Development of downhole cooling charts to prevent drilling problems in geothermal wells through wellbore temperature simulation

Sara Ishikawa and Shigemi Naganawa

School of International Resource Sciences, Akita University, Japan

m6021201@s.akita-u.ac.jp, naganawa@mine.akita-u.ac.jp

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ABSTRACT

In high temperature geothermal well drilling in Japan, it is sometimes reported that MWD tools get damaged because of its insufficient heat resistant temperatures of approximately 175°C to 200°C. To avoid such troubles of downhole tool failure, it is important to properly cool the inside of the wellbore by drilling fluid circulation. The effect of downhole cooling was analyzed and evaluated by downhole temperature simulation, and it was found that the well diameter and pump rate have a significant effect on the downhole temperature. The objective of this study was to create a chart for different well diameters that would allow us to determine the drilling pump rate required to reduce the downhole temperature to 175°C.

The wells used in the simulations were set up based on drilling data from NEDO (the New Energy and Industrial Technology Development Organization) Geothermal Development Promotion reports. Numerical simulations were carried out using the modified wellbore temperature simulation program GEOTEMP2 originally developed at Sandia National Laboratories.

A simple correlation chart between well conditions and pump rates was computed for mud and water as drilling fluids. The correlation chart has the vertical axis as the target depth and the horizontal axis as the geothermal temperature gradient. The ranges of the vertical and horizontal axes were determined from well data drilled in past NEDO geothermal development promotion studies, and the geothermal formation temperature was assumed to vary linearly with depth as assigned by the temperature gradient.

As a result of the simulations, it was found that drilling fluid with mud provided better cooling than only using water for all well diameters. In addition, it was confirmed that the required pump rate increases as the diameter of the well decreases.

1. INTRODUCTION

In past geothermal well drilling operations, we have sometimes encountered drilling troubles where the downhole tools were damaged because of excessive increases in downhole temperatures. The increases in downhole temperatures were estimated to be caused by insufficient downhole cooling during tripping, fixing the surface equipment and cease of drilling operation. Among these troubles, we focused on the case that the battery in MWD (measurement while drilling) tools was damaged during drilling an 8-1/2" hole section. In that case it was estimated that the downhole temperature exceeded the temperature limit of the MWD tool after a long stoppage of drilling fluid circulation because of issues related to surface equipment during tripping of the drill string for bit replacement. So far, we are dealing with such troubles by predicting the increase in the bottomhole temperature from offset well temperature data.

To prevent such problems caused by increases in downhole temperature, the objective of this study is to present operational guidelines for drilling high temperature formations that exceed the temperature limit of MWD tools. We aim to provide guidelines based on the analysis and evaluation of wellbore temperature simulations.

The effect of downhole cooling was analyzed and evaluated by downhole temperature simulation, and it was found that the well diameter and pump rate have a significant effect on the determination of the downhole temperature (Ishikawa et al., 2021). In the case of rotary drilling of very high-temperature geothermal wells, which are different from the well geometry and type of the wells in this study, the influence of the wellbore diameter and flow rate on the downhole temperature has been found to be significant in previous studies (Saito, 1995). The objective of this study was to create a chart for each well diameter that would allow us to determine the drilling pump rate required to reduce the downhole temperature to 175°C.

2. WELLBORE THERMAL SIMULATOR

In this study, we used the GEOTEMP2 wellbore temperature simulator that was developed at Sandia National Laboratories (Mondy and Duda, 1984). In performing simulation, we modified to insert the liner casing because originally GEOTEMP2 deals only full hole casing. Full hole casing is usually run into the hole from the surface to the shoe depth, while a liner casing refers to a casing that is partially installed by hanging from the end of an upper casing string.

3. SIMULATION STUDY

3.1 Determination of geothermal gradient

Based on data from past geothermal well drillings in Japan, five geothermal gradients were selected for simulation in relatively shallow core drilled and normal rotary drilled wells as shown in Table 1. The surface temperature was chosen as 15°C. The depth for rotary drilling was up to 2000 m, and the depth for drilling by coring was up to 1500 m. The relation between the selected geothermal gradient and the well depth for each simulation case is illustrated in Figure 1.

Table 1: Test cases for different geothermal gradients and drilling methods.

Simulation case	1	2	3	4	5
Geothermal gradient (℃/m)	0.37	0.29	0.19	0.14	0.093
Vertical depth for core drilling (m)	750	1000	1500	1500	1500
Vertical depth for rotary drilling (m)	750	1000	1500	2000	2000

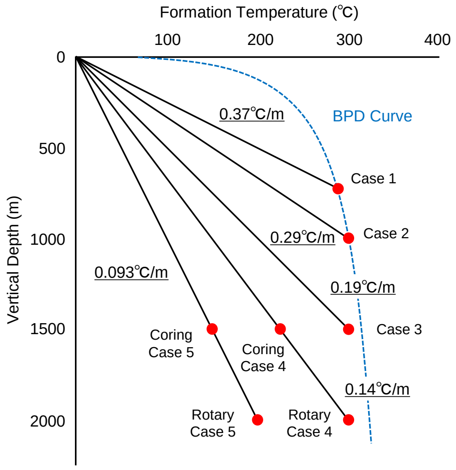

Figure 1: Simulated well cases for different geothermal gradients and vertical depths. The blue dashed curve indicates the boiling point for depth (BPD) curve.

3.2 Determination of drilling conditions

The well profiles used in the simulations were set up based on the drilling data from NEDO (the New Energy and Industrial Technology Development Organization in Japan) Geothermal Development Promotion reports.

The simulations considered four final well diameters: NQ-WL, HQ-WL, 6-1/4 in., and 8-1/2 in. The casing diameters for coring were the same as for the two wells drilled in the "Minase" area of Akita Prefecture, Japan: well MS-3, with a well diameter of NQ-WL, and well MS-6, with a well diameter of HQ-WL. The casing program was the same for MS-3 in both well diameters (NEDO, 1990). For normal rotary drilling, the wellbore geometry of well SY-1 drilled in the “Shimoyu” area, Aomori Prefecture, was adopted. The wells were all vertical with no inclination (NEDO, 2009). The profiles for the different types of simulated wells are shown in Tables 2 and 3, and Figures 2 and 3. Two types of drilling fluids were simulated: water and mud. The properties of the drilling fluids are shown in Table 4.

Table 2: Casing/openhole diameters for core drilled wells.

	NQ-WL	HQ-WL
Conductor pipe	10 in.	14 in.
Surface casing	6-5/8 in.	9-5/8 in.
Intermediate casing 1	4 in.	7 in.
Intermediate casing 2	92 mm	4-1/2 in.
Openhole	75.31 mm	97.50 mm

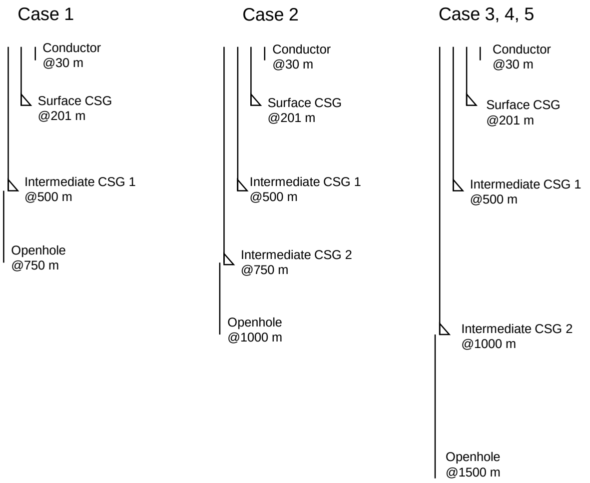

Figure 2: Casing program for core drilled wells.

Table 3: Casing/openhole diameters for rotary drilled wells.

	6-1/4 in. well	8-1/2 in. well
Conductor pipe	14 in.	20 in.
Surface casing	9-5/8 in.	13-3/8 in.
Intermediate casing	7 in.	9-5/8 in.
Openhole	6-1/4 in.	8-1/2in.

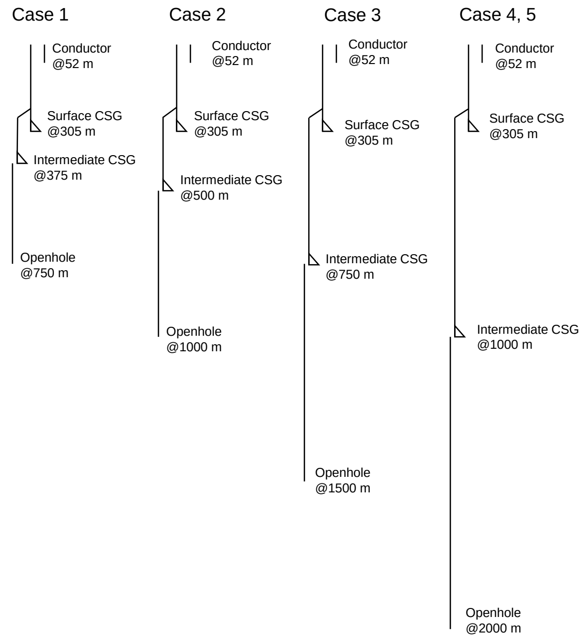

Figure 3: Casing program for rotary drilled wells.

Table 4: Physical properties of fluids.

	Density (lbm/gal)	PV (Plastic viscosity) (cP)	YP (Yield point) (lbf/100ft^2)
Water	8.33	0.94	0
Mud	9.16	21.2	3.13
Cement	15	30	50

3.3 Chart development method

For each combination of geothermal gradient and well profile case, wellbore temperature during drilling to the target total depth was simulated. Then, the maximum well depths at which the bottomhole temperature during circulation became less than 175°C were plotted on a geothermal gradient vs. measured depth graph. The simulation is continued by changing the flow rate until the downhole temperature at the target depth is less than 175°C.

4 RESEARCH RESULTS AND DISCUSSION

4.1 Simulation results of NQ-WL coring well

First, simulation was performed for a NQ-WL cored well when the drilling fluid was water. The results are shown in Figure 4.

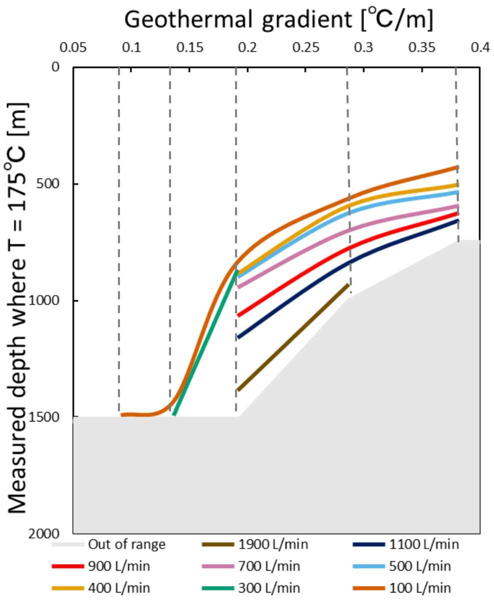

Figure 4: Calculation chart for an NQ-WL cored well drilled with water.

The vertical axis is the well depth, and the horizontal axis is the geothermal gradient. The drilling depth range of the target well is the white area. The colored lines indicate the minimum required flow rate from 100 to 1900 L/min. The five dotted lines represent the temperature gradients used for the simulations. Figure 4 shows that in a formation with a temperature gradient of 0.1°C/m, it is possible to drill down to 1500 m at a flow rate of 100 L/min. On the other hand, as the temperature gradient approaches 0.4°C/m, the depth range that can be drilled decreases even if the flow rate is increased to 1900 L/min.

Next, simulation was performed for a NQ-WL cored well when mud was used as the drilling fluid. The results are shown in Figure 5.

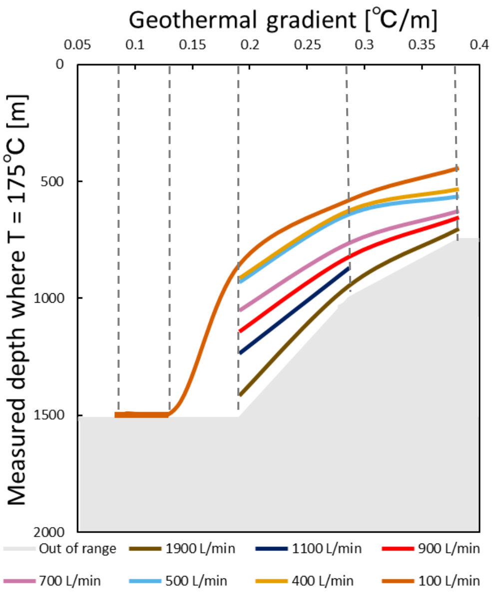

Figure 5: Calculation chart for an NQ-WL cored well drilled with mud.

Figure 5 shows that when the ground temperature gradient is around 0.4°C/m, the well can be drilled down to 750 m when the flow rate is increased to 1900 L/min. Therefore, it was found that the wellbore can be cooled more effectively with mud than when water is used for circulation.

4.2 Simulation results of HQ-WL coring well

Similarly, simulation was performed for a HQ-WL cored well when the drilling fluid was water. The results are shown in Figure 6.

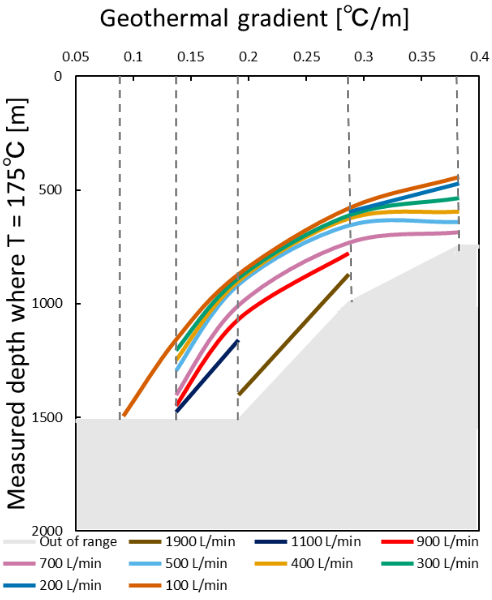

Figure 6: Calculation chart for an HQ-WL cored well drilled with water.

Figure 6 shows that in a formation with a geothermal gradient of 0.1°C/m, it is possible to drill to 1500 m at a flow rate of 100 L/min. At the second calculation point, 1100 L/min is required. For the 0.37°C/m geothermal gradient, increasing the flow rate above 700 L/min resulted in little cooling improvement.

Next, simulation was performed for a HQ-WL cored well when mud was used as the drilling fluid. The results are shown in Figure 7.

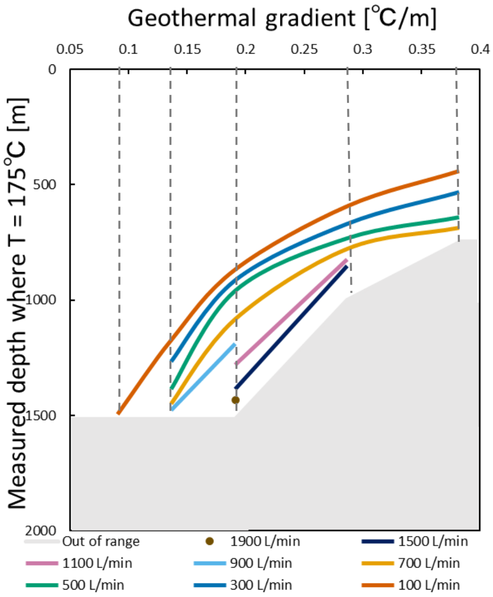

Figure 7: Calculation chart for an HQ-WL cored well drilled with mud.

Figure 7 shows that there was no difference from Figure 6 in the required flow rate when a geothermal gradient was around 0.4°C/m. However, at the second calculation point, Figure 7 shows that a flow rate of 900 L/min is sufficient, whereas using water requires 1100 L/min (Figure 6). Thus, it was found again that the wellbore was cooled more effectively with mud than when circulating with water.

4.3 Simulation results of 6-1/4 in. normal rotary drilling well

Simulation was likewise carried out for a rotary drilled 6-1/4 inch well when the drilling fluid was water. The results are shown in Figure 8.

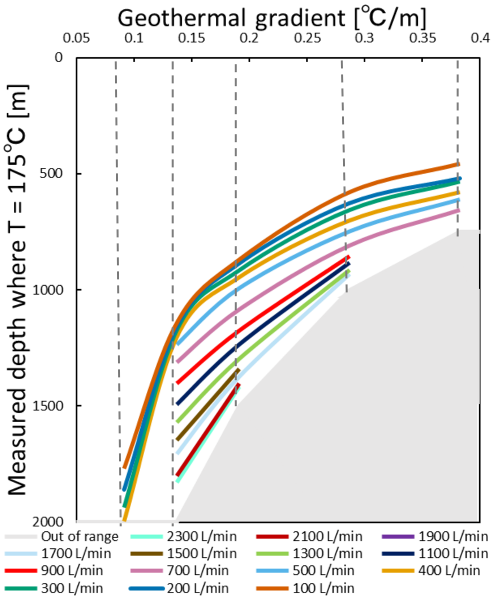

Figure 8: Calculation chart for a 6-1/4 in. well drilled with water.

Figure 8 shows that in a formation with a geothermal gradient of 0.1°C/m, 2000 m of drilling was possible at a flow rate of 400 L/min. For the 0.37°C/m geothermal gradient, increasing the flow rate above 700 L/min resulted in little cooling improvement.

Next, simulation was performed when mud was used as the drilling fluid. The results are shown in Figure 9.

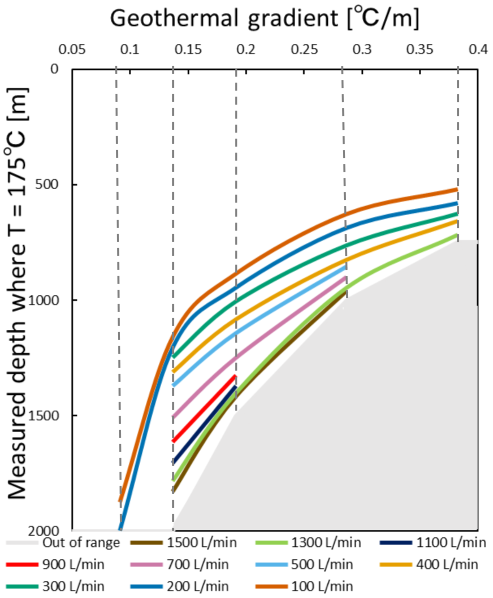

Figure 9: Calculation chart for a 6-1/4 in. well drilled with mud.

Figure 9 shows that in a formation with a geothermal gradient of 0.1°C/m, it is possible to drill 2000 m at a flow rate of 200 L/min. Compared with Figure 8, it was found that the wellbore can be cooled more easily than when circulating with water. On the other hand, as the geothermal gradient approaches 0.4°C/m, it was found necessary to increase the flow rate to 1300 L/min. The chart did not change when the flow rate was increased above 1300 L/min, because the range of depths that could be drilled became smaller.

4.4 Simulation results of 8-1/2 in. normal rotary drilling well

Finally, simulation was performed for a rotary drilled 8-1/2 inch well when the drilling fluid was water. The results are shown in Figure 10.

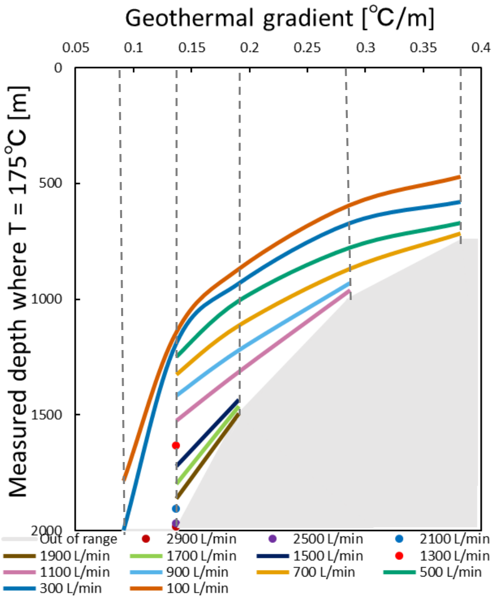

Figure 10: Calculation chart for an 8-1/2 in. well drilled with water.

It was found that 2000 m of drilling was possible at a flow rate of 300 L/min in a formation with a geothermal gradient of 0.1°C/m. On the other hand, when the geothermal gradient is around 0.4°C/m, it is possible to drill to 750 m at a flow rate of 700 L/min.

Next, simulation was performed when mud was used as the drilling fluid. The results are shown in Figure 11.

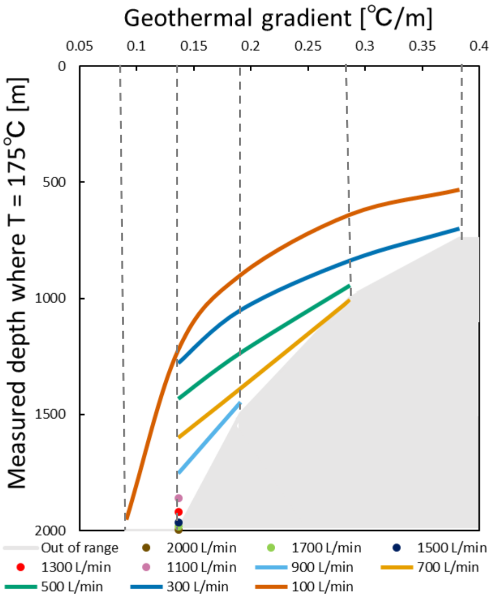

Figure 11: Calculation chart for an 8-1/2 in. well drilled with mud.

It was found that when a geothermal gradient was around 0.1°C/m, the well could be drilled down to 2000 m when the flow rate was increased up to 100 L/min. Therefore, it was confirmed that the wellbore can be cooled more easily than when water is used to circulate the wellbore. The flow rate required was found to be the lowest when compared to the results of the NQ-WL, HQ-WL, and 6-1/4 in. wells.

5 CHART DEVELOPMENT FOR DIRECTIONAL WELLS

5.1 Simulation conditions

Additionally, we considered scenarios with inclined wells. Simulations were performed for the inclined well with 8-1/2 in. diameter. The inclination angles considered were 15°, 30°, and 45°. The casing program was the same as for the vertical well. Therefore, in the case of the 45° inclined well with a large inclination angle, the simulations were performed for geothermal gradient test cases 1 to 3, which have relatively short drilling distances. The geometry of the inclined wells applied to the simulations is summarized in Tables 5 through 7.

Table 5: Geometry of the directional well (inclination angle: 15°) applied to the simulation.

Simulation case	1	2	3	4	5
Kick off point (m)	263	350	525	700	700
Vertical depth (m)	500	1000	1500	2000	2000
Total depth (m)	767	1023	1534	2046	2046

Table 6: Geometry of the directional well (inclination angle: 30°) applied to the simulation.

Simulation case	1	2	3	4	5
Kick off point (m)	263	350	525	700	700
Vertical depth (m)	750	1000	1500	2000	2000
Total depth (m)	825	1101	1651	2201	2201

Table 7: Geometry of the directional well (inclination angle: 45°) applied to the simulation.

Simulation case	1	2	3
Kick off point (m)	263	350	525
Vertical depth (m)	750	1000	1500
Total depth (m)	952	1269	1904

5.2 Simulation results for a well with an inclination angle of 15°

First, simulation was performed for an 8-1/2 in. well with a 15° inclination angle when the drilling fluid was water. The simulation result is very close to the case of a vertical well.

Next, simulation was performed when mud was used as the drilling fluid. The results are shown in Figure 12.

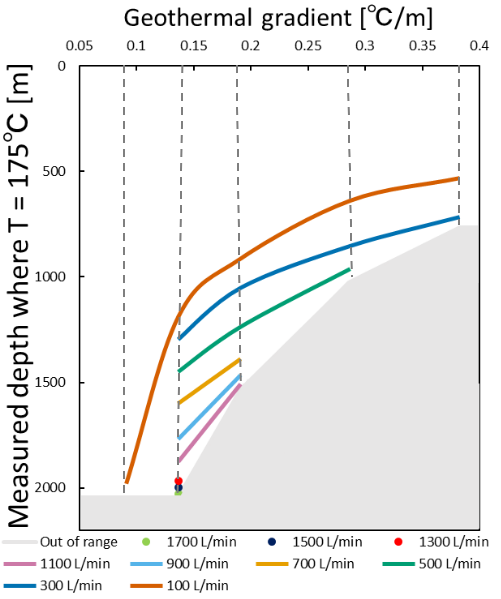

Figure 12: Calculation chart for 15° inclination angle in 8-1/2 in. well drilled with mud.

Figure 12 shows that, compared to the case of a vertical well (Figure 11), the flow rate required increased by about 200 L/min at some points, although the values were generally close.

Therefore, the simulation results for the 15° inclined well were close to those for the vertical well.

5.3 Simulation results for a well with an inclination angle of 30°

Similarly, simulation was performed for an 8-1/2 in. well with a 30° inclination angle when the drilling fluid was water. The results are shown in Figure 13.

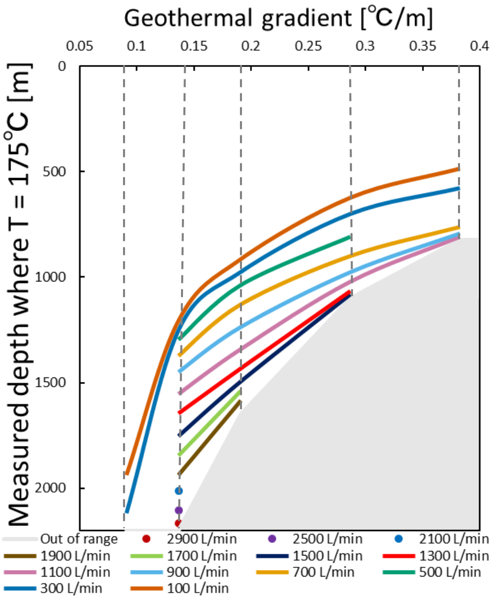

Figure 13: Calculation chart for 30° inclination angle in 8-1/2 in. well drilled with water.

From Figure 13, there were points where the flow rate required increased by about 400 L/min when compared to the case of a vertical well (Figure 10).

Next, simulation was performed when mud was used as the drilling fluid. The results are shown in Figure 14.

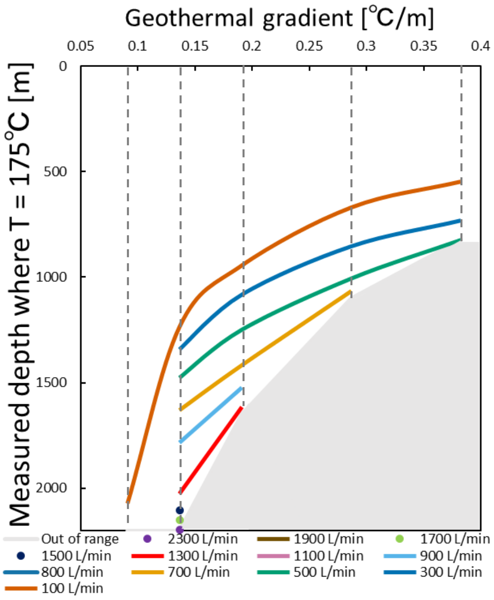

Figure 14: Calculation chart for 30° inclination angle in 8-1/2 in. well drilled with mud.

From Figure 14, there were points where the flow rate required increased by about 400 to 800 L/min compared to the case of a vertical well (Figure 11).

5.4 Simulation results for a well with an inclination angle of 45°

Finally, simulation was performed when the drilling fluid was water. The results are shown in Figure 15.

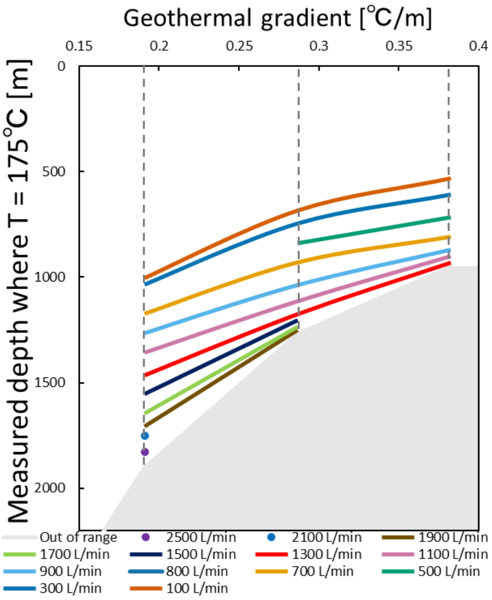

Figure 15: Calculation chart for 45° inclination angle in 8-1/2 in. well drilled with water.

Figure 15 shows that the flow rate required increased by about 600-800 L/min at all calculation points when compared to the case of a vertical well (Figure 10).

Next, simulation was performed when mud was used as the drilling fluid. The results are shown in Figure 16.

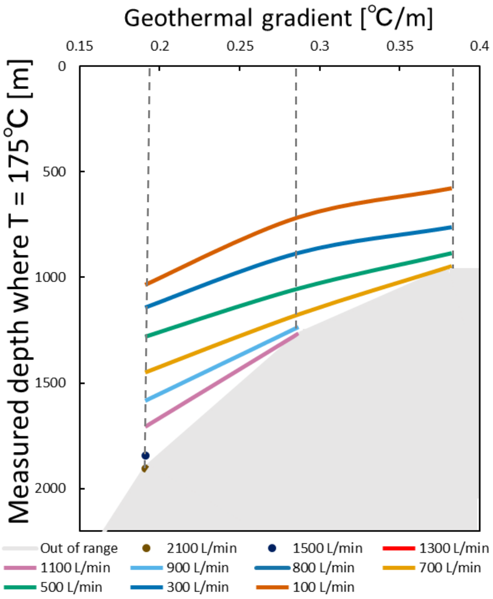

Figure 16: Calculation chart for 45° inclination angle in 8-1/2 in. well drilled with mud.

Figure 16 shows that the required flow rate increased at all calculated points when compared to the case of a vertical well. The required flow rate increased with greater drilling depth, with the largest difference in flow rate being 1200 L/min.

5.5 Comparison of drilling depth and flow rate between vertical and directional wells

A comparison of the results with water as the drilling fluid at inclination angles of 30° and 45°, where the differences from the vertical well simulation results are larger, is shown in Figure 17. The drilling depth is the maximum depth in the range of drilling target.

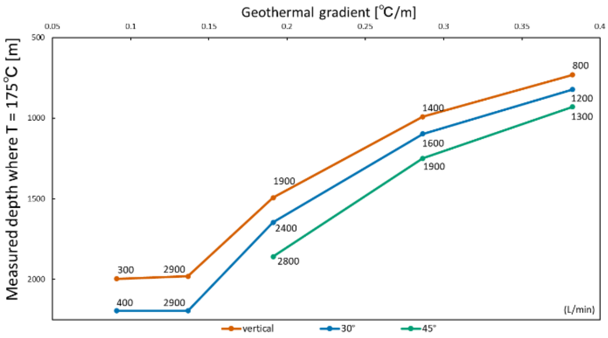

Figure 17: Comparison of drilling depth and flow rate between vertical and directional wells both drilled with water.

Figure 17 shows that the larger the inclination angle of the directional well, the longer the drilling depth, and the higher flow rate required. Similar results were obtained when the drilling fluid was mud.

6 DISCUSSION

From NEDO Geothermal Development Promotion report, the minimum required flow rates are determined using the drilling conditions of the well KB-T-1 drilled in "Kunbetsu," Hokkaido, Japan (NEDO, 2001), and the well N15-AP-6 drilled in the "Appi" area, Aomori, Japan, as examples (NEDO, 2004). Tables 8 and 9 show the drilling conditions for each well.

Table 8: Well dimensions for well KB-T-1.

	KB-T-1 (Vertical well)
Total depth	997 m
Estimated equilibrium bottomhole temperature	86.1°C
Final section diameter	HQ-WL
Drilling fluid	Mud

Table 9: Well dimensions for well N15-AP-6.

	N15-AP-6 (Directional well)
Total depth	1606 m
Vertical depth	1486 m
Estimated equilibrium bottomhole temperature	254°C
Final section diameter	6-1/4 in.
Drilling fluid	Mud

Table 6 shows that the final well diameter of the T-1 well was HQ-WL and mud was used as the drilling fluid. Therefore, the chart in Figure 7 is used to determine the minimum flow rate. Next, the vertical depth is 997 m, and the equilibrium bottomhole temperature is 86.1°C. This indicates that a geothermal gradient is 0.09°C/m. Therefore, as shown by the black circle in Figure 18, the flow rate value for a depth of 997 m and a geothermal gradient of 0.09 °C/m is read.

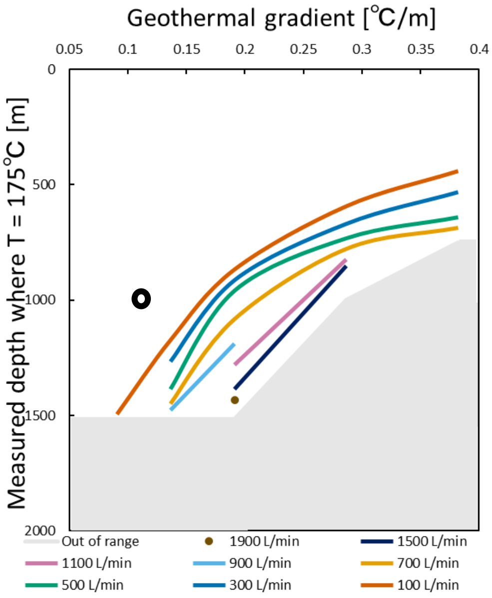

Figure 18: Example usage of developed chart for well KB-T-1. Black circle indicates drilling conditions in Table 8.

The results confirm that the minimum flow rate required is 100 L/min.

Table 7 indicates that the final well diameter of the AP-6 well was 6-1/4 in., and that mud was used as the drilling fluid.

Therefore, the chart in Figure 8 is used to determine the minimum flow rate. Next, the vertical depth is 1486 m, and the well bottom temperature is 254°C, which indicates that a geothermal gradient is 0.17°C/m. Therefore, as shown in the black circle in Figure 19, the value of the flow rate at a depth of 1486 m and a geothermal gradient of 0.17 °C/m is read.

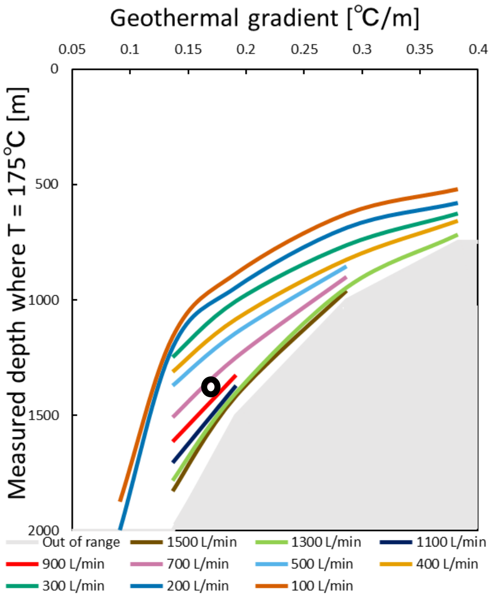

Figure 19: Example usage of developed chart for well N15-AP-6. Black circle indicates drilling conditions in Table 9.

As a result, it was confirmed that the minimum flow rate required was 900 L/min. However, considering that the AP-6 well is a directional well, it is desirable to use a flow rate of 900 L/min or higher.

7. CONCLUSION

The simulation results show that the wellbore cools more easily when mud is used as the drilling fluid than when water is used as the drilling fluid, for all well diameters. This is thought to be due to the difference in specific heat between water and mud.

The flow rate required to avoid overheating of downhole equipment (to maintain downhole temperatures below 175°C) increased with decreasing well diameter.

The flow rate requirements increased as the drilling depth increased with the inclination angle of the wellbore.

From the well data, it was confirmed that the developed chart in this study could be used to determine the minimum required flow rate for a typical design of a geothermal well to be drilled into a formation having a certain geothermal gradient.

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