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Prediction of subsurface temperature in a geothermal site using a convective conductive numerical model

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ABSTRACT: The subsurface temperature at a depth of 2020m in a conceptual geothermal site was predicted by using a convective conductive heat transfer numerical model. The numerical model was verified with available analytical solutions as well as with a previously developed transient model. The sensitivity analysis showed that the optimum thermal conductivity of drilling fluid has a greater impact on the temperature along the annulus and the tube than the variation of thermal conductivity of the formation. A new method is proposed to predict the bottom hole temperature using the outlet temperature, the recovery temperature and the equivalent circulation time. The results from this study can provide a preliminary guideline to optimize various design parameters involved in hydraulic stimulation and geothermal production in an EGS reservoir.

1 INTRODUCTION

Geothermal energy provides an option for renewable energy for base load electricity in alleviating the world's energy and climate predicament (Tester et al. 2007). The most common form of geothermal energy extraction involves injecting cold water through an injection well and extracting heated water from a production well (Jatho 2010) by circulation of the formation water at target depth.

A single borehole heat exchanger system (BHE) is also used for extraction of geothermal energy. A detailed description of borehole heat exchangers is provided in the study by Falcone et al. (2018).

An enhanced geothermal system (EGS) exploration was carried out in the southern part of the Korean peninsula at Pohang in 2010 (Lu 2018). The Pohang geothermal site is geologically characterised by the Tertiary Pohang sedimentary basin overlying Eocene volcanic rock (tuff), Cretaceous sedimentary rocks (sandstone and mudstone) and volcanic (tuff and andesite) rocks, on a Permian granodioritic basement (Min et al. 2015, Ekneligoda 2012).

Drilling of the injection or the production wells involves deep drilling machinery and special techniques as the instruments may experience very high temperature both due to drilling resistance friction and the subsurface temperature. The physical properties of the drilling fluid (mud) measured during this period of drilling can be used to predict the bottom hole temperature, the geothermal gradient, and the thermal properties of the host rock. The present study explains a conductive convective coupled numerical model, developed to capture the bottom hole temperature, geothermal gradient and the thermal properties of the host rock in a conceptual geothermal site. The model geometry was defined similar to the drilling diameter of geothermal sites at Pohang and Weggis.

2 GENERAL MODEL GEOMETRY AND THE BOUNDARY CONDITIONS

The COMSOL Multi Physics Axi Symmetric model was developed to represent and model a conceptual geothermal reservoir. Thermal, hydraulic and symmetric boundary conditions were assigned to the model. The assigned boundary conditions and the model geometry are illustrated in Figure 1a and 1b. The model mesh was refined until the variation between existing analytical and numerical solution become tolerable (i.e. variation < 2%). This factor was exploited in selecting the final dimensions of the model: X = 100 m, Y = 100 m, and Z = 2350 m. At the bottom of the tube an imaginary plane was created for only the meshing purpose. As the expected temperature is very high (over 100°C) near the bottom hole, a fine mesh was used in nearby zones. After a series of trial tests, the inner tube and outer tube were discretised to 2000 elements. Gradually increasing mesh size to the outer boundary was assigned to the host rock. Selecting a smaller size of element would capture the heat transfer process in a more accurate manner.

3 MODEL VALIDATION

The present work used previous data, obtained by Holmes & Swift (1970) and Wu et al. (2011) to validate the numerical model. Finally, a comparison with field measurements was made to validate the model

3.1 *Steady state*

The data provided by Holmes and Swift (1970) are exploited to validate the conductive convective coupled numerical model at the steady state. The depth of the considered thermal well is 4000m, the ambient temperature is 15oC and the geothermal gradient of the site is 47.5 Kkm-1. The fluid temperature in both the tube and the annulus were measured from the ground surface to the bottom of the geothermal reservoir.

3.2 *Transient state*

The transient state calculation was compared to the modelling results provided by Wu et al. (2011). A similar numerical model was constructed with the mass flow rate as given in Wu et al. (2011) and properties of the new model were assigned similar values to the previous model by Wu et al. (2011). The comparison was made for the temperatures from the ground surface to the bottom of the geothermal reservoir, along the drilling tube and along the annulus. The temperature calculation was made for 40 hours. The comparison between the present values and that of the Wu et al. (2011) values w. The maximum error is less than 2% after 20hours of circulation (Fig. 2a). The maximum difference occurs above the bottom outlet where it is less than 4.5% (Fig. 2b).

4 CHARACTERISING OF THERMO MECHANICAL PROPERTIES FOR A TYPICAL GEOTHERMAL SITE AND PREDICTION OF THE BOTTOM HOLE TEMPERATURE

Mud circulation is carried out during drilling to cool the drill bit and to bring the cutting particles to the surface. A conventional type of mud was used for the purpose of modelling, assuming that the properties of mud were similar to those given by Holmes and Swift (1970). The depth of drilling was assumed to be 2250 m. It was assumed that the measured mud inlet and outlet temperatures are 55°C and 60°C, respectively, for the illustration of the procedure (some of the other measured properties are given in Table 1). The numerical model is versatile and any field measured values can be set and the values given here are only for the purpose of illustration. The radius of the drilling bit is 150 mm (12 ¼”). A convective conductive numerical model was calibrated including the above properties. The flow rate in this study was kept to 33 kgs^{-1}. The user should be aware that the parameter can be set according to the mass flow rate. At the first stage, steady state simulation was carried out to identify the outlet temperature of the tube. The geothermal gradient was calculated dividing the difference of the temperatures between bottom hole and the surface by the depth of the geothermal reservoir.

The same model was used for the transient state calculation. The temperature at the top of the annulus and the bottom of the annulus was observed during this numerical modelling. The field measured values of the outlet mud temperature were then compared with the numerically derived surface temperature. It was observed that the outlet temperature becomes steady in a very short time (< 2 days). Outlet temperature values were studied for four different geothermal gradients 42.7, 47.5, 52.5 and 57.5Kkm^{-1}, respectively. As the field measured outlet temperature was assumed to be 60°C, the normalised outlet temperature can be calculated as the ratio of the difference between the numerically measured temperature (T_{num}) and the inlet temperature (T_{in}) to the difference between the field measured temperature (T_{mea}) and the inlet temperature (T_{in}). The thermal gradient of 57.5 Kkm^{-1} gave a temperature at the outlet / surface of 62.0°C while the thermal gradient 52.5 Kkm^{-1} resulted in 59.0°C which are closer to the field measured value of 60.0°C. Selecting a different geothermal gradient away from the above mentioned range would therefore, not give any better matching to the field measured outlet temperature. Other geothermal gradients can thus be ruled out for the studied depth interval and rock properties of the model.

In order to illustrate the concept of the equivalent circulation period, 7 days of shut down period are assumed. Theoretically 7 days can be any days. The thermal recovery calculation was first made for the geothermal gradient of 52.5 Kkm^{-1} as the geothermal gradient resulted in an outlet temperature of 59°C closer to the measured value 60°C. The same geothermal gradient gives the formation temperature at the bottom of the geothermal well as 126°C. All other circulation times either result in comparatively higher or lower temperature values compared to the measured value 103°C.

In the present numerical model and most of numerical models the excavation of the well takes place instantaneously and the mud circulation is carried out to the full depth in contrast to the field mud circulation which is gradually increasing with drilling depths. Therefore, the real excavation period cannot be used as the circulation period of the mud for the modelling but is substituted by an ***equivalent circulation period***. The temperature at the bottom of the geothermal well was measured after 7 days of shut down the drilling process.

According to Table 1 the temperature at the bottom of the geothermal well after seven days of shut down was 102 °C. The measured bottom hole temperature can now be used to validate the previously derived formation temperature (based on the outlet temperature) and the equivalent circulation time.

Table 1. Assumed field measurements

Property	Value
Inlet temperature of the drilling fluid	55°C
Outlet temperature of the drilling fluid	60°C
Circulation period	40days
Shut down period	7days
Measured bottom hole temperature	102°C

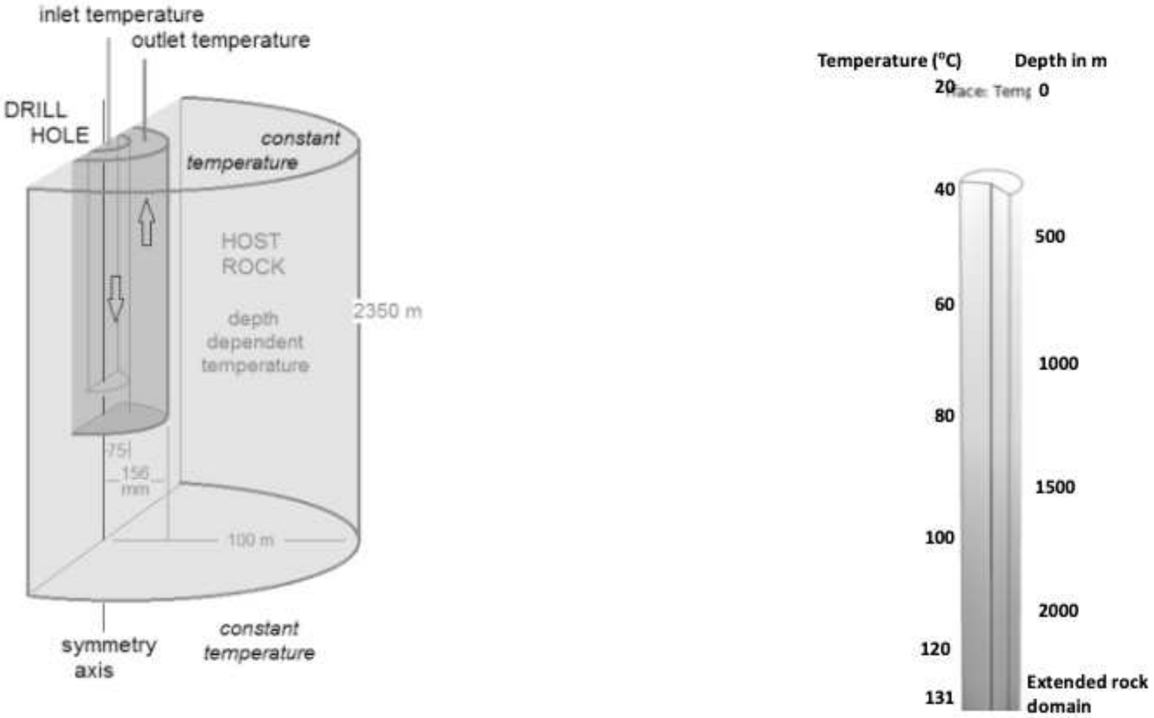

Figure 1. Details of the COMSOL model: a) Boundary condition; b) Schematic view of the temperature distribution.

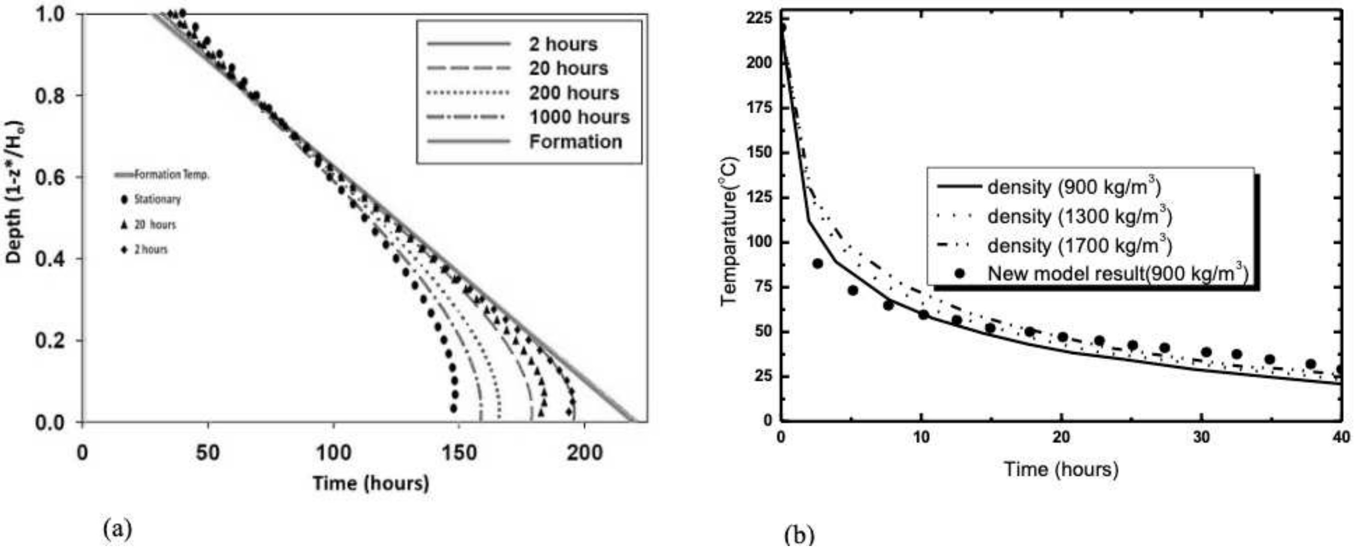

Figure 2. Comparison between the present model and that of the previous presented numerical by Wu et al. (2011) (a) for the temperature at the annulus (b) the variation of bottom hole temperature during 40 hours of circulation.

The recovery of the temperature curve of 10 days equivalent circulation time shows that the temperature at the bottom hole after 7 days of recovery is 101°C. The same geothermal gradient showed that the outlet temperature is 59°C, which fairly matches the field measurement. This will remove the other possible equivalent circulation time of 5 days. The temperature at the bottom of the well, when the geothermal gradient is 57.5 Kkm^{-1} recovers to 114°C after 10 days of equivalent circulation and after seven days of shut down. It can be explicitly shown that the different equivalent circulation time will not give reasonable agreement for the temperature at the bottom of the well. Thus, a unique solution could be obtained for the formation temperature, the equivalent the circulation time and the temperature at the bottom of the geothermal well during circulation. This will finally lead to the geothermal gradient in the field being closer to 52.5 Kkm^{-1} than 57.5Kkm^{-1}, the temperature at 2000m depth to 120°C and the ***equivalent water circulation*** period to 10 days.

Sensitivity studies and the prediction of the temperature at the depth of the geothermal well

4.1 *Thermal conductivity of the formation*

One of the advantages of the present model is that it can be used to study the uncertainty associated with different parameters. In the first part of the sensitivity analysis, the thermal conductivity of the formation was studied. The thermal conductivity of the formation was increased and decreased by 20 % of the average thermal conductivity. The temperature distribution in the annulus and the tube were compared after a long period of circulation (steady state was achieved). The depth of the model is 4500m and the flow rate was maintained at 40kgs^{-1}. Thermal gradient of 47.5Kkm^{-1} was assigned for the sensitivity analysis. The variation of the formation thermal conductivity has a marginal influence on the variation of the temperature at the annulus and in the tube. The maximum variation was even less than 2% when the formation thermal conductivity was changed by 20%.

4.2 *Thermal conductivity of drilling fluid*

A similar procedure and the same model was adopted as in the previous case to carry out the sensitivity study for the drilling fluid. To observe the effect of the thermal conductivity of the drilling fluid, the average thermal conductivity was increased and decreased by 20%. The temperature at the bottom of the geothermal well becomes 69°C when the thermal conductivity of the drilling fluid was reduced by 20% and it becomes 88°C when thermal conductivity was increased by 20%.

5 CONCLUSIONS

A convective conductive numerical model was presented to estimate the temperature at the bottom of a geothermal well for a conceptual geothermal site. A novel method is proposed to predict the geothermal gradient of the site by using the outlet temperature and the bottom hole temperature. The sensitivity analysis shows that the temperature at the bottom of the geothermal reservoir changes 13% when the thermal conductivity of the drilling fluid was changed by 20%. The geothermal gradient based on analysing the outlet temperature became 52.5 Kkm^{-1} which was verified by analysing the recovery temperature after 7 days. By comparing the temperatures at the outlet and the bottom of the geothermal reservoir, a unique equivalent circulation time can be derived, which was 10 days in this study. The numerical model based recovery temperature after 7 days of shut down was 103°C for the above mentioned geothermal gradient. The proposed method can be used to characterise the important aspects of a geothermal site.

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