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Numerical Study on Downhole Cooling by Mud Circulation in Supercritical Geothermal Drilling

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ABSTRACT

Feasibility of supercritical geothermal power generation and the preliminary drilling plans are now studied in Japan as a national research project. The temperature limit of the latest conventional downhole tools and materials is in a range approximately 250°C to 300°C. This is insufficient for drilling supercritical geothermal reservoirs with temperatures exceeding 400°C. Downhole cooling techniques by mud circulation is still considered indispensable for ultrahigh-temperature supercritical geothermal drilling even if the heat-resistant performance of drilling tools will be improved in the future. In this study, first, the computer code of the wellbore temperature simulator GEOTEMP2, which was previously developed at the Sandia National Laboratory, was modified to deal with assumed subsurface formation temperature profiles in supercritical geothermal fields. Using the modified simulator, 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 that was drilled in Japan 25 years ago. In addition, temperature profiles during cementing operations were also simulated for the model well. Based on the simulation studies on various combinations of drilling and cementing operation parameters, downhole cooling strategies in supercritical geothermal drilling are discussed.

1. INTRODUCTION

The main difference between geothermal well drilling and oil and gas well drilling is pressure and temperature profile of the target formation to be drilled. **Figure 1** shows a comparison of pressure and temperature range of target reservoirs for oil and gas development and supercritical geothermal development. The pressure and temperature range categorized in the “HP/HT” area in the figure is the target toward which exploration and exploitation are actively conducted in oil and gas industry. The development target is extending to the “Ultra HP/HT” category, and correspondingly, the development of drilling equipment and materials is in progress by the oil and gas industries worldwide. However, supercritical geothermal development targets to achieve a much higher temperature range where the formation water is in supercritical condition (critical point of pure water is 374°C and 22.1 MPa).

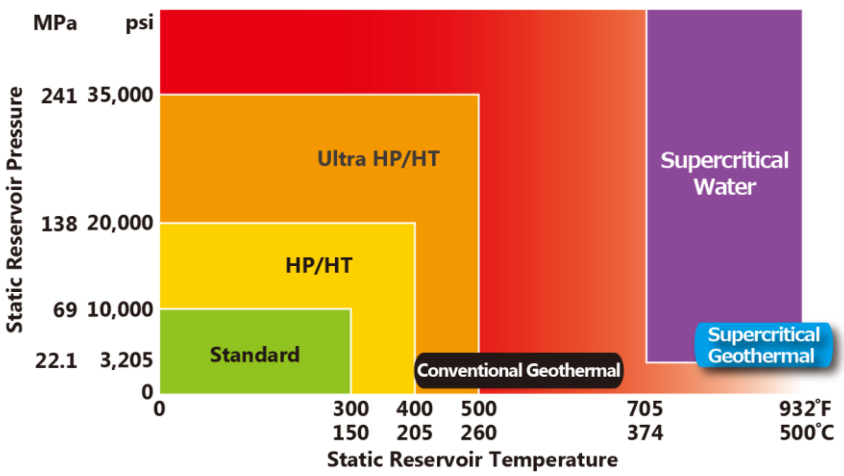

Figure 1: Target subsurface pressure and temperature environments in supercritical geothermal drilling.

Geothermal development including conventional geothermal fields technically differs from oil and gas development because of the differences of formation properties as shown in **Table 1**. In typical geothermal development fields, the formation temperature reaches approximately 250°C to 350°C even at relatively shallow depths of 1000 to 2000 m although the formation temperature in typical oil and gas fields is at most approximately 200°C at a depth of 5000 m. Thus, the heat-resistance performance of downhole tools and materials is the most critical issue. In addition, in a geothermal field, volcanic or granitic hard and abrasive formations are typical, resulting in a very low rate of penetration. On the other hand, the formation pressure in a geothermal field is typically low or subnormal, unlike that in an oil and gas field. Therefore, low-density and/or low-solid drilling fluid, or sometimes aerated fluid that has lower density than brine must be used. Nevertheless, severe lost circulation frequently occurs when drilling at low pressure and naturally fractured or faulted zones. In many cases, the lost circulation encountered during geothermal drilling is a total loss, and the use of lost circulation materials (LCM) is insufficient to stop it. Typically, a lost circulation zone is blindly drilled out, and a cement plug must be embedded to stop the lost circulation. The restriction requiring the use of low-density drilling fluid is disadvantageous for effective cuttings transport or hole cleaning. It also causes a barrier to safe well control operations during influx of H_2S, CO_2 and/or HCl contained formation fluid into the wellbore from the formation being drilled.

Table 1: Differences of formation properties between geothermal fields, and oil and gas fields.

	Oil and Gas	Geothermal
Temperature	At most approx. 200°C at depth of 5000 m	250°C to 350°C even at depth of 1000 to 2000 m
Pressure	High Formation Pressure	Generally Low Formation Pressure
Rock	Sedimentary Rock	Sedimentary/Base Rock (Hard Volcanic)
Fluid	CO_2 and/or H_2S are contained	CO_2, H_2S and/or HCl are contained, Low pH

Table 2 summarizes a comparison of temperature limitations of downhole tools and materials. There are some tools available for use in high-temperature environments over 200 or 300°C, as heat-resistance performances have progressed in past 30 years. However, the overall temperature limitations of rotary drilling equipment remain below the supercritical geothermal development conditions because any tool that uses elastomer components for sealing parts has a temperature limitation of approximately 175°C. The current most-advanced drilling technology and equipment are not adequate for drilling supercritical geothermal wells.

Table 2: Temperature limitations of downhole tools and materials.

		1985*	1996*	2019
Bit	Roller Cone Bit	180°C	190°C	288°C
	Natural Diamond Bit		400°C	
	PDC Bit	350°C		
Directional Drilling Tools	Positive Displacement Motor (PDM)	135°C	175°C	190°C
	Turbine Motor	160°C	315°C	350°C
	Rotary Steerable System (RSS)			175°C
	Single-Shot Survey Tool		250°C	
	MWD	125°C	175°C	230°C
Casing/Cementing Equipment	Float Shoe/Collar	150°C	200°C	230°C
	Stage Tools	135°C	135°C	176°C
	Liner Hanger		230°C	340°C
Drilling Fluid	Water Base Mud (Unweighted)	200°C	300°C	300°C
	Water Base Mud (Weighted)	180°C	250°C	300°C
	Oil Base Mud (Unweighted)		300°C	
	Oil Base Mud (Weighted)		260°C	
	Synthetic Oil-Base Mud (SBM)			315°C
Cement Material	Portland Cement	260°C	260°C	260°C
	Silica Cement	400°C	400°C	400°C

* Data from Ito (1996) and Morita et al. (1997).

We have an experience with extremely high-temperature formation drilling in Japan. A geothermal exploration well "Kakkonda WD-1a" was drilled in 1995 whose maximum formation temperature was estimated to be more than 500°C. The overall temperature limitation of the downhole tools used was approximately 150°C as seen in Table 2. The solution employed at the time was to cool off downhole by continuous mud circulation with a top drive system (Saito et al., 1998). The downhole temperature was successfully cooled and estimated to be maintained below 200°C combined with high-temperature stable drilling mud and closed-type surface mud cooling systems. This technology was not widely used in geothermal well drilling at the time. Although the heat-resistance performance of downhole tools and materials has been steadily improving, supercritical geothermal drilling is of particular interest compared with any ultradeep drilling project carried out so far as shown in **Figure 2**. Downhole cooling by mud circulation is an essential drilling operation for safe and cost effective supercritical geothermal well drilling.

In this study, downhole temperature profiles during drilling were simulated for a model well in which the formation temperature profile was based on the ultrahigh-temperature geothermal exploration well Kakkonda WD-1a drilled in Japan more than 25 years ago. In addition, temperature profiles during cementing operation were also simulated for the model well. Based on the simulation studies on various combinations of drilling and cementing operation parameters, downhole cooling strategies in supercritical geothermal drilling are discussed.

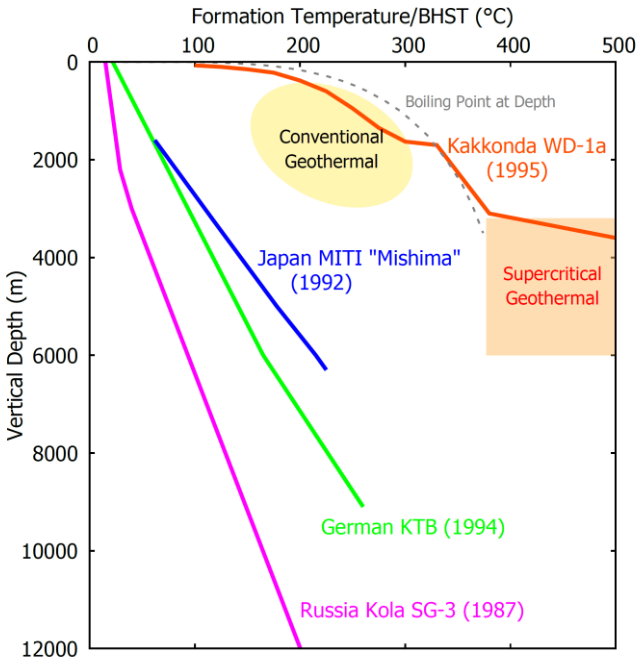

Figure 2: Comparison of subsurface temperature profiles between supercritical geothermal and past ultradeep drillings.

2. WELLBORE THERMAL SIMULATOR

The computer code of the wellbore temperature simulator GEOTEMP2, which was developed at the Sandia National Laboratory (Wooley, 1979; Mitchell, 1982; Mondy and Duda, 1984), was modified to deal with arbitrary subsurface formation temperature profiles in supercritical geothermal fields. However, drilling fluids in a supercritical state are not accurately described in the current simulator model. Moreover, to reflect the change in thermophysical property values due to thickening of cement slurry in the simulation, we developed a model that can consider the time variation of thermal conductivity and specific heat capacity of cement slurry.

3. SIMULATION STUDY

3.1 Simulation Conditions

Using the modified simulator, 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 temperature profile of the Kakkonda WD-1a well was shown in Figure 2. The simulated supercritical geothermal well is modeled as a vertical well and has a total depth of 4000 m. The casing program assumed for the wellbore temperature simulation is shown in **Figure 3.**

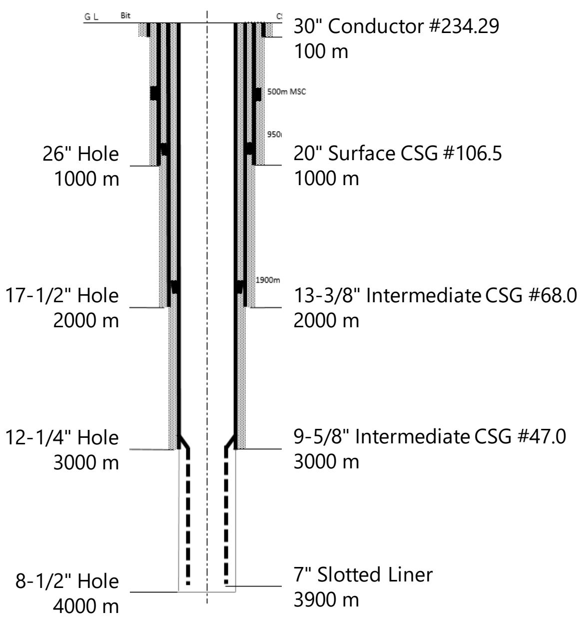

Figure 3: Assumed profile and casing program for simulated supercritical geothermal well.

Drilling parameters were set as follows: two types of drilling fluids, water (1.0 SG, PV=1, YP=0), mud (1.2 SG, PV=15, YP=5) and cement slurry (1.75 SG, PV=30, YP=50); standard pump rate 2000 L/min (528 gal/min); inlet mud temperature at the surface 40°C; rate of penetration 5 m/hr. Thermal properties of materials were set as shown in **Table 3**. Temperature dependency of viscosity was considered in the GEOTEMP2 simulator by a simplified model in which specific heat and thermal conductivity are respectively expressed as function of density. However, this simplified model was made to appropriately be applied to mud. Therefore, the application of this model to cement slurry leads to a large error. In addition, because of the cement slurry thickening phenomenon by hydration reaction, measurement of thermal conductivity and specific heat capacity is difficult. Hence, we applied the following approximate expressions (El-Wakil, 1962; Maxwell, 1904) to determine the specific heat capacity (C_p) and the thermal conductivity (k) of cement slurry.

$$C_p = mC_W + (1-m)C_C \tag{1}$$

where, m: mass fraction [-], C_W: specific heat capacity of water [kJ/kg·K], C_C: specific heat capacity of a cement particle [kJ/kg·K].

$$k = k_W \cdot \frac{2k_W + k_C - 2\varepsilon(k_W - k_C)}{2k_W + k_C + \varepsilon(k_W - k_C)} \tag{2}$$

where ε: volume fraction [-], k_W: thermal conductivity of water [W/m·K], k_C: thermal conductivity of a cement particle [W/m·K].

These approximate expressions are widely used to determine the thermal conductivity and the specific heat capacity in slurry form. To use these expressions, we can get more appropriate values of cement slurry thermal conductivity and specific heat capacity which is based on the thermophyical values of a cement particle.

Table 3: Thermal properties of materials.

		Density (kg/m^3)	Specific Heat Capacity (J/(kg·K))	Thermal Conductivity (W/(m·K))
Formation		2242	1256.04	3.46
Steel		7849	460.55	45.3
Cement Slurry		1750	2299.50	0.787
Cement Solid		1666	837.36	0.870
Drilling Fluid	Water	1000	4186.80	0.7
	Mud	1200	3753.26	2.9

3.2 Simulation Results for Drilling Operation

Figure 4 shows the simulated wellbore temperature profiles during drilling 12-1/4 in. hole section from 2500 to 3000 m. In this section, the formation temperatures are below the critical temperature of drilling fluid and its profile represents typical conventional high temperature geothermal field. The bottomhole temperature does not exceed approximately 200°C in static drilling condition. This result explains that conventional high temperature geothermal wells can be drilled by use of conventional drilling technologies, equipment, and materials with adequate surface mud cooling systems. As for drilling fluid, weighted mud that has some solid content and viscosity, is more effective for downhole cooling than water because of the differences in their thermal properties.

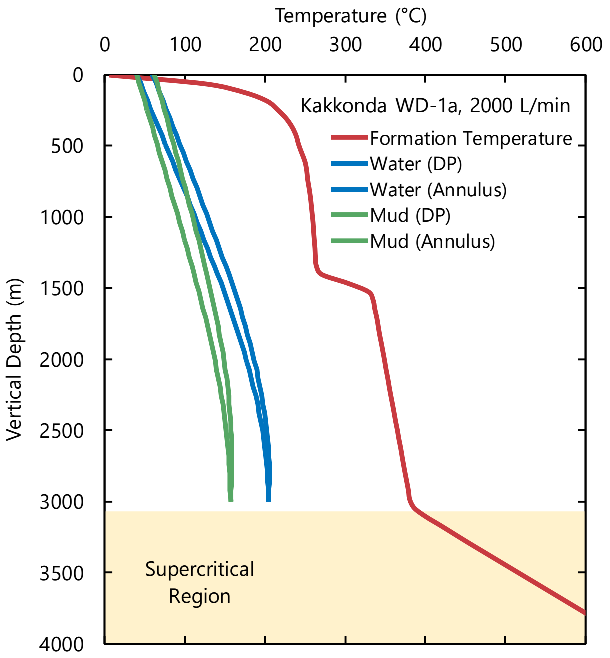

Figure 4: Simulated wellbore temperature profiles during drilling 12-1/4 in. hole section from 2500 to 3000 m.

Figure 5 shows the simulated wellbore temperature profiles during drilling 8-1/2 in. hole section from 3000 to 3500 m. This hole section is drilled through the formation in supercritical condition. At the pump rate of standard 2000 L/m, the bottomhole temperature exceeds 250°C, resulting in difficult drilling operations with conventional drilling equipment and materials. By increasing the pump rate to 3000 L/min, bottomhole temperature can be lowered to approximately 200°C. Mud circulation and hydraulics design may be challenging in drilling this hole section.

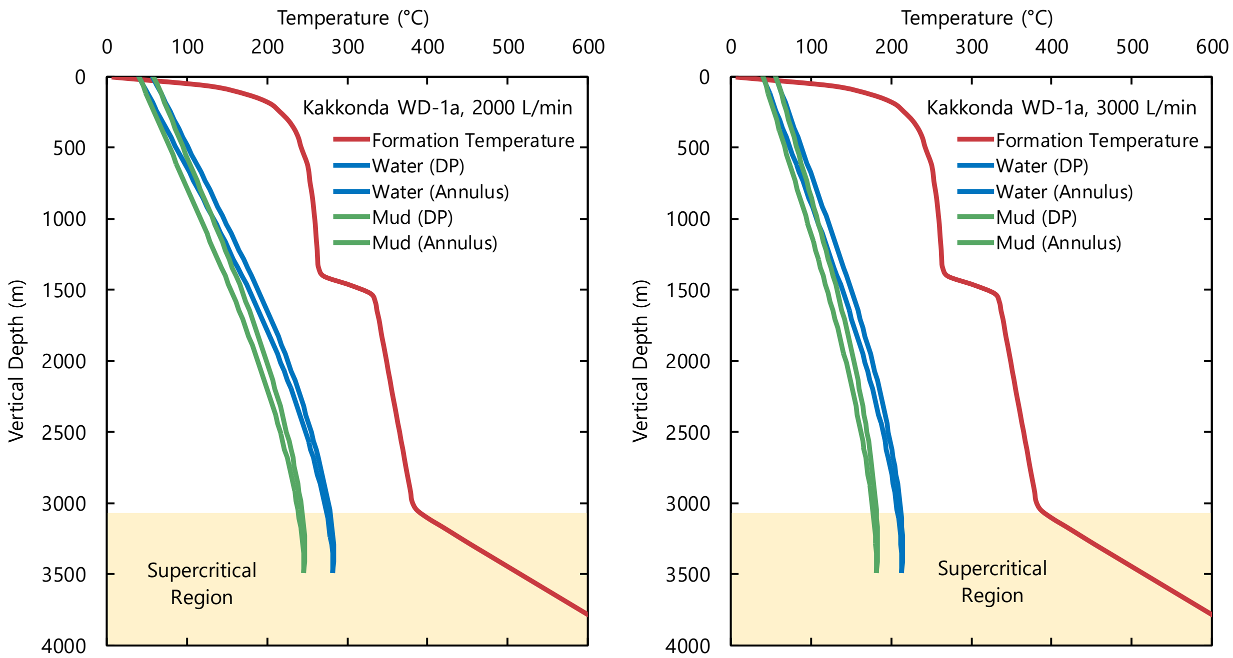

Figure 5: Simulated wellbore temperature profiles during drilling 8-1/2 in. hole section from 3000 to 3500 m. (left: pump rate is 2000 L/min, right: pump rate is 3000 L/min)

Figure 6 shows the simulated wellbore temperature profiles during drilling 8-1/2 in. hole section from 3500 to TD 4000 m. The situation is similar to the actual drilling condition of past Kakkonda WD-1a well. The bottomhole temperature in drilling with water exceeds critical temperatures while the bottomhole temperature with mud is approximately 350°C. Because there are no water base muds or drilling additives which resist temperatures above 300°C as shown in Table 2, water is the first and may be the only choice for drilling fluid during drilling this section. However, from the aspect of effects on bottomhole cooling, weighted mud may be considered as a drilling fluid instead of water. Moreover, the bottomhole temperature still exceeds 250°C even at the higher pump rates of 3000 L/min. Emerging technologies should be developed for deep supercritical geothermal drilling.

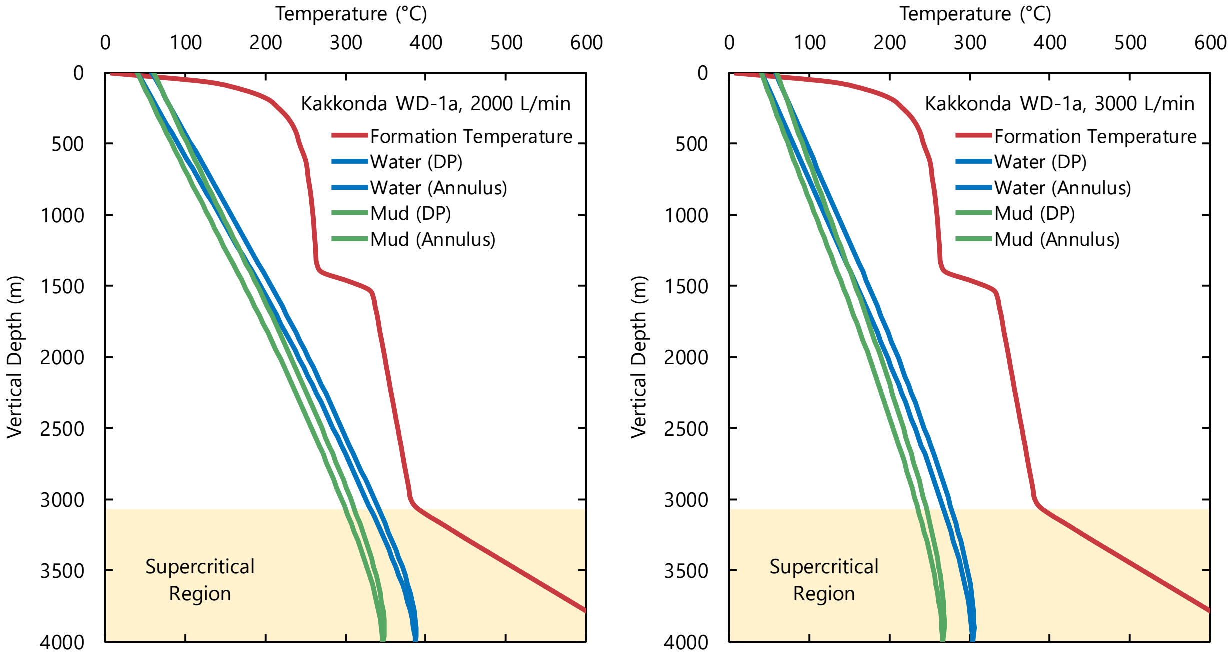

Figure 6: Simulated wellbore temperature profiles during drilling 8-1/2 in. hole section from 3500 to TD 4000 m. (left: pump rate is 2000 L/min, right: pump rate is 3000 L/min)

Figure 7 shows the simulated wellbore temperature profiles during drilling 8-1/2 in. hole section from 3000 to 3500 m for the case with a moderate geothermal gradient in a supercritical region. The geothermal gradient is approximately 3°C/100m. In this case, the bottomhole temperature can be maintained below 250°C even with water as a drilling fluid. Deep supercritical geothermal drilling is especially harsh without the difference of temperature profile or geothermal gradient in the supercritical formation.

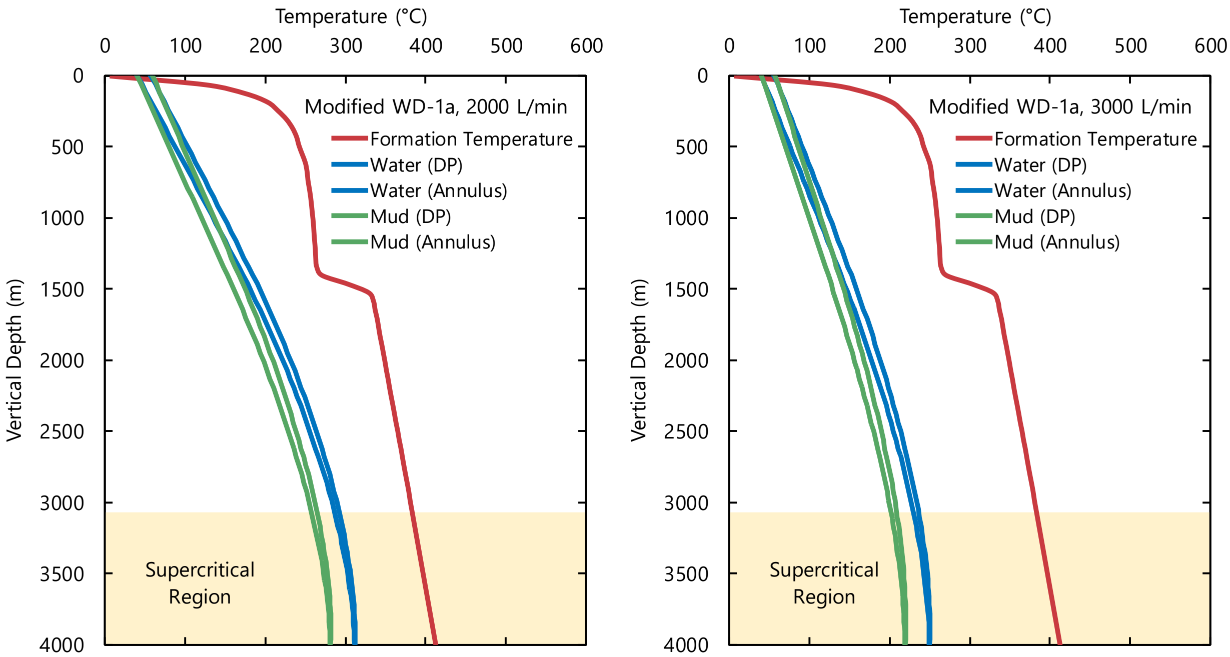

Figure 7: Simulated wellbore temperature profiles during drilling 8-1/2 in. hole section from 3000 to 3500 m for the case with a moderate geothermal gradient in supercritical region. (left: pump rate is 2000 L/min, right: pump rate is 3000 L/min)

3.3 Simulation Results for Cementing Operation

Figures 8 through 10 show the cement column temperature profiles during cementing 20 in., 13-3/8 in. and 9-5/8 in. casings assuming the thickening time of cement is 1 hour, 6 hours, and 12 hours respectively. It was assumed that sufficient circulation was conducted for bottomhole cooling before pumping cement slurry into the casing string. In the 13-3/8 in. and 9-5/8 in. casing sections, there is a sharp increase in cement temperature at the top of the cement column because of the differences of borehole geometries. Moreover, form these graphs, it can be seen that in all cases of the thickening time, the cement column temperature rise is the largest from the start of wait on cement (WOC) to 3 hours later, then gradually approaches the undisturbed formation temperature with time elapsed.

Further, the temperature rise is more rapid in the case of short thickening time than long thickening time. In the 20 in. casing section, when the thickening time is set to 1 hour, 6 hours and 12 hours, the temperature rises after 12 hours from the start of WOC are 125°C, 123°C and 120°C respectively. Similarly, in 13-3/8 in. casing section, the temperature rises after 12 hours from the start of WOC is 108°C (in the case of thickening time is 1 hour), 106°C (in the case of thickening time is 6 hours) and 102°C (in the case of thickening time is 12 hours). Additionally, in 9-5/8 in. casing section, the temperature rises after 12 hours from the start of WOC is 107°C (in the case of thickening time is 1 hour), 104°C (in the case of thickening time is 6 hours) and 101°C (in the case of thickening time is 12 hours). It is because, cement slurry with short thickening time has a steeper increase in the thermal conductivity and decrease in the specific heat capacity than cement slurry with long thickening time. This can also be seen in **Figure 11.** Figure 11 shows the cement temperature change over time for each thickening time at 3000 m depth where the bottom of the cement column is located. It can be observed that the cement column temperature rise in the early stage of WOC becomes more rapid as the thickening time becomes shorter.

From these results, slurry properties and the thickening time controls should be carefully designed according to the cementing schedule. As well, ordinary Portland cement or silica stabilized thermal cement cannot be used in a condition that the set cement is subject to temperatures above 400°C. Development of new thermal cements may be one of the critical issues for supercritical geothermal drilling and completion.

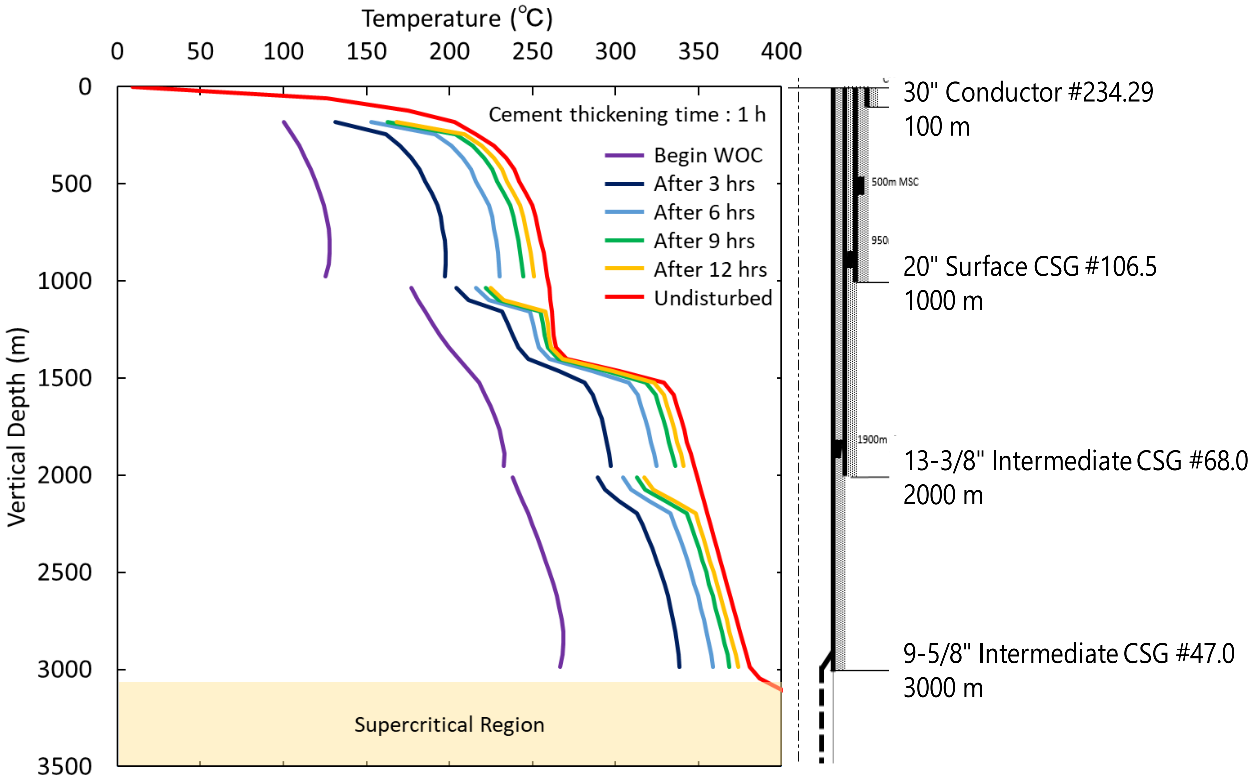

Figure 8: Simulated cement column temperature profiles during cementing 20 in. surface casing, 13-3/8 in. intermediate casing and 9-5/8 in. intermediate casing assuming the cement thickening time is 1 hour.

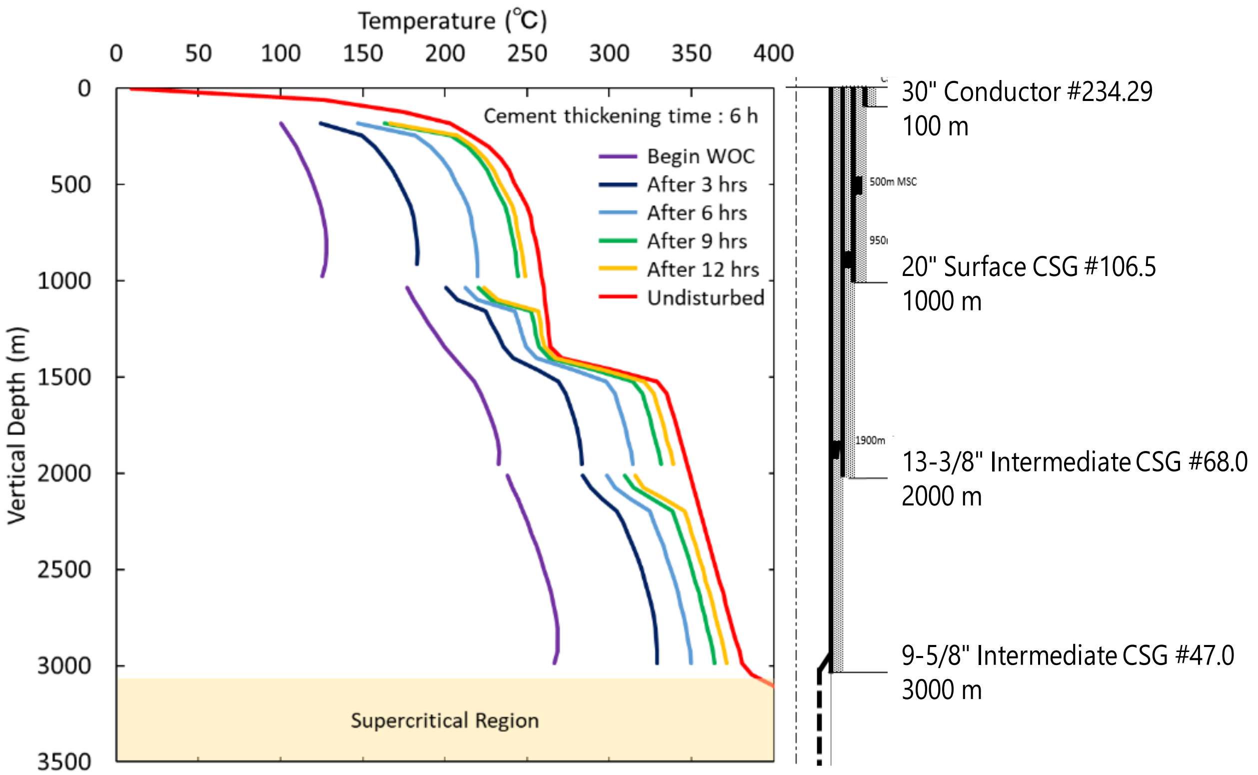

Figure 9: Simulated cement column temperature profiles during cementing 20 in. surface casing, 13-3/8 in. intermediate casing and 9-5/8 in. intermediate casing assuming the cement thickening time is 6 hours.

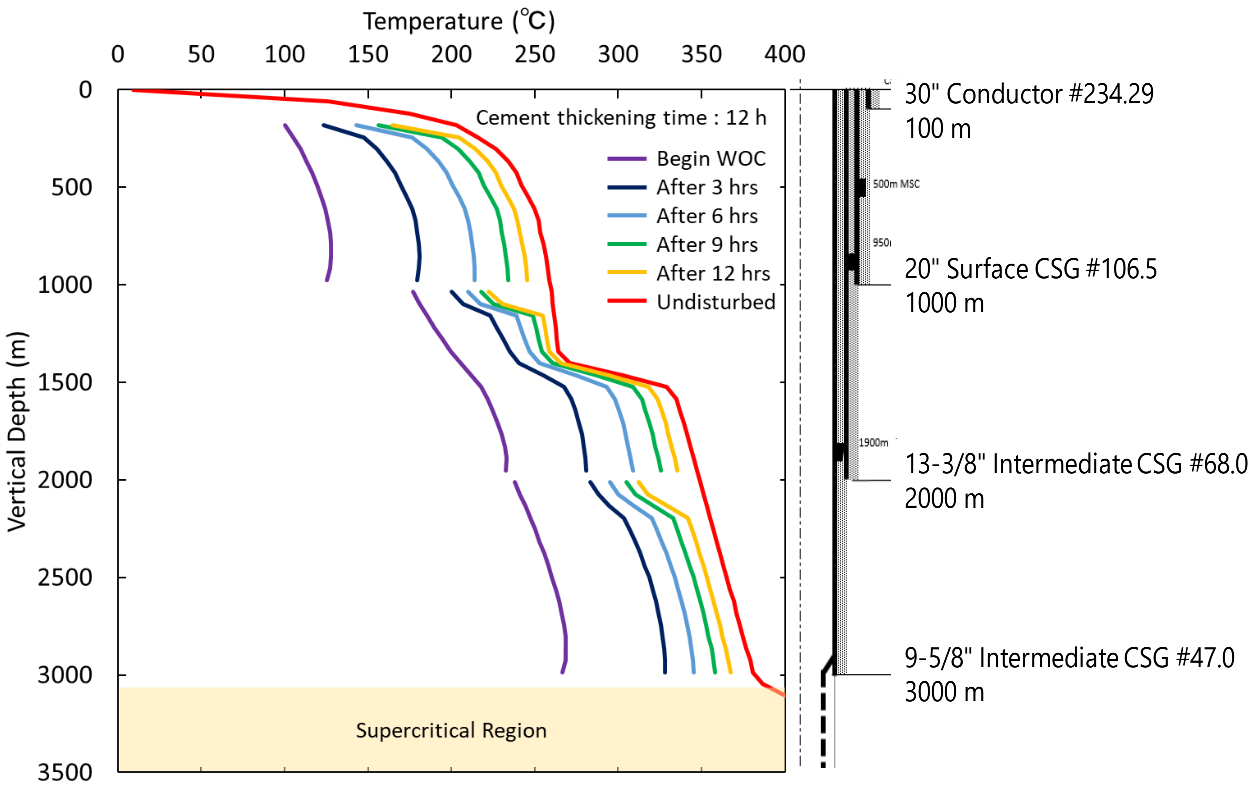

Figure 10: Simulated cement column temperature profiles during cementing 20 in. surface casing, 13-3/8 in. intermediate casing and 9-5/8 in. intermediate casing assuming the cement thickening time is 12 hours.

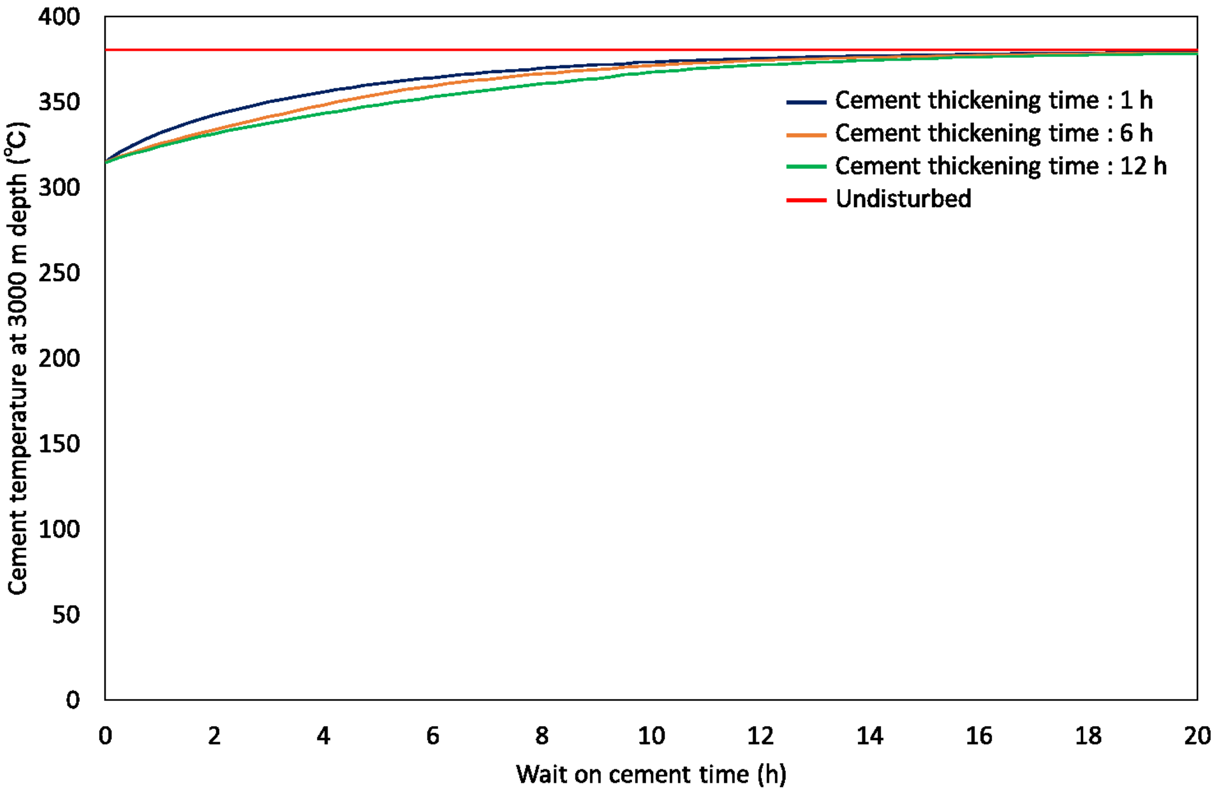

Figure 11: Simulated cement temperature change over time for each thickening time at 3000 m depth where is the bottom of the cement column.

4. CONCLUSIONS

In this study, downhole temperature profiles during drilling and cementing operations were simulated for a model well in which the formation temperature was based on the ultrahigh-temperature geothermal exploration well Kakkonda WD-1a.

- It was confirmed that a conventional high temperature geothermal well can be drilled by use of conventional drilling technologies, equipment, and materials with adequate surface mud cooling systems.
- For drilling relatively shallow supercritical geothermal formation, bottomhole cooling can be managed, but mud circulation and hydraulic design may be challenging.
- Deep supercritical geothermal drilling is especially harsh even without including the effects of steep temperature profiles or geothermal gradients in the supercritical formation. Emerging technologies should be developed for deep supercritical geothermal drilling.
- Development of new thermal cement may be one of the critical issues for supercritical geothermal drilling and completion as well as cement slurry properties, and as such, the thickening time controls should be carefully designed.
- For the design of supercritical geothermal drilling and cementing operations, further development of wellbore thermal simulators that can fully support supercritical geothermal conditions is of great importance.

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