PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2019
SGP-TR-214

Modeling of heat transfer in abandoned oil and gas wells

Arjav SHAH, Sachchida Nand PANDEY, Vikram VISHAL, Sandip K. SAHA

Indian Institute of Technology Bombay, Main Gate Road, IIT Area, Powai, Mumbai, Maharashtra 400076, India

arjav.shah98@gmail.com, snp.iitm@gmail.com, v.vishal@iitb.ac.in, sandip.saha@iitb.ac.in

Keywords: depleted wells, production temperature, numerical simulation, finite element method, parametric study

ABSTRACT

As the demand for energy continues to grow with population in emerging countries, use of alternative renewable sources of energy is imperative for the near future. The impending climate change and current economic development have forced a shift to more sustainable sources of energy like geothermal, solar, and wind. The widening of supply-demand gap over years has led to global energy crisis and resulted in exhaustive use of non-renewable natural resources to meet the energy demands. This extensive use of fossil fuels has been made possible by the current development of human civilization. However, burning of fossil fuels, which are becoming increasingly scarce, has led to an increase in emissions of carbon dioxide, which is a greenhouse gas, into the atmosphere. This, in turn, has also led to a detrimental impact on the environment and an imbalance in the natural ecosystem. Geothermal energy is a green, environment-friendly, low carbon, renewable and sustainable source of energy since there are relatively less investments and is pollutant-free. The major advantage of geothermal energy over other sources of renewable energy is that the underground heat/energy mining does not depend on the weather conditions and geothermal power runs at a much higher load factor than wind or solar. Nearly 40% of the total investment cost that goes into setting up a geothermal plant is the drilling cost. However, this problem can be potentially tackled by utilizing the currently decommissioned and abandoned oil and gas wells for geothermal purposes. Retrofitting an abandoned well to produce geothermal energy also saves the cost of exploring sites for geothermal fields. The estimated potential for the geothermal energy that can be harnessed in India is about 10 million kW. In this study, abandoned oil and gas wells have been simulated as a source of geothermal power to generate electricity. Simulations have been performed by coupling thermal reservoir with bore well heat transfer and laminar flow model. Water, which is chosen as working fluid is circulated down through the annulus and extracted back through the shorter insulated inner pipe. A parametric study to assess the production temperature using finite element method with various operating parameters such as injection mass flow rate, re-injection temperature, well depth and geothermal gradient is performed. The results of this study indicate that heat extraction rate increases with increasing mass flow rate as well as the well depth while all other injection parameters remain constant. At higher injection temperature, the net heat extraction rate from the reservoir decreases with time due to lower temperature difference between injected fluid and reservoir formation temperature.

1. INTRODUCTION

Achieving solutions to environmental problems that we face today requires long-term potential actions for sustainable development. In this regard, renewable energy resources appear to be one of the most efficient and effective solutions. The diversification and decentralization of energy resources can make energy and electrical systems more resilient (World Energy Trilemma, 2017). During the past two decades, the risk and reality of environmental degradation have become more apparent. Growing evidence of environmental problems is due to a combination of several factors since the environmental impact of human activities has grown dramatically because of the sheer increase of world population, consumption, industrial activity, etc. (Ibrahim Dincer, 2000). According to BP Statistical Review of World Energy 2018, global primary energy consumption grew strongly in 2017, led by natural gas and renewables, with coal's share of the energy mix continuing to decline. The report also states that renewable power grew by 17% in the year 2017 (Statistical Review of World Energy, 2018).

Geothermal energy is a sustainable and renewable source of thermal energy which is generated and stored in the earth's crust. As a promising alternative to the declining fossil energy sources, it is extremely important to be able to develop and utilize renewable sources of energy like geothermal energy. Deeper the penetration into the earth, warmer is the interior. It is assumed that temperature in the earth's core of about 5,000 - 7,000°C can be achieved. This heat stored in the earth is inexhaustible as per human standards. Its production is relatively less expensive, reproducible and pollutant-free. An added advantage of geothermal energy over other sources of renewable energy is that the underground heat/energy mining does not depend on the weather conditions. Apart from this, one of its important characteristics is a high load factor, which means that each MW of capacity produces significantly more electricity during a year than a MW of wind or solar capacity. Geothermal power runs at a much higher load factor than wind or solar as this energy source is continuous rather than intermittent, hence geothermal produces significantly more electricity per MW of capacity.

According to BP Statistical Review of Geothermal Energy 2017, geothermal capacity grew by 4.3% (600 MW) in 2017, to reach 14.3 GW. The largest additions to capacity were in Turkey (243 MW) and Indonesia (220 MW). 26% of the world's total capacity is in the US which has the largest capacity of 3.7 GW, followed by the Philippines (1.9 GW), Indonesia (1.9 GW) and New Zealand (1 GW). There has been a concentration of geological conditions that are required for geothermal power development in relatively small number of countries (Review of Geothermal Energy 2017).

In the past few years, the direct utilization of geothermal energy has increased by 31.58% reaching up to 70,885 MW worldwide (Lund and Boyd, 2016). In addition to direct use, the electricity generation installed capacity has also reached to 12.729 GW in 2015 from 10.895 GW in 2010 with a growth of 14.40% (Bertani, 2016). The total geothermal energy production and usage for India accounted to 986 MW and 4302 TJ/year in 2014 (Lund and Boyd, 2016). Geothermal energy has less than 0.5% share of current electricity generation. By 2050, geothermal energy could be able to provide approximately 3.5% of the world energy demand (Annual U.S. Geothermal Power Report, 2015).

Surprisingly, only 6-7 % of the total global potential for geothermal power based on current geologic knowledge and technology has been tapped yet by the communities and governments around the world. There are vast untapped resources that could provide base load renewable energy to grids across the globe. However, there have been factors such as natural disasters, permitting delays, and trouble obtaining financing which have impeded the global growth of geothermal power (Annual U.S. Geothermal Power Report, 2016).

One of the ingenious ways to extract geothermal energy is by employing the abandoned oil and gas wells. These wells can be retrofitted as a geothermal system as they are generally deep enough to access higher temperature strata of the earth. These wells are rendered abandoned, decommissioned, and reclaimed when petroleum reservoirs are depleted beyond an economically viable point. In general, the oil and gas wells are abandoned when the cost of production is higher than income (Cheng et al., 2014). Petroleum wells that access a reservoir containing an economically unfeasible type or amount of petroleum are also abandoned, and are referred to as “dry” wells. Since most of the total costs, as much as 12 million dollars for a 4 km deep well (Song et al., 2018), for all kinds of geothermal reservoirs goes into drilling, geothermal reservoirs can be re-used for geothermal energy production without drilling of new wells. Most of the wells globally, more than 30 million, which can be re-used for local power generation are abandoned (Kotler, 2011). The initial costs of a geothermal development plant can be significantly reduced along with the reduction in environmental pollution, if these abandoned oil and gas wells can be successfully re-used. A comparison between installed capacities of geothermal energy in the world and Asia is drawn in Figure 1:

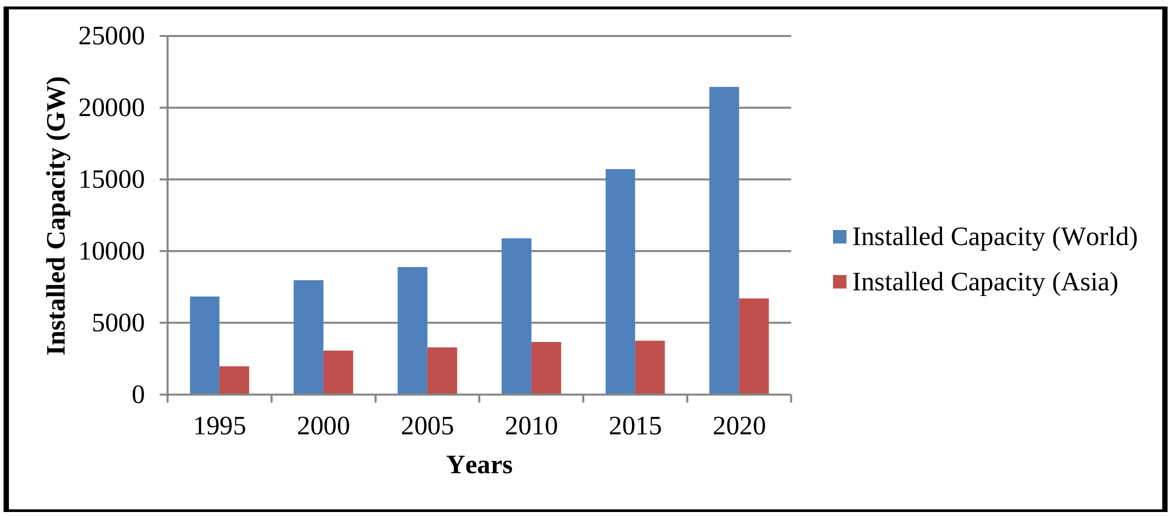
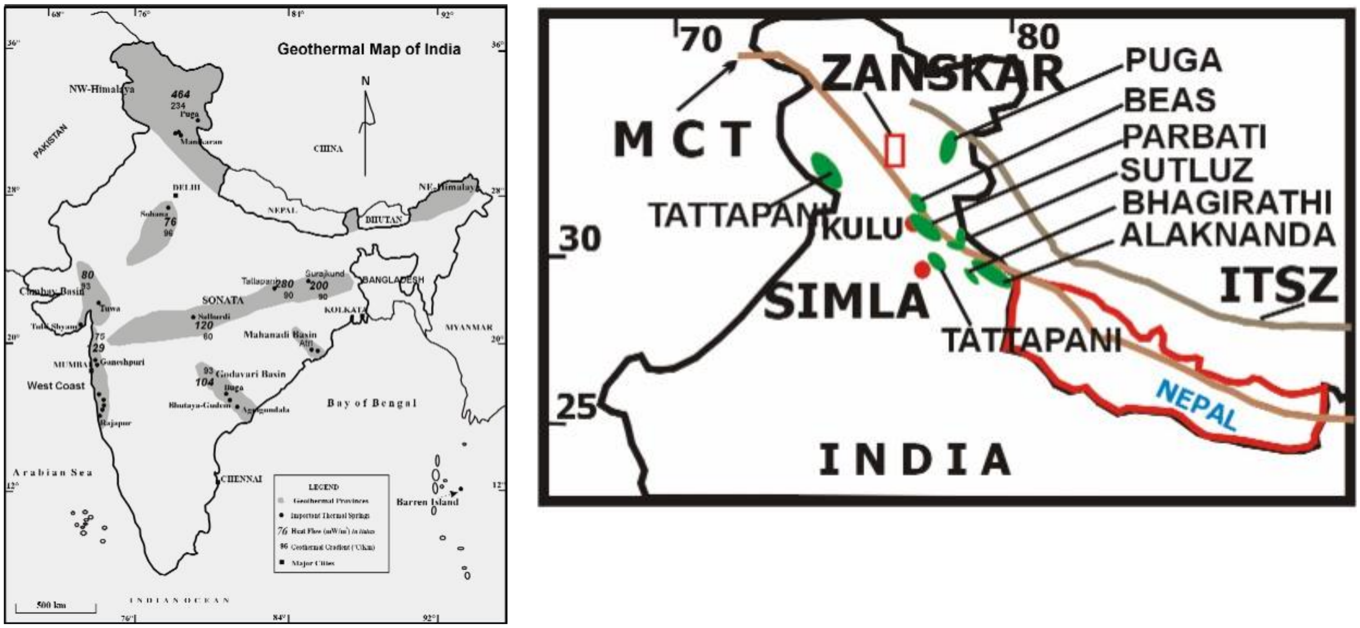


Figure 1: Comparison of installed capacity of geothermal energy
(Lund and Boyd, 2016)

2. GEOTHERMAL ENERGY IN INDIA

In India, exploration and study of geothermal fields started in 1970. The Geological Survey of India (GSI) has identified around 350 geothermal energy locations in the country. The most promising of these is in Puga valley located in Ladakh region of Jammu and Kashmir in North India. The estimated potential for geothermal energy in India is about 10000 MW (India Energy Portal, 2017). India also has a large scope to utilize this energy source for greenhouse cultivation in the cold climatic regions like Ladakh and Kargil as well as for dehydration of agricultural produce (Chandrasekharam et al., 2015). These small initiatives will save power and CO2 and bring thousands of rural villages under electricity grid. This geothermal energy may also prove to be a good substitute to fossil fuels in low to moderate temperature uses.

There are seven geothermal provinces in India: The Himalayas, Sohana, West coast, Cambay, Son-Narmada-Tapi (SONATA), Godavari, and Mahanadi. These seven provinces are located in a wide lithological and tectonic regime varying from a passive continental margin to active subduction related tectonics. The location of these geothermal provinces is shown in figure 2 along with important thermal manifestations (Chandrasekharam et al., 2015).



(a) (b)

Figure 2: Map showing the geothermal provinces of (a) India and (b) North-West Himalayas
(Chandrasekharam et al., 2005)

3. METHODOLOGY

3.1 Modeling Approach

After the oil and natural gas at a well location are exhausted, it is rendered useless. Hence, instead of plugging the well, the existing oil and gas wells can be retrofitted as geothermal wells. This can be done by sealing the bottom and casing the well, as shown in Figure 3. The circulating fluid, chosen as water in this case, is injected through the annulus. Water flows downward along the channel and is gradually heated by surrounding rocks due to a temperature gradient that exists between the reservoir rocks and the fluid. The flow is reversed at the bottom of the well, and then the fluid ascends through the inside channel and flows out to the earth's surface (Davis et al., 2009). A variety of processes take place within the reservoir when relatively cold water is injected. The processes that occur are: convection (at the solid-fluid interface by the motion of fluid), advection (transport of heat as well as reactants products by bulk motions of fluids), and heat conduction in the low permeable rock matrix, molecular diffusion, hydrodynamic dispersion and thermo-poro-elastic deformation of pore/fracture/rock (Pandey et al., 2018). A schematic diagram of the modeled system is shown in Figure 3:

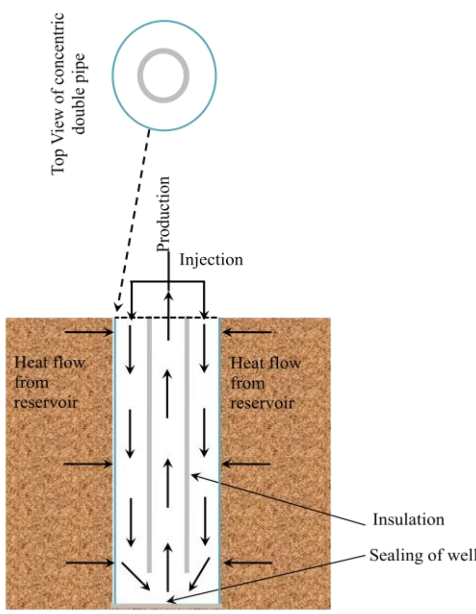


Figure 3: Schematic diagram of the modeled system

The difference between enhanced geothermal systems and conventional geothermal systems lies in the fact that the circulating fluid does not directly touch the rocks in Enhanced Geothermal Systems, like a double-pipe heat exchanger. Therefore, only heat transfer occurs without mass transfer. On the contrary, in the conventional geothermal systems, the fluid is extracted from the porous rock or soil. The fluid flow rate required to maintain high temperature is less for EGS as compared to the conventional geothermal systems due to smaller heat exchange areas between well walls and rocks. Mathematical modeling of fluid flow through a two dimensional coaxial deep Borehole Heat Exchanger configuration is used to investigate the feasibility of reusing depleted oil and gas wells as deep borehole heat exchangers (Caulk and Tomac, 2017). Darcian flow is often considered inside a geothermal reservoir. However, in few cases where the flow changes to turbulent from laminar, non-Darcian flow is adopted. (Zimmerman et al., 2004).

Finite element method is used to find the numerical solutions to the equations for fluid flow and heat transport in COMSOL Multiphysics software. As summarized by Pandey et al.(2018), the software is utilized for thermo-hydro-mechanical modeling while it is primarily used for systems which have elastic continuum and stress dependent permeability. It is desired to determine an envelope of crustal temperature gradients, well depths, and flow rates. The geothermal gradient is approximated to be linearly increasing at a value of 5^oC/100 m, which is chosen as a reference value from Caulk and Tomac (2017). An abandoned well with a depth of 2 km is chosen as the object of study. The coaxial BHE configuration dimensions have outer and inner diameters of 200 mm and 120 mm respectively.

3.2 Governing Equations

The mathematical model includes the fluid flow and energy equations. Neglecting the variation of the tube wall temperature of injection well and extraction well, heat transfer takes place between fluid and rocks and between injected fluid and extracted fluid simultaneously.

The governing equations for the model include Navier-Stokes equation for fluid flow through the BHE and conservation of energy for heat transfer. The working fluid is assumed to be incompressible. Hence, the continuity equation can be written as,

$$\nabla . \boldsymbol{u} = 0$$

where $\boldsymbol{u}$ is the velocity vector *(ms^{-1})*.

For an incompressible and Newtonian fluid, Navier-Stokes equation reduces to,

$$\rho \frac{\partial u}{\partial t} + \rho(u.\nabla u) = \nabla.[-pI + \mu(\nabla u + (\nabla u)^T)]$$

where p is the fluid pressure *(Pa)* and μ is the fluid dynamic viscosity *(Pa.s)*.

The temperature of extracted fluid is higher than that of injected fluid; hence heat transfer occurs from the geothermal reservoir to the injected fluid. The equation for conservation of energy equation for heat transfer can be expressed as,

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u.\nabla T = \nabla.(k\nabla T) + Q_c$$

Where ρ is the water density (kgm^{-3}), c_p is the water specific heat capacity($Jkg^{-1}K^{-1}$), T is the temperature(K), Q_c is a heat source (crustal heat flow) (Wm^{-2}) and k is the thermal conductivity of rock or water ($Wm^{-1}K^{-1}$).

Thermal heat extracted from the reservoir can be calculated as:

$$\dot{Q}_R = c_p \rho q(\dot{T}_{out} - \dot{T}_{in})$$

where $\dot{Q}_R$ is the rate of thermal heat extraction (W), c_p is assumed independent of temperature, which is usually the case for small temperatures in the range of $30^oC - 180^oC$ (Perry, J. H. (1950)). q is the flow rate through the BHE. $\dot{T}_{out}$ is the rate of change of production temperature with time (Ks^{-1}). The expression for power consumed by the electrical water pump can be found from (Caulk and Tomas, 2017),

$$W_p = (q\rho g h_f)/\eta$$

where, W_p is the work consumed by the electrical water pump (W), g is the acceleration due to gravity (ms^{-2}), η is the pump efficiency which is assumed as 80% and h_f is the headloss due to friction (m) as defined by the Darcy-Weisbach equation as,

$$h_f = f_D\left(\frac{L}{D}\right)\left(\frac{u^2}{2g}\right)$$

where L is the length of the heat exchanger (m), D is the hydraulic radius of the pipe (m), and f_D is the friction factor, which can be found from Moody's chart for a given relative pipe roughness, ε/D, (ε is 0.025 for steel). Reynolds number (Re) is defined as:

$$Re = \frac{\rho u D}{\mu}$$

The Coefficient of Performance (COP) is used as a metric for comparison different parameter combinations (Caulk and Tomac, 2017). It is defined as:

$$COP = \frac{Q_R}{W_p}$$

The well and geothermal reservoir domain is as shown below in Figure 4. The modeled well depth is 2000 m for a reservoir which is 3000 m deep. The domain width is chosen to be 200 m since beyond that value of domain width, the change of the steady state outlet temperature is negligible (Caulk and Tomac, 2017). The inlet mass flow rate of the coaxial heat exchanger is parameterized to 1, 4.4, 6, 8, 10 kg/s. The medium is non-porous and has no groundwater flow. Also, it is assumed that no hydraulic fracturing takes place when water is injected at high velocity and pressure. The inlet fluid, water, is pumped in at 300 K and the temperature gradient of the system is taken to be $50^{o}C/1000\ m$ (Chandrasekharam, 2005). Initial temperature at the top is 50^{o}C and it increases as one goes down into the reservoir, maximum being 150^{o}C at a depth of 2000 m. The thickness of inner pipe is taken to be 10 mm and the resistance to heat transfer across the layer is extremely high and as a result negligible amount of heat is transferred from the incoming working fluid in the annulus to the high temperature outgoing fluid.

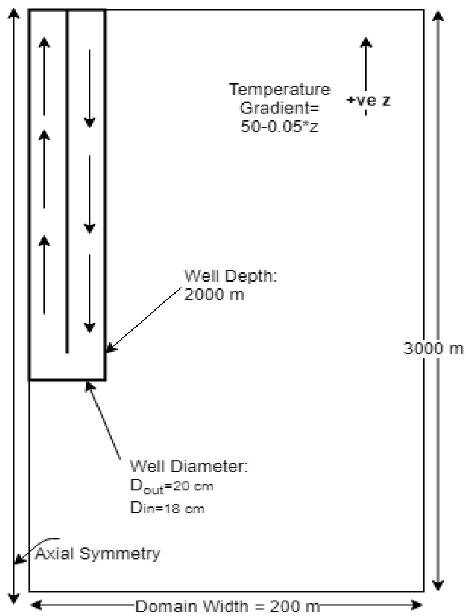
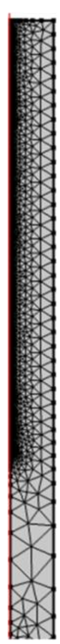


Figure 4: Computational domain

The discretization of domains in 2D is done through *mapped and free quad meshes*. The final solution is axisymmetric. Beyond 200 m domain width, the change of the steady state outlet temperature is negligible (Caulk and Tomac, 2017). The meshing done for well and reservoir geometry is shown below in Figure 5(a) and 5(b):



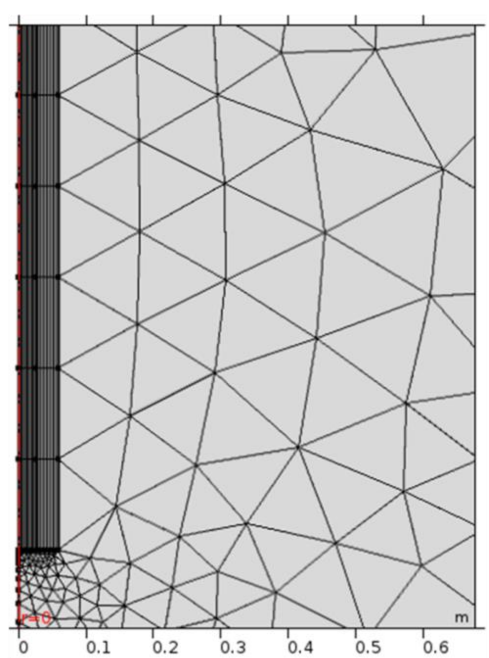


Figure 5(a): FEM discretization of complete domain *(left)*
Figure 5(b): Mapped and Free Quad Mesh (enlarged view) *(right)*

. The initial temperature gradient of the reservoir is shown in Figure 6:

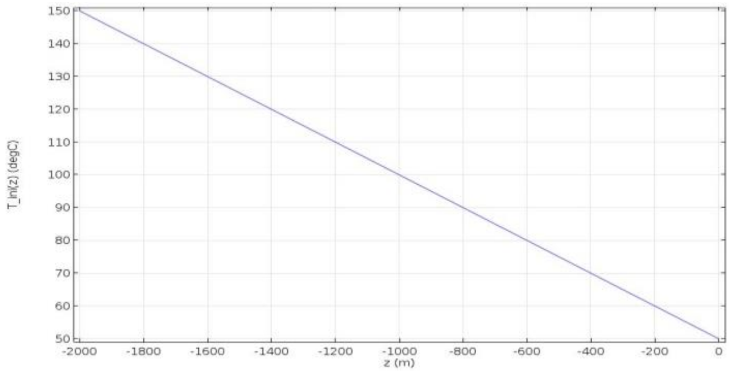


Figure 6: Temperature gradient of the geothermal reservoir (at time t = 0)

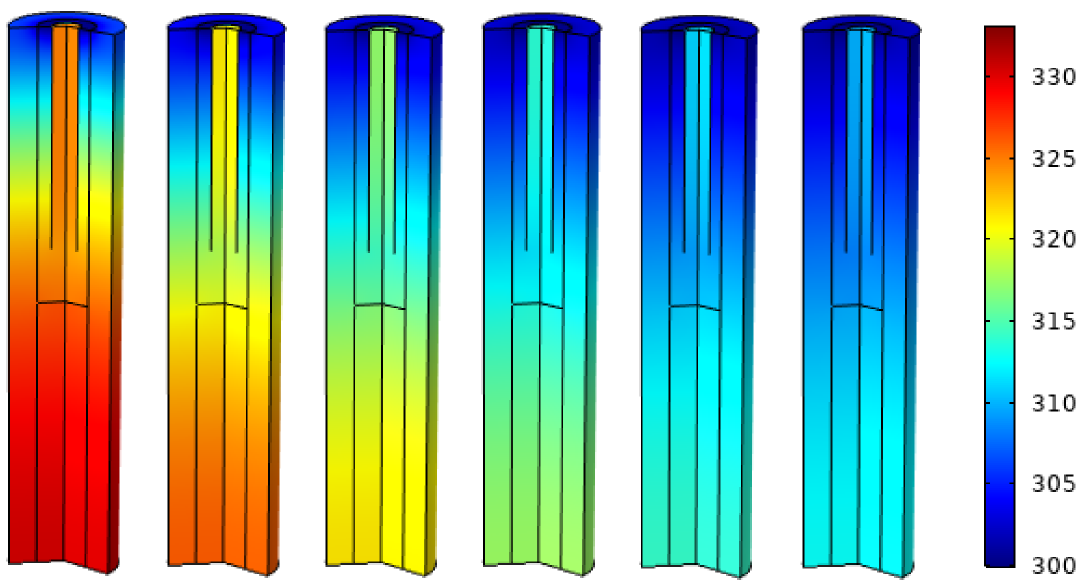
At the boundary, the fluid flow velocity is zero due to *no-slip* condition. ($\boldsymbol{u}$ = 0). A constant pressure boundary condition (*0 Pa*) is used at the outlet of coaxial heat exchanger. A constant crustal heat flux of $50\ mW/m^2$ exists at the end of the reservoir as a part of the Neumann boundary condition:

$$Q'' = 50\frac{mW}{m^2}$$

The effects of 20 parameter combinations in the study are considered to understand heat transfer process in the ground. The parameters include well depth, mass flow rate, geothermal temperature gradient, crustal heat flow, and injection temperature.

4. RESULTS & DISCUSSION

The results of mathematical model conclude that 200 mm diameter coaxial BHE yields greater than 50^{O}C production temperatures for a well depth of 2000 m and a mass flow rate of 4.4 kg/s. However, the production temperature reduces with time since the reservoir cools down as more heat is transferred to the fluid. The contours of variation of surface temperatures of the geothermal well and reservoir are as shown in Figure 7 at different instances (in years).



(a) t = 1 year (b) t = 3 years (c) t = 5 years (d) t = 7 years (e) t = 9 years (f) t = 10 years

Figure 7: Surface temperature (K)

The results of this study show that increasing mass flow rate leads to a higher heat extraction rate as compared to the lower mass flow rate. The result also depicts that heat extraction increases with the increase in well depth for all injection parameters (i.e. injection temperature and mass flow rate). At higher injection temperature, the net heat extraction rate with time from the reservoir decreases due to lower temperature difference between injected fluid and reservoir formation temperature. The variation of production temperature with time is shown in Figure 8. It can be clearly seen from the figure that the production temperature decreases with time.

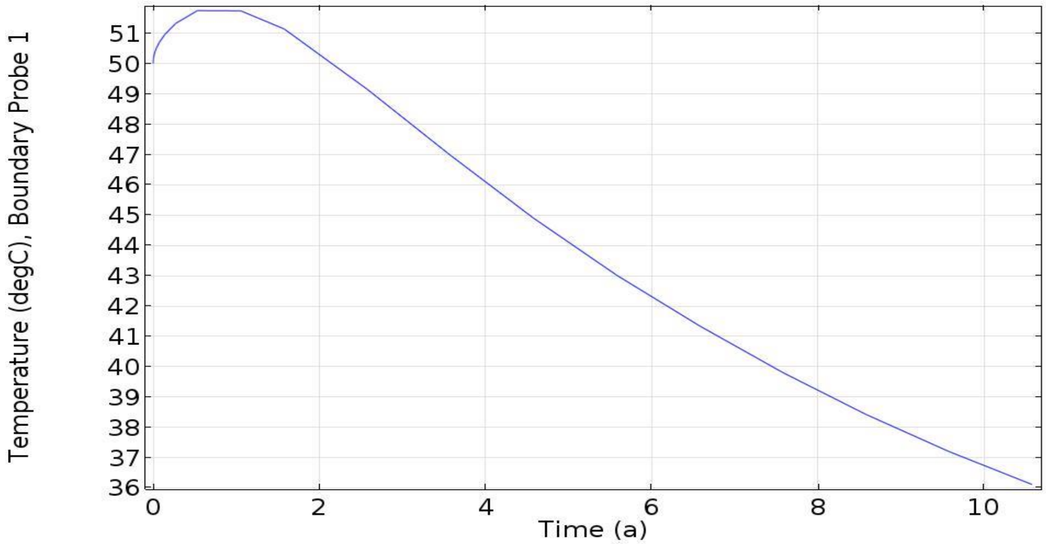


Figure 8: Temporal variation of temperature(^{o}C) at the production well (in years)

The production temperature reaches a maximum of $52^{o}C$ and gradually falls with time as more heat is extracted from the reservoir. However, it is observed that it remains greater than $40^{o}C$ for a period of 7 years. This extracted geothermal energy can be used for ground-source heat pumps, balneology, space heating, greenhouses and open ground heating etc. *(Lund and Boyd, 2016).*

The rate of heat extracted from the reservoir is computed using the temperature profile obtained in Figure 8 and the following expression, where c_p of water is 4.185 kJ/kg.K, density is 1000 kg/m^3 and the volumetric flow rate, q is known:

$$\dot{Q}_R = c_p \rho q (\dot{T}_{out} - \dot{T}_{in})$$

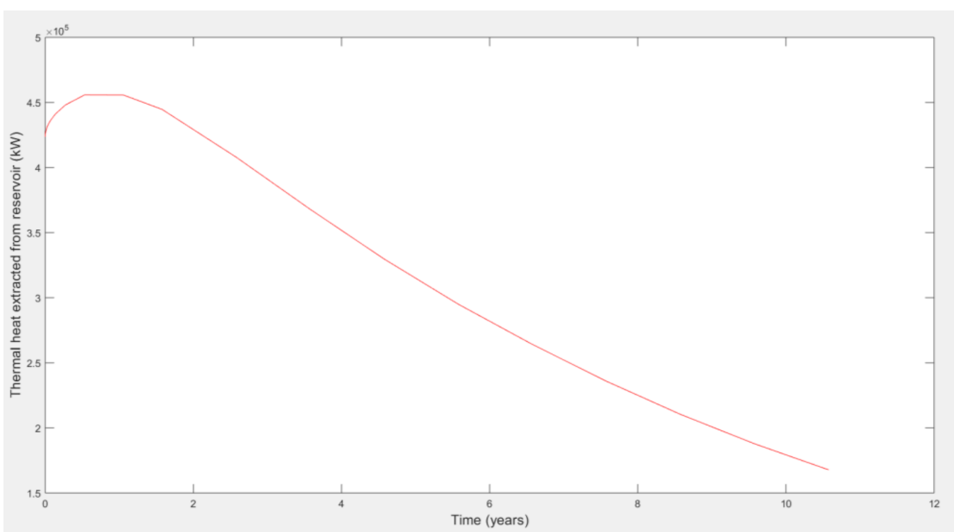


Figure 10: Temporal variation of heat extracted (kW) from the reservoir at the production well (in years)

The total amount of heat energy that is extracted can be known by computing the area under the curve in Figure 9. For the values of system parameters mentioned above, it is numerically equal to $2.91 * 10^{10}\ kWh$ for a period of 10 years. The coefficient of performance is validated from the work by Caulk and Tomac (2017), for similar parameters used in both studies.

The ongoing work focuses on understanding the relationship between various parameters and optimizing them for extraction of maximum heat. The study further aims to validate the results obtained using oil and gas well data for various locations in India that has been requested.

5. CONCLUSIONS

The economical aspect of a geothermal energy project would benefit from utilization of abandoned petroleum well. Deep coaxial BHE is a feasible low cost, low-risk alternative to EGS. For the circulation of water as working fluid in 2000 m deep well, temperatures in the range of 40 –52 °C can be expected for period of 7 years, which in turn could operate a binary cycle power plant. Higher amounts of electricity can be generated from a working fluid which can potentially gather more heat. The pumping system, at the same time, is required to operate efficiently for pumping and injecting fixed amount of working fluid under different conditions of injectivity. Potential returns from the project should be weighed against the feasibility, economical and environmental aspects of introducing an enhanced working fluid.

6. ACKNOWLEDGEMENTS

We extend our gratitude to Indian Institute of Technology Bombay, India for their support to pursue this research work. Special thanks to the Dean (Research and Development) and Dean (Alumni and Corporate Relations), IIT Bombay for their funding support to publish and present this work at the 44th Annual Stanford Geothermal Workshop at Stanford University, CA, USA.

7. REFERENCES

Augustine, C., Tester, J. W., Anderson, B., Petty, S., & Livesay, B. (2006, January). A comparison of geothermal with oil and gas well drilling costs. In *Proceedings of the 31st Workshop on Geothermal Reservoir Engineering* (pp. 5-19). ^ eNew York New York: Curran Associates Inc..

Bertani, R. (2016). Geothermal power generation in the world 2010–2014 update report. *Geothermics*, *60*, 31-43.

Bu, X. B., Tan, Y. F., Li, B. X., & Song, C. (2009). Heat and mass transfer and creep in underground oil storage with cavern. *Journal of Xi'an Jiaotong University*, 43(11), 104-108.

Caulk, R. A., & Tomac, I. (2017). Reuse of abandoned oil and gas wells for geothermal energy production. *Renewable Energy*, *112, 388-397.*

Chandrasekharam, D. (2005, April). Geothermal energy resources of India: past and the present. In *Proceedings world geothermal congress* (pp. 1-9)

Chandrasekharam D and Varun Chandrasekhar: Geothermal Energy Resources, India: Country Update *Proceedings, World Geothermal Congress 2015*

Cheng, W. L., Li, T. T., Nian, Y. L., & Wang, C. L. (2013). Studies on geothermal power generation using abandoned oil wells. *Energy*, 59, 248-254.

Cheng, W. L., Li, T. T., Nian, Y. L., & Xie, K. (2014). An analysis of insulation of abandoned oil wells reused for geothermal power generation. *Energy Procedia*, 61, 607-610.

Davis, A. P., & Michaelides, E. E. (2009). Geothermal power production from abandoned oil wells. *Energy*, 34(7), 866-872.

Dincer, I. (2000). Renewable energy and sustainable development: a crucial review. *Renewable and sustainable energy reviews*, 4(2), 157-175.

Garcia-Gutierrez, A., Espinosa-Paredes, G., & Hernandez-Ramirez, I. (2002). Study on the flow production characteristics of deep geothermal wells. *Geothermics*, 31(2), 141-167

https://www.worldenergy.org/wp-content/uploads/2017/11/World-Energy-Trilemma-2017_Full-report_WEB.pdf

https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/renewable-energy/geothermal-power.html

Kim, E. J., Roux, J. J., Rusaouen, G., & Kuznik, F. (2010). Numerical modelling of geothermal vertical heat exchangers for the short time analysis using the state model size reduction technique. *Applied Thermal Engineering*, 30(6-7), 706-714.

Kotler S. Abandoned oil and gas wells are leaking. 2011. www.zcommunications.org/abandoned-oil-and-gas-wells-are-leaking-bystevenkotler.

Lund, J. W., & Boyd, T. L. (2016). Direct utilization of geothermal energy 2015 worldwide review. *Geothermics*, 60, 66-93.

Nian, Y. L., & Cheng, W. L. (2018). Evaluation of geothermal heating from abandoned oil wells. *Energy*, 142, 592-607.

Pandey, S. N., Vishal, V., & Chaudhuri, A. (2018). Geothermal reservoir modeling in coupled thermo-hydro-mechanical-chemical approach: A review. *Earth-Science Reviews*.

Perry, J. H. (1950). Chemical engineers' handbook.

Revellin, R., & Thome, J. R. (2008). A theoretical model for the prediction of the critical heat flux in heated microchannels. *International Journal of Heat and Mass Transfer*, 51(5-6), 1216-1225.

Song, X., Shi, Y., Li, G., Yang, R., Wang, G., Zheng, R., ... & Lyu, Z. (2018). Numerical simulation of heat extraction performance in enhanced geothermal system with multilateral wells. *Applied Energy*, 218, 325-337.

Tester, J. W., Anderson, B. J., Batchelor, A. S., Blackwell, D. D., DiPippo, R., Drake, E., ... & Petty, S. (2006). The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century. *Massachusetts Institute of Technology*, 209.

Tester, J. W., Herzog, H. J., Chen, Z., Potter, R. M., & Frank, M. G. (1994). Prospects for universal geothermal energy from heat mining. *Science & Global Security*, 5(1), 99-121.

Zimmerman, R. W., Al-Yaarubi, A., Pain, C. C., & Grattoni, C. A. (2004). Non-linear regimes of fluid flow in rock fractures. *International Journal of Rock Mechanics and Mining Sciences*, 41, 163-169.

2015 Annual U.S. & Global Geothermal Power Production Report

2016 Annual U.S. & Global Geothermal Power Production Report