

Control of Radial Heat Transfer Model on Performance Prediction of Closed Loop Geothermal Systems

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Summary

The use of CO₂ as a working fluid in geothermal systems has attracted much interest because of its special thermophysical qualities, including superior heat transfer characteristics, strong thermal expansibility, and low viscosity. To evaluate the performance of such systems, numerical simulations are usually required due to complex configurations and boundary conditions. In the modeling of reservoir-well interaction, radial heat transfer mechanisms usually control the heat extraction and subsequently overall performance of the system. One of the important parameters in the radial heat transfer models is Nusselt numbers (Nu) which abstracts the interaction between convective and conductive heat transfer processes on the walls. Through numerical simulations carried out in COMSOL and CMG STARS, this work examines the impact of the Nusselt number on heat transfer efficiency inside CPG systems. Based on the results, we provide some suggestions on feasibility of converting reservoir simulators such as STARS for geothermal applications.

Theory / Method / Workflow

Geothermal resources can be found in hot water and rock located several kilometers below the surface of the Earth, as well as in shallow rock and sediments that are saturated with groundwater. Closed-loop geothermal systems, which is not relied on a steady supply of groundwater, are one way to recover heat from low-permeability rocks hypothetically everywhere. The working fluid in these systems is circulated by a closed-loop wellbore system, which exchanges heat with the nearby bulk rock through well-reservoir contact area. This technique avoids the technical difficulty of creating a sequence of cracks as needed in Enhanced Geothermal Systems (EGS) and lowers the possibility of created seismicity. A closed-loop system, also known as Advanced Geothermal Systems (AGS), harness heat from the surrounding rock by conduction as the working fluid travels upward and below. Compared to open loop systems that have direct contact with the formation, the overall rate of heat extraction may be slower since conduction inherently slow. For geothermal purposes, closed loop wells typically come in three varieties: A) A coaxial well B) U-Loop setup, and C) Multi-string configurations. In a coaxial setup, the well consists of a pipe inside a pipe, with the inner pipe, known as tubing, returning the working fluid to the surface after being injected via the annulus [1].

In recent years, there has been a lot of interest in using CO₂ in place of water in geothermal systems since it would have the combined advantages of reducing environmental problems and removing heat from reservoirs. CO₂ can be used for both conventional high-permeable

reservoirs called CO₂ plume geothermal (CPG) and low-permeable reservoirs called CO₂-enhanced geothermal systems (CO₂-EGS). The fact that the pump needs less energy to return the fluid to the surface is one of the main advantages of CO₂ to water. While cooler fluid sinks, CO₂ naturally rises since its density drops with heat. This process where the fluid circulates solely by thermal gradients is called Thermosiphon effect [2].

This study examines the effects of changing the Nusselt number on the thermal performance of CO₂ in a variety of reservoir settings, including permeability distributions, injection rates, and temperature gradients. Greater convective heat transfer efficiency results in higher Nusselt values, which are associated with heat extraction [3,4]. The Nusselt number in geothermal reservoirs is influenced by several factors. Nu is directly impacted by the working fluid's thermophysical characteristics, including viscosity, specific heat, and thermal conductivity. For instance, supercritical CO₂ (sCO₂) has significant thermal expansion characteristics and low viscosity, which contribute to its high heat transfer efficiency [4,5]. Moreover, The Nusselt number is strongly dependent on the Reynolds number (Re), which characterizes the flow regime. In turbulent flows (Re > 4000), Nu is significantly higher due to enhanced mixing and convective heat transport [6,7]. The temperature gradient, permeability, and porosity of the geothermal reservoir influence heat transfer dynamics are reservoir conditions that impact the Nusselt number. Higher temperature gradients increase the driving force for heat exchange, thereby increasing Nu. Other factors, such as pipe diameter, length and the configuration of the heat exchanger might influence the value of the Nusselt number [8,9].

This model investigates the injection of CO₂ in a closed loop geothermal well drilled 2500 m to the reservoir where the fluid is heated and back to the surface. The numerical model is developed by coupling three-dimensional energy equations in a reservoir with one-dimensional flow and energy equations in a well using a finite element scheme in COMSOL Multiphysics. The simulation results are inter-compared with CMG STARS for one case. The Nusselt number correlations are swapped in the developed model to investigate the outlet temperature sensitivity of these correlations. The inter-comparisons are made for three different scenarios.

The model incorporates three main domains, namely Reservoir, Annulus and Tubing. Reservoir, a porous medium which indicates the geothermal reservoir where heat conduction and convection occurs. Although the working fluid has no contact with the reservoir as it moves in a closed loop system, the presence of reservoir is necessary to study how that heat is transferred between reservoir and the annulus in long term. In this model, the reservoir is divided into three porous media with different properties. The surroundings of this domain are insulated and has fixed temperature, with a constant heat flux from the bottom boundary. The coaxial closed loop well consists of an annulus and a tubing where the working fluid, i.e., CO₂ is injected through the annulus and returns to the surface via the tubing. To perform the simulation, it is assumed that there is no heat convection caused by fluid flow in the surrounding rock mass, either naturally or induced. Within the wellbore system, a heat convection mechanism predominates in the heat transfer process along the fluid flow direction.

The implemented Nusselt number correlations are usually based on Reynolds and Prandtl number defined as:

$$Re = \frac{\rho \cdot v \cdot d_h}{\mu} \quad (1)$$

$$Pr = \frac{c_p \cdot \mu}{k} \quad (2)$$

where ρ and v are the density and the velocity of the fluid. μ , c_p and k represent viscosity, specific heat capacity and thermal conductivity, respectively, while d_h is the hydraulic diameter of the either annulus or tubing. For the annulus d_h is defined as:

$$d_h = d_{out} - d_{in} \quad (3)$$

Here, d_{out} and d_{in} define the outer and inner diameter of annulus or casing.

Eq.4 and Eq.5 show the Nusselt number correlations used in CMG STARTS for the annulus and tubing when turbulent regime is dominant ($Re > 10^4$), respectively [10].

$$Nu = 0.02Re^{0.8} Pr^{1/3} \left(\frac{d_{ann,in}}{d_{tub,out}}\right)^{0.53} \quad (4)$$

$$Nu = 5 + 0.06Re^a Pr^b \quad (5)$$

Here, $d_{ann,in}$ and $d_{tub,out}$ are the inner diameter of the annulus and outer diameter of the tubing, respectively. To define **a** and **b**, the following correlations can be used:

$$a = 0.88 - \left(\frac{0.24}{4 + Pr}\right) \quad (6)$$

$$b = 0.33 + 0.5 \exp(-0.6Pr) \quad (7)$$

The Nusselt number equation for pipe walls in the literature has the following form [11,12,13]:

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{0.5} (Pr^{2/3} - 1)} \quad (8)$$

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{(1/3)} \quad (9)$$

Where f is Darcy friction factor and defined as:

$$f = (0.79 \ln(Re) - 1.64) \quad (10)$$

Where for turbulent flow (i.e., $Re > 10^4$), equation (8) and (9) are internal and external Nusselt number used by COMSOL in annulus and tubing, respectively.

As equations show, Reynold's and Nusselt number have the direct relation with each other, as though increasing the Reynold's number will raise the Nusselt number as well. Figure.1 shows the relation between Renold's and Nusselt numbers in the annulus calculated by equation (4).

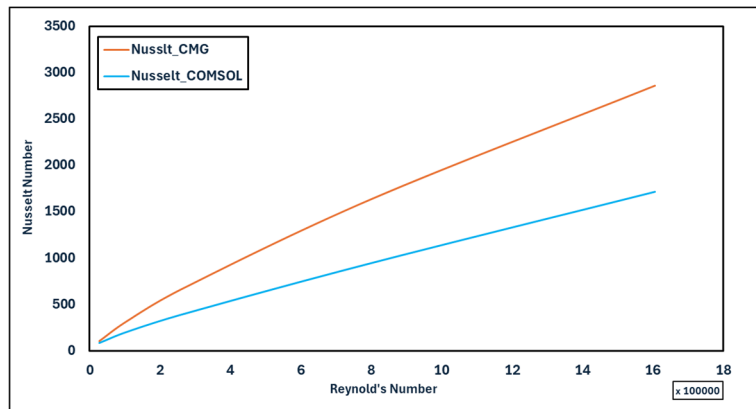


Figure.1- Nusselt-Reynold's Number relationship provided by CMG [10] and COMSOL [11,12,13]

Results, Observations, Conclusions

Fig. 2 show the 3-D configuration of the reservoir and the coaxial closed loop well. The coaxial well is drilled to 2000 m below the surface consisting of annulus where the working fluid is injected, and the tubing where the heated fluid is produced. The fluid is injected at supercritical condition, i.e., 31°C and 7300 Kpa. Table.1 demonstrate more reservoir and fluid properties used in our models. Note that the model undergoes a 30-year simulation where the figures and values shown here is the latest data set.

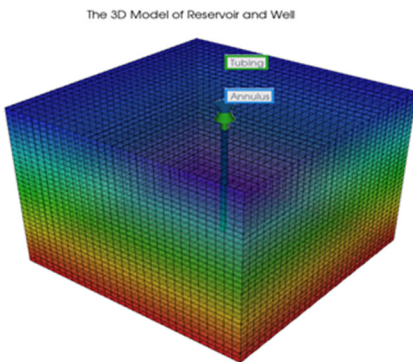


Figure 2- 3D Schematic of the Model depicted by CMG

Properties	Values
Reservoir Depth (m)	1000
Reservoir Height (m)	2500
Reservoir Width (m)	1000
Well Depth (m)	2000
d_(ann,out)(m)	0.351
d_(ann,in)(m)	0.279
d_(tub,out)(m)	0.089
d_(tub,in)(m)	0.076
Conductivity(k)(w/m.k)	0.069
T_Gradient(k/m)	0.07
T_Surface (°C)	15

Table 1- Reservoir and Fluid Properties

The first simulation case where the mass injection flow rate is 2 kg/s is used to show that simulation results from our tuned models using Nusselt numbers from equation. (4) and (5) are in a good agreement with STARS outputs.

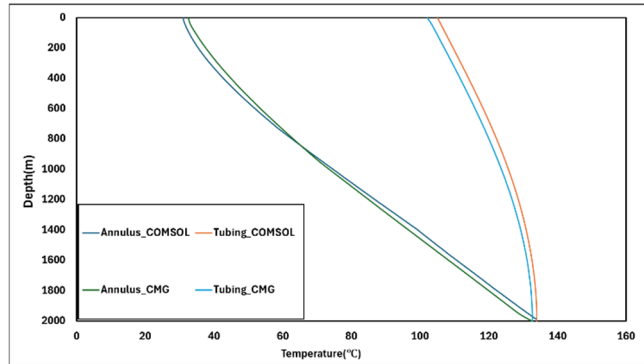


Figure 3- Annulus and Tubing Temperature Profile in CMG and COMSOL at rate 2kg/s

Figure 3 illustrates the temperature profiles along the depth of the annulus and tubing as simulated by the developed model here and CMG’s STARS, with outlet temperatures of about 105 °C and 102 °C, respectively. These values exhibit reasonable agreement, with a difference of approximately 3 °C, suggesting that both simulators effectively capture the dominant heat transfer mechanisms under the given conditions. However, a key distinction arises from the modeling capabilities: CMG may not account for internal film resistance, an additional heat transfer term we incorporate in the modeling. The omission of internal film resistance in CMG likely underestimates the convective heat transfer, leading to the observed lower outlet temperature.

Figure 4 shows the temperature profile in our developed model at 2 kg/s injection rate with and without internal film resistance.

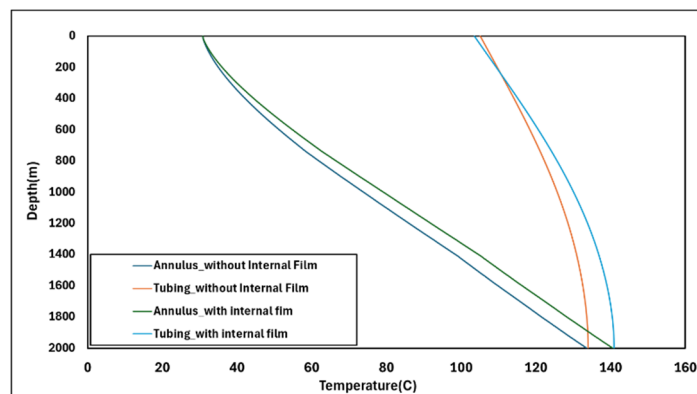


Figure 4- Annulus and Tubing Temperature Profile COMSOL with and without internal film resistance in Tubing at rate 2kg/s

Figure 4 presents the temperature profiles along the depth of the annulus and tubing, as simulated with and without the inclusion of internal film resistance in COMSOL. The profiles reveal distinct differences, particularly at the bottom of the annulus, where the temperature with

internal film resistance reaches almost 141°C, compared to about 134°C without it, resulting in a notable temperature difference of approximately 7°C. This discrepancy arises due to the internal film resistance, which accounts for convective heat transfer at the tubing wall.

This temperature difference has significant implications for energy output, as a 7°C increase at the base can translate into a considerable enhancement in the thermal energy extracted from the geothermal well. For instance, assuming a mass flow rate of 2.5 kg/s (as identified as optimal in prior simulations), the additional thermal energy could boost the system's efficiency, potentially increasing the usable heat output by several percent depending on the specific heat capacity of the working fluid.

Since the Nusselt number is directly related to the convective heat transfer coefficient, changing the correlation has significant impact on the tubing's output temperature as can be seen in Figure 5. Mass injection or velocity also has changed the Reynold's number, which in turn affects the Nusselt number. The temperature profiles for various mass flow rates, as simulated using COMSOL Multiphysics, are presented in Figure 5. After conducting a series of simulations with different flow rates and their corresponding Nusselt numbers, the optimal mass flow rate yielding the highest outlet temperature was determined to be 2.5 kg/s. At this flow rate, the system achieves an optimal balance between convective heat transfer and residence time, maximizing the outlet temperature. However, at significantly higher flow rates, such as 10 kg/s, the outlet temperature reaches almost 104 °C at the end of the simulation period but does not increase beyond this value, even with further increases in the injection rate. This behavior indicates a diminishing return in heat transfer efficiency at very high flow rates, likely due to reduced residence time of the fluid in the heat exchanger, which limits the extent of heat absorption despite the higher convective heat transfer coefficient.

The Nusselt number, which quantifies the convective heat transfer relative to conductive heat transfer across a fluid boundary, plays a critical role in determining the heat transfer performance at different flow rates. In the context of geothermal wells, where flow rates are typically moderate (e.g., on the order of 1–5 kg/s for many systems), the Nusselt number's impact is significant. In contrast, the Nusselt number's impact on heat transfer may be less critical at the higher flow rates typically encountered in oil wells. Oil wells often operate at much higher mass flow rates (e.g., 50–100 kg/s or more, depending on production rates), where the flow is deeply in the turbulent regime. In geothermal wells, where maximizing heat extraction efficiency is critical, operating at an optimal flow rate like 2.5 kg/s ensures that the Nusselt number facilitates effective heat transfer without compromising residence time.

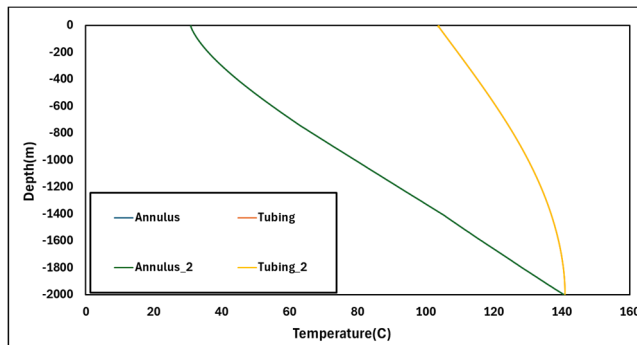


Figure.5a- Temperature Profile based on the Nusselt number formula provided by CMG STARS [10] and COMSOL [11,12,13] at 1.5 kg/s

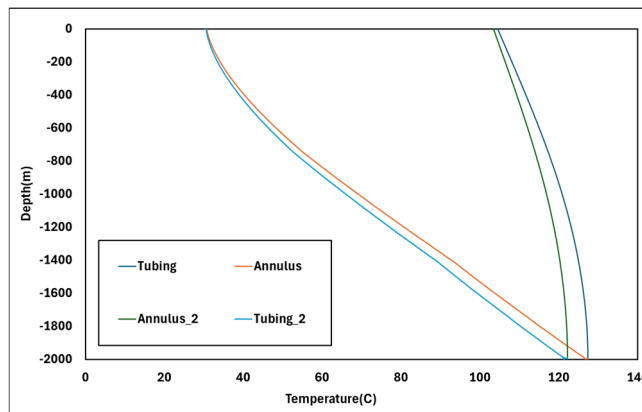


Figure.5b- Temperature Profile based on the Nusselt number formula provided by CMG STARS [10] and COMSOL [11,12,13] at 3 kg/s

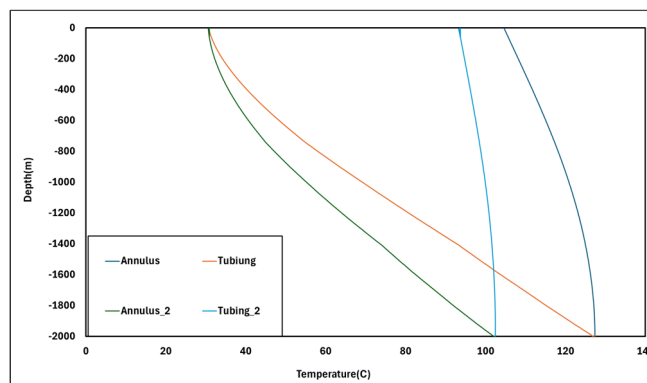


Figure.5c- Temperature Profile based on the Nusselt number formula provided by CMG STARS [10] and COMSOL [11,12,13] at 5 kg/s

As can be observed, the outlet temperature determined by the Nusselt number based on equations (4), (5) and (8) changes not much at lower flow rates (0.5 kg/s). However, there is a noticeable variation in the output temperatures, about 10 degrees, as the flow rates increase, as seen above at 5 kg/s. To obtain the most precise results, it is also essential to use an exact Nusselt value at high flow rates.

Simulations reveal that the bottom-hole temperature at the base of the annulus increases as the mass injection flow rate decreases. This trend can be attributed to the longer residence time of the working fluid in the annulus, allowing for greater heat absorption from the surrounding formation. However, at lower flow rates, the heated fluid experiences greater heat loss as it ascends through the tubing to the surface, due to the extended exposure to the cooler surroundings and reduced convective heat transfer efficiency. One potential strategy to mitigate this heat loss involves increasing the fluid velocity, which can be achieved through the implementation of downhole facilities such as a choke. Such facilities modify the fluid's phase and pressure, thereby influencing its velocity and thermal behavior. However, a detailed investigation of these effects falls beyond the scope of the present study.

Novel/Additive Information

Following a review of the evaluations provided in the Results and Conclusion sections, the following findings and conclusions are described:

- Nusselt number has a significant impact on outlet temperatures at high mass injection flow rates, although at low rates, the difference between the outlet temperature is negligible.
- Higher injection rates lead to a lower temperature at the bottom of the annulus, although the fluid with higher velocity will have lower heat loss.
- Incorporating internal film resistance significantly improves heat transfer modeling in geothermal wells, increasing the bottom-hole annulus temperature.
- This study offers the groundwork for future studies on how to improve system performance by utilizing subsurface facilities, such as choke.

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