Study of The Heat Loss Effect in Geothermal Steam Production Well

Andrian Putra Wardana, Nenny Miryani Saptadji and Dimas Taha Maulana
Geothermal Engineering Master’s Program, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia

Email: andrian15035@gmail.com
https://orcid.org/0000-0001-6589-906X

Abstract. Well casing and cement temperature can change during geothermal production operation. The change of temperature occurs because of the heat transfer from the geothermal fluid to the formation. The heat transfer occurs because of the temperature difference in geothermal fluid and formation. The heat of fluid moves to the casing, cement, and formation through convection and conduction. This research aims to develop the heat transfer model in the steam production well, predict the steam heat loss and its effect on every 100 m well increment, and predict the well casing and cement temperature distribution and their effect on every well segment. The heat transfer model is an analytical calculation model developed to be the base of the calculation of heat loss and a temperature drop of well casing and cement. This model was developed for the calculation of heat loss in steam production well. The model was compared with a simulator to test the suitability. The fluid flow pressure drop and well lithology were considered in this model. The heat loss was very low during the steam production. The heat loss could be higher, along with the formation temperature drop. The material thermal conductivity and the well segment’s layer thickness could affect the steam heat transfer in the production well.

1. Introduction
The geothermal well is a main component of the production facility in geothermal utilization. The well is a geothermal fluid flow media that were connecting between the surface and the geothermal reservoir. The characteristics of a geothermal well can change during geothermal production operation, especially the temperature of well casing and cement due to heat loss of the geothermal fluid. As fluids move through a wellbore, there is heat transfer between fluids and the earth due to the difference between fluid and geothermal temperatures [1]. The heat of fluid moves to the casing, cement, and formation by convection and conduction. Convection heat transfer occurs when the heat moves from the geothermal fluid to the production casing. Conduction heat transfer occurs when the heat moves from well casing to cement and formation. The heat transfer from geothermal fluid during production operation will cause several impacts, such as the temperature change of geothermal fluid, well casing, and well cement.

The heat transfer model was developed to facilitate heat loss and temperature changes of casing and cement. The previous heat transfer model has been developed by [2]. They developed the heat transfer model for oil production well when the brine presented in the annulus and noticed the formation lithology around the well. Based on [3], Fourier’s law and Newton’s cooling law are applied.
to calculate the conduction and convection heat transfer. Fourier’s law and Newton’s cooling law on cylindrical media are used in this model to calculate conduction and convection heat transfer. The cylindrical media represent the well geometry. [1] developed the heat transfer equation for water and gas injection well and was developed by [4] for geothermal production well. In this research, the heat transfer model was developed to calculate heat loss that is occurred in steam production well. The model results are the heat loss of every 100 m well increment and the final temperature of steam, casing, and cement during the production activity.

2. Methodology
This research was conducted by analytical calculation using the heat transfer model. The heat transfer model was developed with the pressure drop and heat transfer equations using Microsoft Excel. A literature study was done to collect information about well data analysis and heat loss in geothermal well. Well data interpretation was conducted to interpret the well data, such as well configuration, static pressure and temperature, casing and cement characteristics, steam rate, and formation lithology. These well data were used as the input parameters in the heat transfer model for steam production well that is built in this research. In a geothermal well, pressure drop calculation was conducted in this research to predict the steam pressure in flowing conditions. The homogeneous flow model was used for pressure drop calculation. The heat transfer equations were used to build the heat transfer model. Fourier’s law and Newton’s cooling law on cylindrical media were used to calculate conduction and convection heat transfer in this model. The Ramey’s heat transfer equation was also used to calculate heat loss in geothermal well by considering the flow rate time. The well static temperature is assumed as the formation temperature and the initial temperature of casing and cement. The casing and cement final temperature was determined using this model based on the temperature difference between the steam temperature and the formation temperature. The WellSim software, which is commercial software for pressure drop calculation, was conducted for this model validation. The result of the model was compared with the result of WellSim software (free trial version). The steam pressure and temperature were used for comparison. If the steam pressure and temperature from this model were matched or quite match with the steam pressure and temperature from WellSim calculation, this model was suitable for predicting heat loss in a geothermal well. The heat loss calculation was done for every 100 m well increment. The final temperature of steam, casing, and cement during the steam production was done to determine the final temperature distribution in steam, casing, and cement. The schematic flow diagram of this research is shown in (Figure 1).

There are several limitations to this research. The heat transfer model is developed for steam in wells during the production operation. The heat transfer model uses Fourier’s Law for the conduction heat transfer calculation and Newton’s Cooling Law for the convection heat transfer calculation in cylindrical media. The heat transfer model uses the [1] and [4] equations to calculate the steam heat loss. The pressure drop calculation is using the homogeneous flow model.

Several assumptions are used in this research. The well static temperature is assumed as the initial temperature of casing, cement, and formation. The formation temperature is assumed to be unchanged because the heat transfer condition is a temperature difference. In this research, the temperature difference is between the steam and the formation. The heat transfer in the liner is neglected because the production zone is in the liner and the reservoir simulation is needed to determine the heat transfer in the liner.
2.1. Pressure Drop

The pressure drop of steam was considered in this research. The pressure drop would occur in steam when it was produced to surface through the production well. In this research, the homogeneous flow model was used to predict the steam pressure drop. The homogeneous flow model equation is set in Equation (1).

\[
\left( \frac{dp}{dz} \right) = \rho_m g \sin \theta + \frac{\lambda V_m^2}{2 \nu_m D}
\]  

(1)

Where \(dp/dz\) is pressure drop with depth (in Pa/m), \(\rho_m\) is mixture fluid density (in kg/m\(^3\)), \(g\) is gravity acceleration (in m/s\(^2\)), \(\theta\) is well inclination angle (in degree), \(\lambda\) is friction factor, \(V_m\) is the fluid velocity (in m/s), \(\nu_m\) is mixture fluid specific volume (in m\(^3\)/kg), and \(D\) is the inner diameter of production casing (in meter).

2.2. Heat Transfer

The heat loss of geothermal fluid would occur when it is produced through the production well. [1] developed the heat transfer equation for cold water injection, air injection, and hot natural gas injection. The Ramey’s heat transfer equation was developed by [4] for geothermal production well. The heat transfer equation is set in Equation (2).

\[
q = \frac{dT}{dz} \dot{m} C_f \left[ z + A \left( e^{-\frac{z}{A}} - 1 \right) \right]
\]  

(2)
With

\[ A = \frac{m \dot{C} f(t)}{2\pi k_e} \]  \hspace{1cm} (3)

\[ f(t) = -\ln \left( \frac{r_2}{2\sqrt{at}} \right) - 0.29 \]  \hspace{1cm} (4)

\[ \alpha = \frac{k_e}{\rho_e C_e} \]  \hspace{1cm} (5)

Where \( q \) is fluid heat loss (in Watt), \( \frac{dT}{dz} \) is temperature gradient (in \( ^\circ C/m \)), \( \dot{m} \) is the fluid mass rate (in kg/s), \( C_f \) is fluid specific heat (in J/kg.\( ^\circ C \)), \( z \) is the length of each well increment (in meter), \( f(t) \) is dimensionless time function, \( k_e \) is the thermal conductivity of formation (in W/m.K), \( r_2 \) is the radius from fluid to outside production casing (in meter), \( t \) is fluid flow rate time (in second), \( \rho_e \) is the density of formation (in kg/m\(^3\)), and \( C_e \) is the specific heat capacity of the formation (in J/kg.\( ^\circ C \)).

Ramey’s heat transfer equation considered the flow rate time shown by Equation (4) because the heat loss can be different based on the flow rate time.

The heat transfer is energy in transit due to a temperature difference [5]. The heat transfer occurs because of a temperature difference driving force, and heat flows from the high to the low-temperature region [6]. The heat transfer is occurred by convection and conduction. Convection heat transfer will occur between a surface and a moving or stationary fluid at different temperatures. Convection heat transfer occurs when the heat moves from geothermal fluid to the production casing. The amount of convection heat transfer can be determined using Newton’s cooling law [3]. Newton’s cooling law on cylindrical media equation is set in Equation (6).

\[ q_{\text{conv}} = h \times 2 \times \pi \times r \times L \left( T_\infty - T_s \right) \]  \hspace{1cm} (6)

Where \( q_{\text{conv}} \) is convection heat transfer (in Watt), \( h \) is convection heat transfer coefficient (in W/m\(^2\).K), \( r \) is the radius from fluid to inside production casing (in meter), \( L \) is the length of well segment (in meter), \( T_\infty \) is the fluid temperature (in \( ^\circ C \)), and \( T_s \) is inside production casing surface temperature (in \( ^\circ C \)).

Conduction heat transfer refers to a heat transfer that occurs across the medium when a temperature gradient exists in a stationary medium, which may be a solid of a fluid. In geothermal wells, conduction heat transfer occurs when the heat moves from well casing to cement and formation. The amount of conduction heat transfer can be determined using Fourier’s law [3]. The equation of Fourier’s law on cylindrical media is set in Equation (7).

\[ q_{\text{cond}} = \frac{2 \times \pi \times k \times L (T_{s,i} - T_{s,o})}{\ln \left( \frac{r_o}{r_i} \right)} \]  \hspace{1cm} (7)

\( q_{\text{cond}} \) is conduction heat transfer (in Watt), \( k \) is the thermal conductivity of the material (in W/m.K), \( L \) is the length of well segment (in meter), \( T_{s,i} \) is the inside surface temperature (in \( ^\circ C \)), \( T_{s,o} \) is the outside surface temperature (in \( ^\circ C \)), \( r_o \) is the radius from the center of the wellbore to outside layer (in meter), and \( r_i \) is the radius from the center of the wellbore to inside layer (in meter).

The cylindrical media represent the well geometry. The cylindrical media geometry is shown in (Figure 2). Ohm’s law analogy for the electrical circuit can be used to simplify the heat transfer calculation. The heat transfer in a geothermal well will form the temperature distribution with a different thermal resistance of every layer. The temperature distribution and thermal resistance of cylindrical media in Figure 2 are shown in Figure 3.
Based on Figure 3, the overall heat transfer equation is set in Equation (8).

\[
q = \frac{T_{\infty} - T_s}{\left(\frac{1}{h_2\pi r_1 L} + \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_{A1} L} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi k_{B1} L} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{2\pi k_{C1} L} + \frac{\ln\left(\frac{r_5}{r_4}\right)}{2\pi k_{D1} L}\right)}
\]  

(B)

The result of fluid heat loss from Equation (2) is substituted to Equation (8) to calculate fluid, casing, and cement temperature.

3. Case Study
Well A-01 is a steam production well with a total depth of 1608 m and a vertical well type. Well A-01 was divided into three segments for heat transfer calculation. These segments were divided based on the presence of conductor casing, surface casing, and production casing. The slotted liner was assumed to have no heat transfer, and the feed zones were along there. The configuration and segmentation of Well A-01 are shown in (Figure 4). Well A-01 used three casings, there are conductor casing, surface casing, and production casing. The cement is between the casings and between casing and formation. The casings, cement, and formation configuration of Well A-01 are shown in (Figure 5).
The composite log could identify the formation lithology and alteration in Well A-01. The epidote mineral presence could be identified by the composite log and indicate the top of the reservoir. The composite log of Well A-01 (Figure 6). The epidote begins to present at 348 m depth, but the presence of this epidote is not continuous, then it could not be indicated as the top of the reservoir. The continuous epidote begins to present at 707 m depth, and then it could be indicated as the top of the reservoir in Well A-01. Based on the composite log of Well A-01, there was an indication of two types of formation rocks. There were andesite and breccia-tuff. The andesite was at a depth of 0-300 m and 459-1608 m. The breccia-tuff was at a depth of 300-459 m. Based on the composite log of Well A-01, there was an indication of two alterations. There were argillic and propylitic.

The static pressure, static temperature, and Boiling Per Depth (BPD) graph of Well A-01 (Figure 7). The indication of the reservoir zone can be determined using the static temperature graph. The
reservoir zone can be indicated based on the convective zone of the static temperature graph. Based on the static temperature, the reservoir zone’s indication was shown by the presence of the convective zone at 707-1608 m depth.

The static pressure and temperature graph can also determine the type of reservoir fluid. The fluid contained in the subsurface can be determined from the pressure and temperature measured in the well [7]. If the static temperature curve is on the right side of the BPD curve, the type of reservoir fluid is superheated steam. If the static temperature curve is on the left side of the BPD curve, the type of reservoir fluid is compressed liquid. Based on Figure 7, the static temperature curve is on the right side of the BPD curve. This condition indicates that the reservoir fluid was superheated steam. The maximum temperature based on static temperature was 224°C, and it was assumed as the reservoir temperature.

Well A-01 has certain specifications of the components that exist in there. The specifications of well A-01 consist of the inner and outer diameter of casing and formation, the casing roughness, the steam mass rate, the well inclination angle, and thermal conductivity of casing, cement, and formation. The thermal conductivity and casing roughness depend on the type of casing material. The specification of Well A-01 is shown in Table 1.
### Table 1. Well A-01 specifications.

| Specifications                  | Value  | Unit |
|---------------------------------|--------|------|
| Slotted liner ID                | 9½     | in   |
| Slotted liner OD                | 10¾    | in   |
| Production casing ID            | 12⅜    | in   |
| Production casing OD            | 13¾    | in   |
| Surface casing ID               | 18¾    | in   |
| Surface casing OD               | 20     | in   |
| Conductor casing ID             | 29½    | in   |
| Conductor casing OD             | 30     | in   |
| Conductor casing cement OD      | 0.914  | m    |
| Formation OD                    | 2      | m    |
| Casing thermal conductivity     | 75     | W/m.K|
| Cement thermal conductivity     | 0.5    | W/m.K|
| Andesite thermal conductivity   | 2.5    | W/m.K|
| Andesite density               | 2565   | kg/m³|
| Andesite specific heat          | 920    | J/kg.°C|
| Breccia-tuff thermal conductivity | 2  | W/m.K|
| Breccia-tuff density            | 2202   | kg/m³|
| Breccia-tuff specific heat      | 800    | J/kg.°C|
| Casing density                  | 7850   | kg/m³|
| Casing specific heat            | 460.24 | J/kg.°C|
| Cement density                  | 1920   | kg/m³|
| Cement specific heat            | 750    | J/kg.°C|
| Casing roughness                | 4.57×10⁻⁵ | m |
| Steam mass rate                 | 0.1    | kg/s |
| Well inclination angle          | 90     | degree |
| Enthalpy                        | 2800   | kJ/kg |

#### 4. Result and Discussion

The heat transfer model was developed using Ramey’s well heat transfer equation, Newton’s cooling law for convection heat transfer, and Fourier’s law for conduction heat transfer. The model also considered the pressure drop that will occur in the steam produced through the production well. The pressure drop was calculated using the homogeneous flow model. The pressure and temperature profile of Well A-01 using this model were compared with the calculation using WellSim shown in (Figure 8). The calculation was done for 0-784 m depth or throughout the production casing. The liner’s heat loss was neglected due to the steam entering the well along with the liner. As the model was quite matched with the WellSim, this model could calculate the heat loss of steam and steam, casing, and cement temperature.
9

Figure 8. Comparison of the result of the model and WellSim calculation.

The heat loss of every 100 m well increments from the bottom of Well A-01 during the steam production is shown in (Figure 9). The heat loss was less than 2 W/m. The heat loss increased along with the increase of well increment. The formation temperature drop also increased along with the increase of well increment. The formation temperature drop could affect steam heat loss. The heat loss of steam could be higher along with the increase of formation temperature drop.

Figure 9. Heat loss of every 100 m well increments from the bottom of Well A-01.

The final temperature of steam, casing, and cement was calculated using this model. The static temperature of Well A-01 is assumed as the initial temperature of casing and cement. Table 2 is shown the steam pressure and the final temperature of steam, casing, and cement for every well segment. The temperature drop of steam was very low during the steam production. It is possible that the heat loss of
steam was very low. Based on Figure 10, the heat loss was less than 2 W/m. Because heat loss was very low, the heat of the steam will not be transferred entirely to the formation. Based on the result, the steam heat was estimated to only transfer to the surface casing because the final temperature of surface cement, conductor casing, and conductor cement were very close to the initial and the formation temperature. The material thermal conductivity and the layer thickness of the well segment could affect the steam heat transfer. The production casing had high thermal conductivity, and the final temperature was very close to the steam temperature. The surface casing had high thermal conductivity, but the final temperature was not close to the steam temperature because the heat transfers through the production cement with low thermal conductivity, and steam heat would be reduced. The temperature increase of the production casing and the surface casing is higher than the temperature increase of its cement because the casing’s thermal conductivity is higher than the thermal conductivity of cement. The casing and cement could have a lower increasing temperature along with the lower material thermal conductivity and the thicker well segment layers. The casing and cement final temperature distribution of every well segment is shown in (Figure 10, 11, and 12).

**Table 2. Steam, casing, cement, and formation final temperature of Well A-01.**

| Depth (m) | Segment | Pressure (bar) | Temperature (°C) |
|-----------|---------|----------------|------------------|
| 0-30.5    | I       | 23.22          | 222.84 Prod. Casing | 221.36 Prod. Cement | 136.73 Prod. Surface Casing | 136.63 Prod. Surface Cement | 39.54 Prod. Conductor Casing | 39.43 Prod. Conductor Cement | 37.95 Prod. Formation |
| 30.5-459  | II      | 23.27          | 222.84 Prod. Casing | 221.36 Prod. Cement | 136.79 Prod. Surface Casing | 136.69 Prod. Surface Cement | - Prod. Conductor Casing | - Prod. Conductor Cement | - Prod. Formation |
| 459-784   | III     | 24.02          | 223.13 Prod. Casing | 221.43 Prod. Cement | 137.58 Prod. Surface Casing | - Prod. Surface Cement | - Prod. Conductor Casing | - Prod. Conductor Cement | 134.38 Prod. Formation |

**Figure 10.** Temperature distribution at segment I.

**Figure 11.** Temperature distribution at segment II.
Figure 12. Temperature distribution at segment III.

5. Conclusion
Based on this research, heat loss in geothermal steam production well could be determined using the heat transfer model. The temperature of steam, casing, and cement could be determined in this research. This research concludes several points:
1. The heat transfer model result matched with the WellSim result, and then this model could be used to calculate the heat loss of steam and the temperature of steam, casing, and cement.
2. The heat loss was very low during the steam production, then the heat of steam will not be completely transferred into the formation.
3. The heat loss of steam could be higher, along with the increasing formation temperature drop.
4. The material thermal conductivity and the well segment’s layer thickness could affect the steam heat transfer in the production well.

6. Recommendation
This research was carried out by developing the heat transfer model by considering the steam pressure in the well. This research needs to be validated with laboratory-scale experiments or field measurements. This heat transfer model can be developed with other pressure drop correlations. This heat transfer model can be developed for water dominated production well and two-phase fluid production well. Applying the model in the casing and cement design before the drilling activity is conducted may reduce the risk of drilling activity.

Acknowledgment
The authors would like to thank the people in the Geothermal Engineering Master Program of ITB who helped the authors, especially to IIGW 2020 committee that organized a spectacular event.

References
[1] Ramey H J 1962 Wellbore Heat Transmission Journal of Petroleum Technology 14 427–35
[2] Sui D, Horpestad T and Wiktorski E 2018 Comprehensive modeling for temperature distributions of production and geothermal wells Journal of Petroleum Science and Engineering 167 426–46
[3] Incropera F P, Bergman T L, Lavine A S and Dewitt D P 2011 Introduction to Heat Transfer (New Jersey, United States: John Wiley & Sons, Inc.)
[4] Horne R N and Shinozaka K 1979 Wellbore Heat Loss in Production and Injection Wells Journal of Petroleum Technology 116(8)
[5] Moran M J, Shapiro H N, Munson B R, Dewitt D P, Wiley J, Hepburn K, Grossman H and Fleming L 2011 *Introduction to Thermal Systems Engineering and Heat Transfer* vol 169

[6] Geankoplis C J 2003 *Transport Processes and Separation Process Principles (Includes Unit Operations)* (New Jersey, United States: Pearson Education, Inc.)

[7] Saptadji N M 2018 *Teknik Geotermal* (Bandung, Indonesia: ITB Press)