Evaluating Wellbore Cooling Effect with Insulated Drill Pipes in Supercritical Geothermal Well Drilling

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Keywords

Supercritical geothermal well, drilling technology, insulated drill pipe, wellbore temperature simulation

ABSTRACT

In Japan, a research and development program on geothermal power generation by use of supercritical geothermal fluids is ongoing. One of the challenges in supercritical geothermal drilling is that the extremely high formation temperature conditions are likely to result in damage to downhole tools. Thus, it is essential to design an effective method of downhole cooling during drilling. In this study, the authors conducted simulation studies focusing on the effect that using insulated drill pipes have on the downhole temperature during drilling fluid circulation. The objective is to reduce the downhole temperature in supercritical geothermal wells to below 175℃ that is the lowest heat resistant temperature of most downhole tools.

A conventional drill pipe is made of carbon steel. The insulated drill pipe has a structure similar to a conventional drill pipe but insulation materials with low thermal conductivity is added inside the pipe body with a liner tube. Formation temperatures and drilling conditions for the simulation study were based on the former highest temperature geothermal research well “Kakkonda WD-1a”. The well has a depth of 4000 m and a maximum formation temperature of over 600℃. In the simulation study, the authors used a modified downhole temperature simulation program “GEOTEMP2” which was originally developed at the Sandia National Laboratory.

It was found that drilling with insulated drill pipes effectively controlled the downhole temperature by reducing the heat influx conducted from the formation. Considering the additional cost of using insulated pipes, cases where the insulated drill pipes were applied to sections of the drill string were considered. It was found to be more effective for cooling the downhole temperature of the entire well to place insulated drill pipes along the shallower sections of the well than placing them in the deeper sections.

1. Introduction

Supercritical geothermal systems are unconventional high temperature geothermal systems in which the reservoir fluid exists at supercritical conditions. The critical point for pure water is at 374.1°C, and 22.1 MPa. In 2017, the Iceland Deep Drilling Project research well IDDP-2 in Iceland was drilled to a depth of 4.5 km where it successfully reached supercritical conditions. The observed bottom hole conditions showed that the well had reached a supercritical zone where the fluid pressure was 34 MPa and the temperature was at least 426°C (Friðleifsson et al., 2017). In 2010, the Japan Beyond Brittle Project (JBBP) was launched in Japan that also considers the development of technology for supercritical geothermal energy generation (Asanuma et al., 2021). JBBP members proposed that supercritical reservoir fluids could be reached by drilling into and beyond the brittle-ductile transition zone (Asanuma et al., 2021; Muraoka et al., 2014).

Japan faces a convergent trench-type plate boundary, and it is thought that as the Pacific Plate subducts, a large amount of seawater is pulled in with the plate. This water mixes with magma and rises. As a result, a large amount of extremely high-temperature, high-pressure, supercritical fluid of seawater origin is thought to be stored in the upper part of magma pools deep underground. Recently, it has also been discovered that there are supercritical rock bodies containing supercritical water. Utilization of supercritical geothermal resources has been pursued to improve the efficiency and capacity of geothermal power generation as a next generation renewable energy.

However, there are many challenges. The material supercritical water, the supercritical rock body containing it, and the high-temperature, high-pressure environment 4 to 5 km deep underground are not understood, and research on supercritical resources is still in the exploration stage. The difference between conventional and supercritical geothermal systems is shown in this Figure 1.

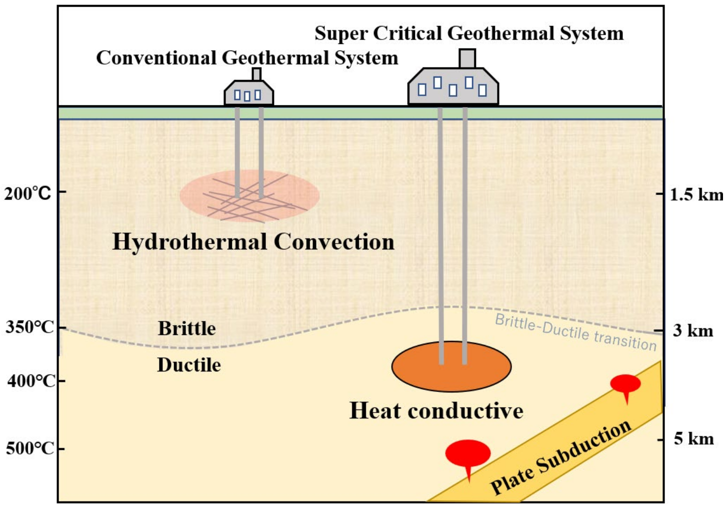


Figure 1: Schematic diagram of supercritical geothermal generation.

2. Temperature Durability of Equipment

The overall temperature limitation of the downhole tools used for drilling geothermal wells is approximately 175°C (Table 1). In supercritical geothermal drilling, it is a concern that the upper temperature tolerance limit of downhole equipment could be exceeded. In the case of the Kakkonda WD-1a well, it was drilled with continuous cooling mud circulation with a top drive system (Ikeuchi et al., 1998). The downhole temperature was successfully cooled and estimated to be maintained below 200°C by the combined use of high-temperature stable drilling mud and a closed-type surface mud cooling system. Although this technology was not widely used in geothermal well drilling at the time, downhole cooling by mud circulation is an essential drilling operation for safe and cost effective supercritical geothermal well drilling.

Table 1: Heat resistance temperature of different types of wellbore equipment.

Drilling Bit	Roller Cone Bit	288°C
	Natural Diamond Bit	400°C
	PDC Bit	350°C
Directional Drilling Tools	Positive Displacement Motor	190°C
	Turbine Motor	350°C
	Rotary Steerable System	175°C
	Single-Shot Survey Tool	250°C
	Measurement While Drilling Tools	230°C
Casing/Cementing Equipment	Float Shoe/Collar	230°C
	Stage Tools	176°C
	Liner Hanger	340°C
Drilling Fluid	Water Base Mud (Unweighted)	300°C
	Water Base Mud (Weighted)	300°C
	Oil Base Mud (Unweighted)	300°C
	Oil Base Mud (Weighted)	260°C
	Synthetic Oil-Base Mud	315°C
Cement Material	Portland Cement	260°C
	Silica Cement	400°C

In this study, we consider the effectiveness of using insulated drill pipe technology, which was developed at Sandia National Laboratory (Finger et al., 2000; Champness et al., 2009), for reducing temperatures experienced by drilling equipment when drilling into supercritical zones. We analyze its effectiveness by carrying out numerical simulations of wellbore temperatures during drilling. For our analysis, we need to consider high formation temperature conditions like those observed in the Kakkonda field. Therefore, in this study, the downhole temperature profile during drilling was simulated based on actual drilling conditions for the Kakkonda WD-1a well and the associated formation temperature of the WD-1a well.

3. Wellbore Thermal Simulator

In this work, we used the GEOTEMP2 code (Mondy and Duda, 1984) to simulate wellbore temperature profiles. GEOTEMP2 was developed at the Sandia National Laboratory. It was modified to deal with arbitrary subsurface formation temperature profiles in supercritical geothermal fields.

The temperature of the fluid in the wellbore and the formation is calculated by solving unsteady heat transport equations. The calculation is divided between solid and liquid components. For the solid component, the heat transport is assumed to be through thermal conduction in both vertical and horizontal directions. For the liquid component, natural and forced convection are assumed in the vertical direction, and heat transfer in the horizontal direction is only through thermal conduction. The temperature dependence of drilling fluid viscosity is considered in GEOTEMP2. The specific heat capacity and thermal conductivity for the drilling fluid were calculated as functions of the fluid density. The data which GEOTEMP2 needs are as shown in Figure 2. For the simulations, we used Kakkonda WD-1a well drilling operation data for the formation temperature.

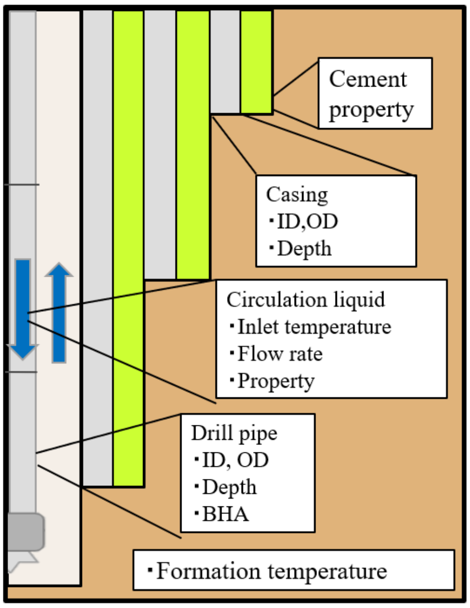


Figure 2: Input values required for the GEOTEMP2 wellbore simulations.

4. Insulated Drill Pipe

The Geothermal Research Department at Sandia National Laboratories, in collaboration with Drill Cool System Inc., developed an insulated drill pipe (IDP). Using an IDP is expected to result in much cooler drilling fluids reaching the bottom of the hole, making it possible to use various downhole instruments. IDP construction design consists of welding a 3.5-in. outer diameter by 3.06-in. inner diameter liner tube inside a conventional 5-in. drill pipe and filling the annulus between tubulars with an insulation material. The conventional type of drill-pipe is made of steel. A schematic model of an insulated drill pipe is shown in Figure 3.

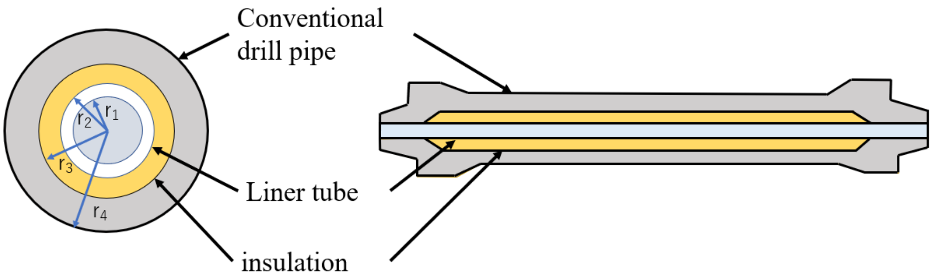


Figure 3: Schematic diagram of insulated drill pipe.

The following equation indicates the amount of heat transfer for an insulated drill pipe between annulus fluids and fluids in drill pipe. In the use of conventional drill pipe, heat resistance value almost equal to upper formula apart from term 3, including insulation property.

$$q = 2\pi \Delta T \left[\frac{1}{\frac{1}{h_4 r_4} + \frac{\ln(r_4/r_3)}{k_{steel}} + \frac{\ln(r_3/r_2)}{k_{insulation}} + \frac{\ln(r_2/r_1)}{k_{steel}} + \frac{1}{h_1 r_1}} \right] \tag{1}$$

k: thermal conductivity [W/m/K]

h: boundary heat transfer coefficient [W/m$^{2/}$K]

r: pipe radius [m]

5. Simulation Setup

Downhole temperature profiles during drilling were simulated for a model well whose profile was based on the ultrahigh-temperature geothermal exploration well Kakkonda WD-1a. The WD-1a well was modeled as a 4000 m deep vertical well and the assumed casing design is presented in Figure 4. The temperature profile follows the boiling point for depth curve up to about 3100 m depth. Below 3100 m where the formation fluid is estimated in critical condition, the formation temperature profile is conduction heat transfer dominant with very high geothermal gradient higher than 20°C/100m such as Figure 5 (Ando and Naganawa, 2020).

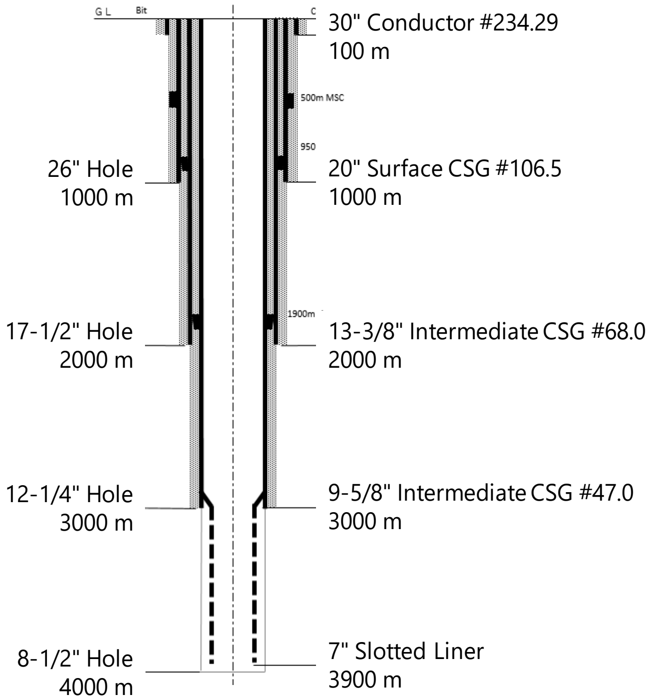


Figure 4: Assumed casing program for the simulated supercritical geothermal well.

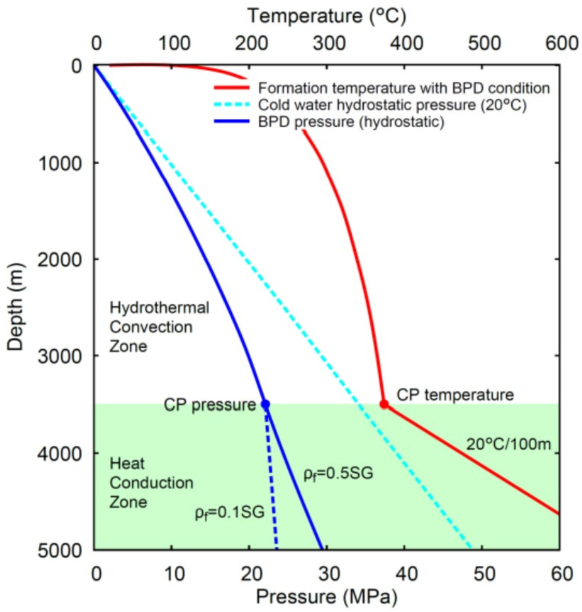


Figure 5: Example temperature profile for supercritical geothermal drilling conditions considered in (Naganawa et al., 2017).

The injection temperature for the circulation mud at the wellhead and the initial pump rate was defined as 40°C and 2000 L/min, respectively. The other properties and drilling plan were set as shown in Tables 2 to 6.

Table 2: Depth and hole diameter.

Drilling depth [feet]	Vertical depth [feet]	Maximum diameter [inches]
13200	13200	37.5

Table 3: Mud water and water property.

	Density [lbm/gal]	Viscosity [cP]	Yield point [lbm/100ft^2]	Flow rate [gal/min]
Mud water	9.996	15.0	5.0	528
water	8.33	1.0	0.0	528

Table 4: Outer and inner diameter in each drill pipe.

	OD [inch]	ID [inch]
Conventional drill pipe	5.0	4.276
Insulated drill pipe	5.0	3.068

Table 5: Thermal conductivity of each drill pipe.

	Thermal conductivity	
	(W/m/K)	(BTU/hr/ft/F)
Conventional drill pipe	45.3	26.2
Insulated drill pipe	3.1	1.8

Table 6: Input values for drilling schedule.

Depth[feet]	Days of Drilling	Days of cementing	total working days
328.08	2	1	3
3280.8	20	1	21
6561.8	40	1	41
9842.6	60	1	61
13200	80		

6. Results

Figure 6 shows the simulated wellbore temperature profile during drilling of the 12 1/4-in. hole section down to 3000 m. The figure highlights the difference between the bottom hole temperature when using the insulated drill pipe (IDP) and the conventional drill pipe (CDP). The 200 m long BHA (bottom hole assembly) is applied at the bottom of the well and the IDP are applied above that.

Note that for the drilling of the 12 1/4-in. hole section, the formation temperatures are below the critical temperature of water.

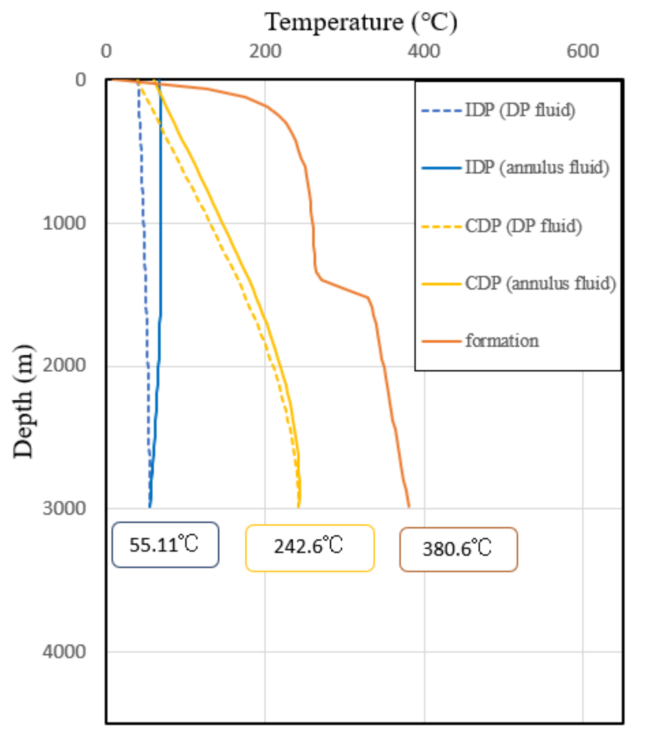


Figure 6: Simulated wellbore temperature profiles during 12-1/4 in. hole diameter drilling.

Figure 7 shows the simulated wellbore temperature profile during drilling of the 8-1/2 in. hole section down to 4000 m with cooling mud circulation. The situation is similar to actual drilling conditions of the Kakkonda WD-1a well. Below a depth of 3100 m in this temperature simulation, the drilling conditions are at temperatures and pressures that are high enough to result in supercritical water. For IDP drilling, the bottom hole temperature is considerably lower than that for CDP drilling.

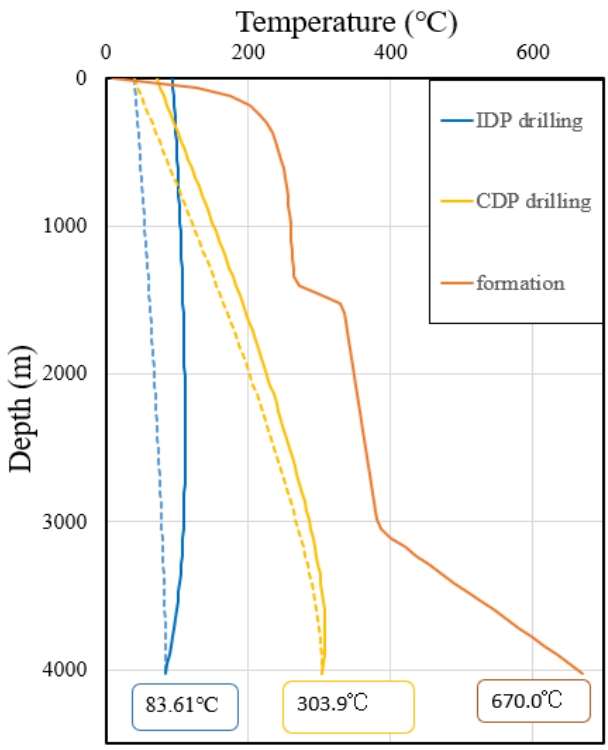


Figure 7: Simulated wellbore temperature profiles after drilling of the 8-1/2 in. diameter well section is completed.

Because the insulated drill pipes considered here need to be order made by Drill Cool Systems Inc., their use can increase the cost of drilling to a depth of 4000 m considerably. Considering cost, we also considered wellbore temperature simulations where IDP drilling is only used for limited sections of the well.

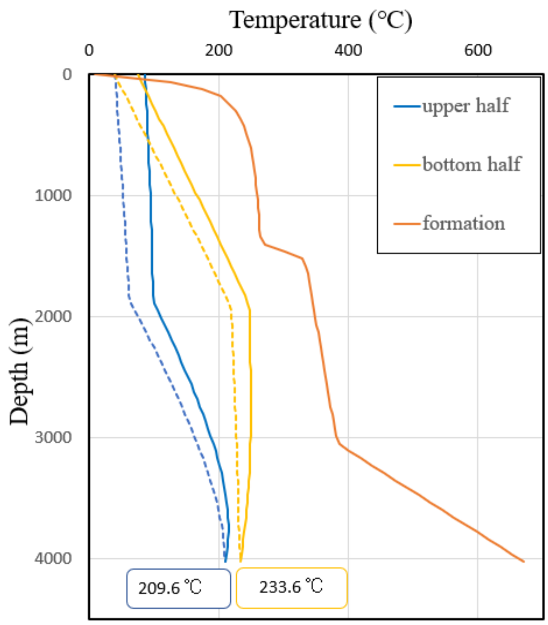


Figure 8: Temperature profiles when drilling half of the total depth with IDP application.

Figure 8 shows simulated temperature profiles for: 1) a case where IDPs are applied to the upper half of the well and 2) a case where IDPs are applied to the lower half of the well. As the figure shows, the heat resistance temperature of 175°C is exceed at the bottom of the hole for both cases that consider using IDPs for only half the well (at a fluid flow rate of 2000 L/min).

Increasing the fluid injection rate tends to help to reduce temperatures in the wellbore. Therefore, for saving the downhole equipment, we also considered using a variety of flow rates ranging from 1500 L/min to 3000 L/min (Figure 9). The results in Figure 9 and Table 7 show that it is more effective to place the IDPs along the upper sections of the well. The bottom hole temperature could be maintained below the threshold of 175°C when placing the IDPs in the upper half of the well and increasing the flow rate to 2500 L/min A larger flow rate was required to achieve the same result when placing IDPs in the lower half of the well.

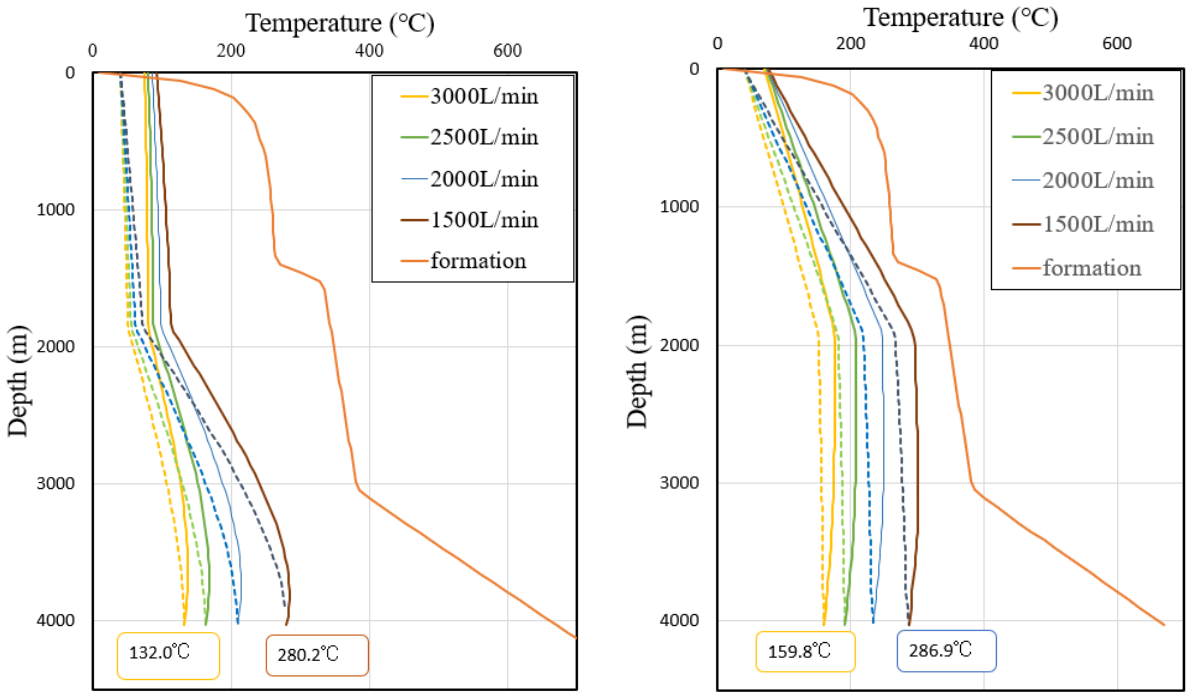


Figure 9: Temperature profiles when applying IDPs along (Left) the upper half of the wellbore and (Right) the bottom half of the wellbore. The results shown here are for mud circulation at various flow rates.

Table 7: Bottom hole temperature for different mud circulation flow rates in a partial (1/2) IDP application.

	1500 (L/min)	2000 (L/min)	2500 (L/min)	3000 (L/min)
Up half (°C)	280.2	209.6	163.0	132.0
Bottom half (°C)	286.9	233.6	191.6	159.8

When drilling geothermal wells, large-scale mud lost circulation are more likely to occur than when drilling oil and gas wells because geothermal wells are commonly drilled into formations containing permeable formations and fractures. The lost circulation results in considerable additional costs when drilling mud is used and large quantities of drilling fluid are lost into the formation. Considering that economical factor, we also carried out simulations of the temperature distribution in the wellbore with circulating water, which is cheaper to use than using mud.

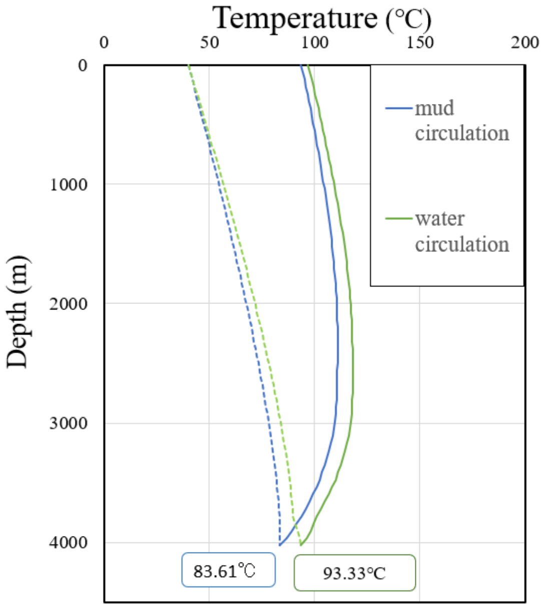


Figure 10: Comparison of temperature profiles for water and mud water circulation in IDP drilling.

As shown in the Figure 10, well bottom temperatures in the water circulation case were greater than those in the mud circulation case. Since the specific heat of water is lower than that of mud, the amount of heat transported is smaller, and the temperature at the bottom of the well seems to have risen. Therefore, the temperature distribution in the wellbore was simulated again using water circulation (Figure 11).

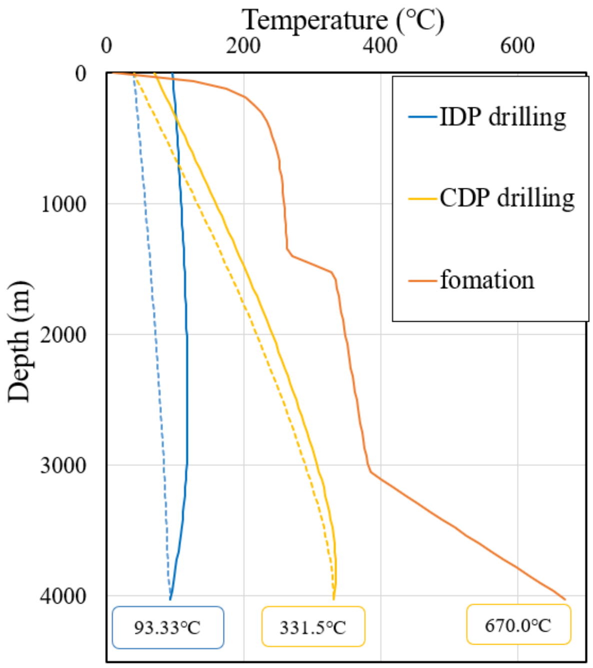


Figure 11: Wellbore temperature profiles when drilling with water circulation.

The bottom hole temperature was 93.33°C and 331.5°C, respectively, for the CDP and full IDP drilling with a 2000 L/min water flow rate as shown in Figure 11. Using an insulated drill pipe is extremely effective at lowering wellbore temperatures for supercritical geothermal drilling. As we did for the mud circulation case, we also carried out wellbore temperature simulations with IDP drilling used in only half of the well and changed the water flow rate from 1500 L/min to 3000 L/min. The resulting temperature profiles are shown in Figure 12 and each resulting bottom hole temperature is listed in Table 8.

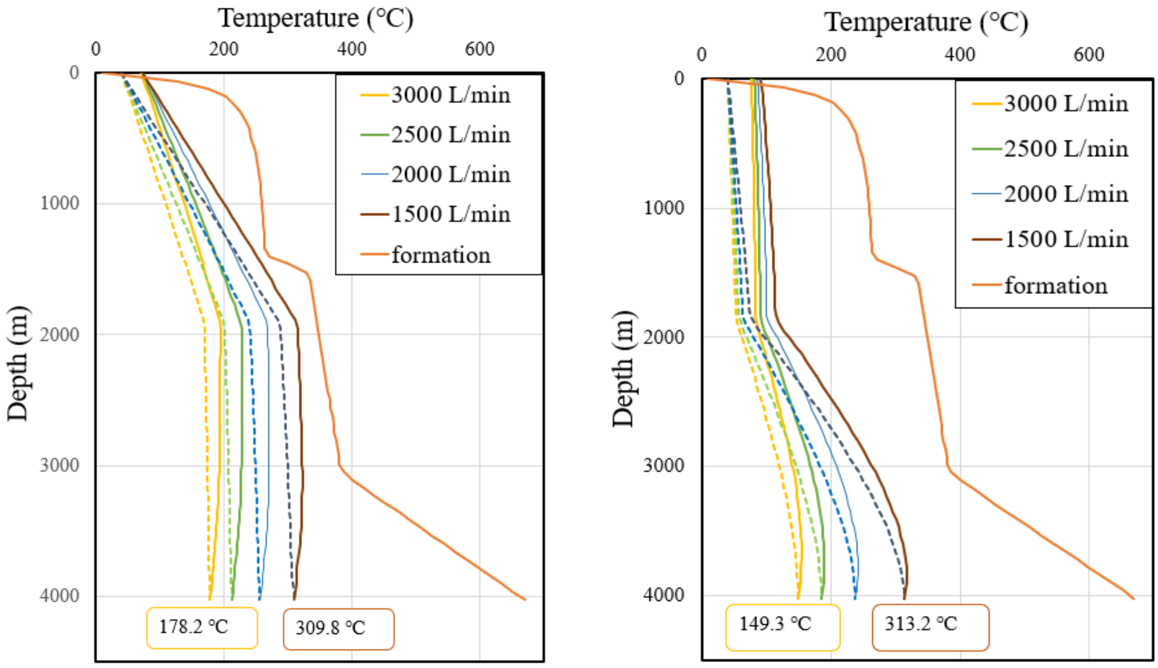


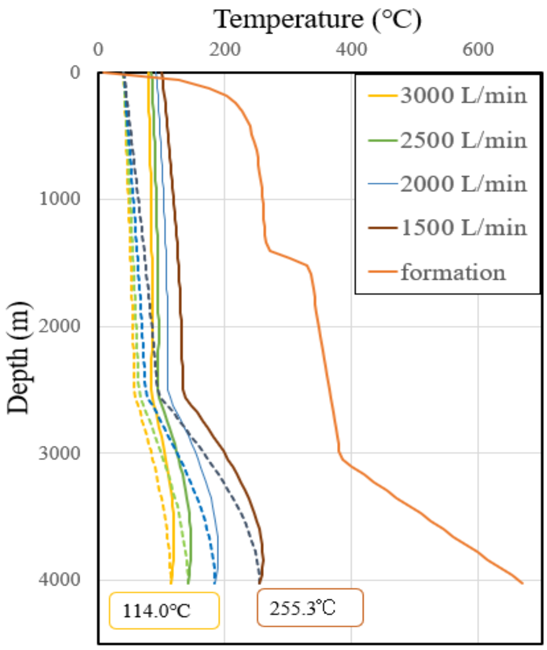
Figure 12: Temperature profiles when applying IDPs along (Left) the upper half of the wellbore and (Right) the bottom half of the wellbore. The results shown here are for water circulation at various flow rates.

Considering the heat endurance temperature of 175°C, appropriate cooling was achieved only for the case where IDP drilling was used in the upper half of the well with a 3000 L/min water flow rate. But 3000 L/min is considered to be too high a flow rate. Therefore, we carried out more temperature simulations with longer IDP drilling sections.

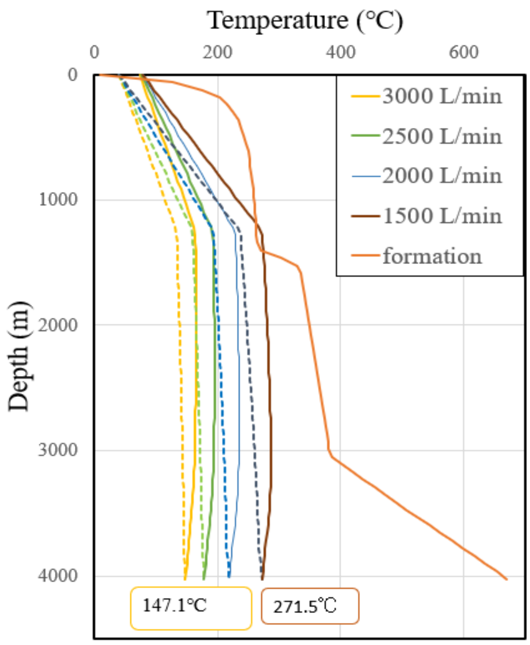
Table 8: Bottom hole temperature for different water flow rates in a partial (1/2) IDP application.

	1500 (L/min)	2000 (L/min)	2500 (L/min)	3000 (L/min)
Up half (°C)	313.2	237.3	185.0	149.3
Bottom half (°C)	309.8	256.3	212.6	178.2

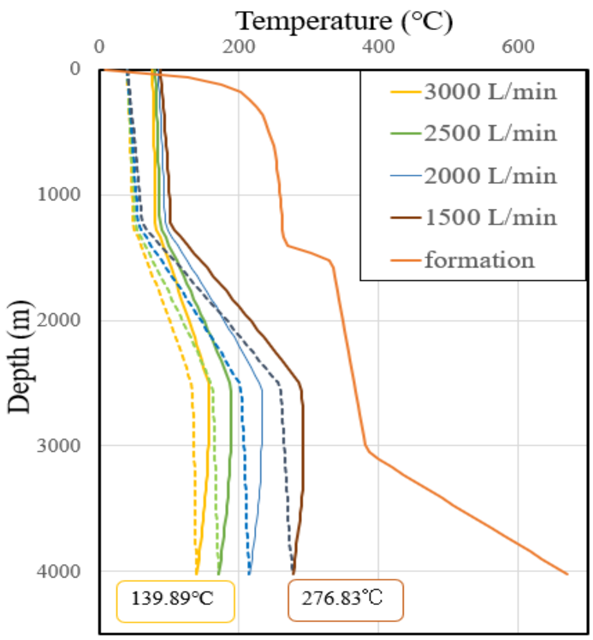
As shown in Figure 13, three cases of temperature distribution simulations were performed for IDP drilling placed along 2/3 of the total well depth. In the results, it was again found that drilling the upper half with a drill pipe is most effective for downhole cooling and requires a flow rate of about 2500 L/min to keep wellbore temperatures below 175°C. The bottom hole temperature is listed in Table 9 for these test cases.



(a) IDPs are at upper 2/3



(b) IDPs are at lower 2/3



(c) IDPs are at upper 1/3 and lower 1/3

Figure 13: Temperature profiles for three different cases where 2/3 of the total well depth uses IDP drilling. The results shown are for various water flow rates.

Table 9: Bottom hole temperature for different water flow rates in a partial (2/3) IDP application.

	1500 (L/min)	2000 (L/min)	2500 (L/min)	3000 (L/min)
Top 2/3 (°C)	255.3	184.4	141.2	114.0
Bottom 2/3 (°C)	271.5	218.1	177.3	147.1
Each top and bottom (°C)	276.8	215.2	171.0	139.9

7. Conclusion

In this work, the effectiveness of utilizing insulated drill pipes for cooling the wellbore was studied. The use of insulated drill pipes was found to be very effective for downhole cooling. For cost considerations, we looked at studying simulation cases where IDP drilling was carried out along parts of a well that was drilled into a supercritical formation. The simulation results show that IDP drilling is most effective at cooling the entire wellbore when available insulated drill pipes are placed in the upper sections of the well. For a realistic formation temperature profile based on the high-temperature Kakkonda WD-1a well, we found that suitable cooling was achieved for the well even at a water flow rate of 2500 L/min when IDP drilling was used for the upper two-thirds of the well.

The use of insulated drill pipes was demonstrated to effectively keep the downhole temperature low. In the simulations presented in this work, there were cases in which the downhole bottom temperature was lower than 175°C, which was set as the heat-resistant temperature of the downhole equipment. However, it is necessary to consider the economics of the insulated drill pipe and the pressure applied by the pump when drilling. Since there is little geothermal field experience using IDP drilling, we consider that new issues such as strength problems due to the increased weight of IDPs and mud leakage due to increased pump pressures might emerge.

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