determine its feasibility in the modeling of Stockton's well field.

The emphasis of this paper is to determine appropriate boundary conditions that will be necessary for the comprehensive simulation of the Stockton field with its given geological conditions.

2. COMSOL Model

Here we are investigating the extent of the computational domain in all five directions and at the surface that would be required to appropriately model Stockton's well field. This is being done by looking at the steady state solutions to the heat transfer in the presence of a source term. Initial two years of collected data of the well field[1] gave a qualitative estimate of the power output/input as

$$q = \left(1.47 + 3.7\cos\left(\left(\frac{2\pi}{365\text{days}}\right)t + 2.5\right)\right) \times 10^{10}\,\frac{\text{J}}{\text{day}}$$

The average power as represented by this expression is used in the COMSOL model distributed uniformly over a volume similar to that of the well field. The orientation of the computational domain is kept along the direction of the flow to study the effect of ground water flow. The actual geothermal field is about 45° to the direction of flow in the aquifer. Table 1 lists the input data for the different ground layers. A sand layer was added in the model below the third confining layer. Initially, a preliminary model with all boundaries assumed as thermally insulated except for those of the inlet and outlet of the water flow in the aquifers was used to explore the problem. The size of the model was about four to five the width of the well field and the depth included a sand layer of a height 150 feet below the well field. Based on the results of the preliminary model, two advanced models were developed to provide better simulation of the system. Both models are stretched further along the ground water flow direction to avoid a steep temperature gradient at one of the insulated boundaries in the preliminary model. The size of the new models is selected such that the temperature change across any insulated vertical boundary is reasonably small and gradual. The advanced models assumed a sand layer of 300 feet below the well field and replaced the insulated top boundary by a different interaction between the top surface of the model and air. One of the two models included a layer of moving air of height 200 feet above the well field. The air flow speed is taken as 4.5 m/s and the initial temperature as 12°C which are the average values for this region.[3,4] The other assumed that the top surface is kept at a constant temperature of 12°C. In the first advanced model, three coupled equations were used by COMSOL to compute the temperature distributions of the ground which are the heat equation, Darcy's Law as well as the laminar flow equation for the region of air flow. In the second advanced model two coupled equations were used in the analysis which are the heat equation and Darcy's law.

Table 1: Input data for Stockton well field

Layer	Material	Section Depth (ft)	Flow (in/day)	Porosity
Upper Cohansey	Sand	82	3-4	0.35
Confining Bed I	Clay	30	0	0.50
Lower Cohansey	Sand	51	3-4	0.35
Trace I	Sand/Clay	65	0	0.35/0.50
Confining Bed II	Clay	16	0	0.5
Trace II	Clay/Sand	91	0	0.35/0.50
Rio Grande	Sand	20	3-4	0.35
CB III	Clay/Sand	38	0	0.35/0.50

3. Results

3.1 The Preliminary Model

The purpose of this model was to explore the impact of the size of the model a well as the use of thermally insulated boundaries on the temperature distribution

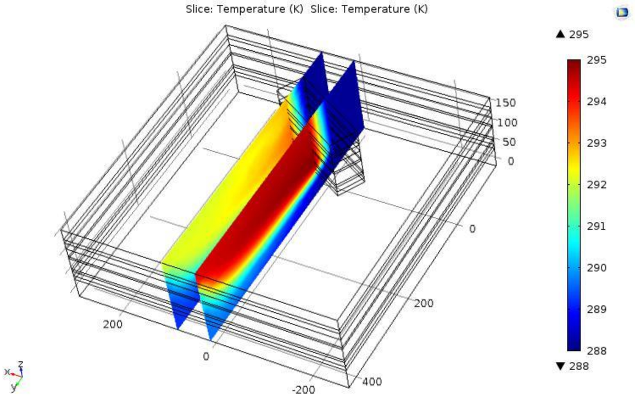

Figure 2: Temperature distribution along mid and side slices of the field. Distances in m, temperature in K.

in the ground. The ground water flow is along the positive y-axis direction. Figure 2 shows the temperature distribution along two vertical planes; one at the middle of the field and the other close to the edge of the field. The model shows a high temperature at the top boundary and steep temperature gradient at the end side of the model along the y-axis. Considering that air average temperature in this region is around 12°C. Thus considering the top boundary as an insulated surface is not practical. Also the steep temperature gradient at the end side of the model is an indication that the size of the model along the y-direction is short.

3.2 The Two Advanced Models

The models have a length along the y-direction that is almost ten times the longer side of the well field and a depth of about 300 feet for the sand layer below the well field. The first model includes a layer of moving air on top of the ground while the second model assumes a constant top temperature. The results of the two models are very close. Figures 3 and 4 show the temperature distribution for the mid plane in the model. The two figures show similar temperature distribution in the ground with the peak temperature in the region between the second and third aquifers as close as possible to the well field. Temperature distribution is gradual with a small drop along the insulated boundaries which is an indication that the size of the model is appropriate. The temperature in the air layer seems to be almost constant.

Figures 5 and 6 show the temperature distribution on multiple planes that are perpendicular to the direction of the ground water flow for both models. Both show similar temperature distribution in the ground.

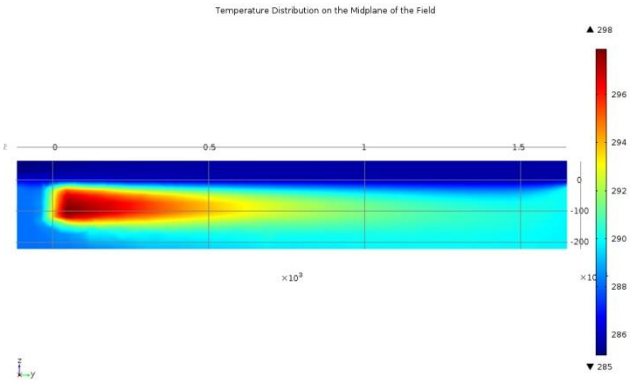

Figure 3: Midplane temperature distribution for the model with moving air layer. Distances in m, temperature in K.

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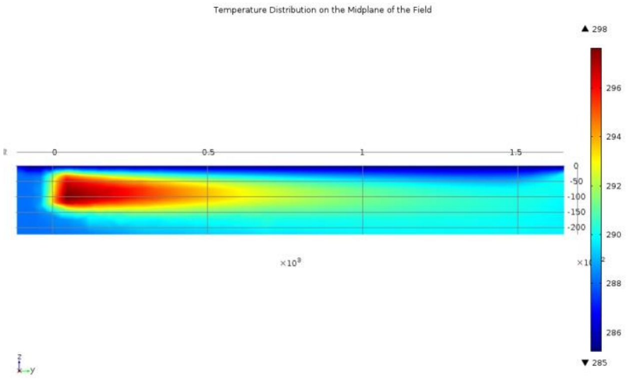

Figure 4: Midplane temperature distribution for the model with constant top surface temperature. Distances in m, temperature in K.

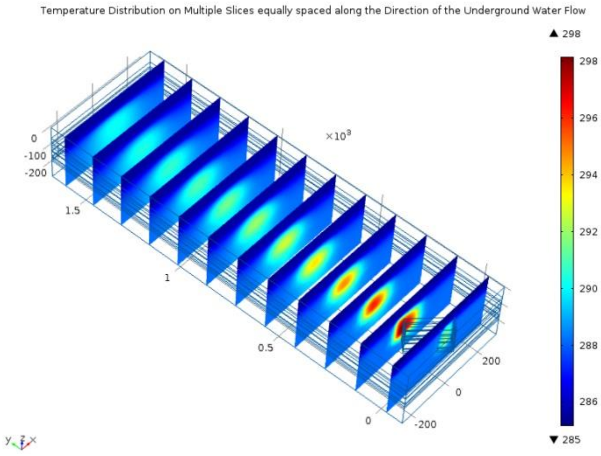

Figure 5: Temperature distribution of equally spaced slices along direction of underground water flow in the model with moving air layer. Distances in m, temperature in K.

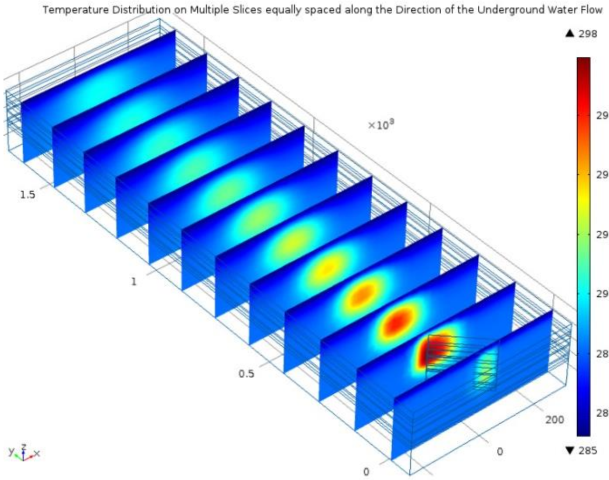

Figure 6: Temperature distribution of equally spaced slices along direction of underground water flow for the model with constant top surface temperature. Distances in m, temperature in K.

Figures 7 and 8 show the temperature variation along the depth of the ground for both models at different distances from the well field along the direction of the ground water flow starting from the edge of the field to a distance of 1500 meter away from the well field. The model with the air layer shows low temperature gradient in the air layer. This is because of the high speed of the air layer in comparison of the speed of the water in the aquifers. The speed of air is about 4.4 x 10^6 times the speed of the underground water. The temperature at all locations gradually drop to a value close to the initial ground temperature of 288.15 K at the bottom boundary of the model which is an indication of having practical depth for the model. The temperature variation within the ground is almost identical at the different locations for both models. The peak temperature occurs in the layer just above the lower aquifer.

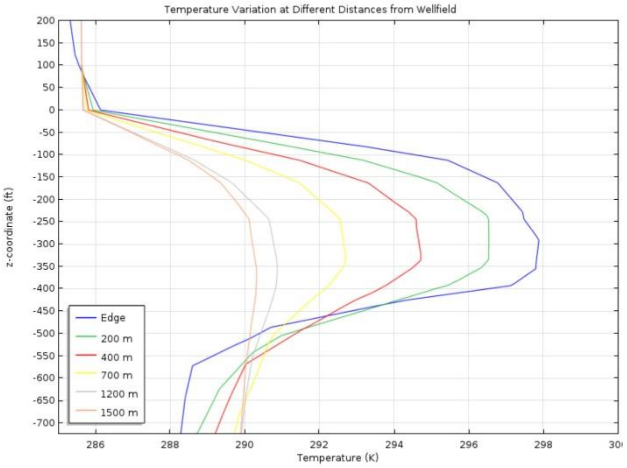

Figure 7: Temperature variation at difference distances from well field for the model with moving air column at the ground surface. Depths in ft, temperature in K.

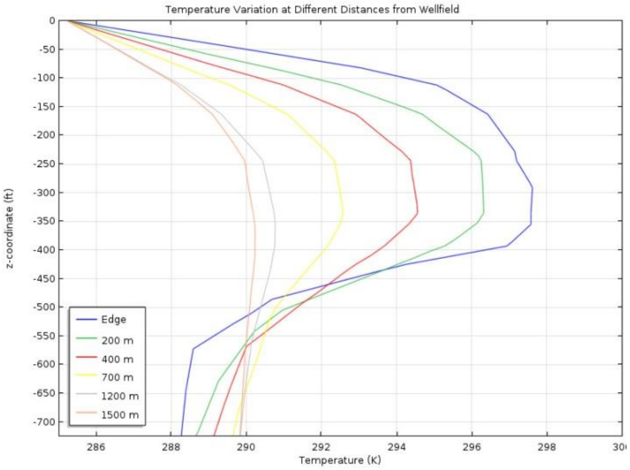

Figure 8: Temperature variation at different distances from well field for the model with constant top surface temperature. Depth in ft, temperature in K.

4. Conclusions

The results obtained from the steady state solution of the heat transfer equation for the Stockton geothermal well field indicate that it will be necessary to extend the dimensions of the computational region many hundreds of feet beyond the extent of the source. It is interesting to observe that the surface air and air flow has very little impact on the ground temperature distribution and that it can be readily replaced with a constant surface temperature. Maintaining a constant surface temperature and no air flow can reduce the computational time considerably.

5. Future Work

This current piece of work serves only as an introduction to the full-fledged modeling of the geothermal field. Now that we have a handle on the boundary conditions, in future work, we will be experimenting with the transient behavior of the field where the surface temperature will be represented by a time varying function and the heat source/sink will be modeled with a seasonal depended function. It will be interesting to know if the heat injected in the summer can be recovered in the winter and over an extended time of operation if the ground will settle to an overall constant temperature.

6. References

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