

A Wellbore Hydrothermal Simulation Technology Applicable to Supercritical Conditions

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ABSTRACT

Drilling simulations under supercritical geothermal conditions have been extremely limited due to the lack of reliable thermal–hydraulic models applicable to ultra-high temperature and pressure environments. In this study, we developed GEOTEMPSC, an advanced wellbore hydrothermal simulator capable of handling supercritical fluids, by integrating the IAPWS-97 supercritical water and steam property formulation into the established GEOTEMP2 code.

Two representative reservoir scenarios with distinct pressure–temperature gradients were assumed, and drilling operations for a 5,000m-deep vertical well, including casing and cementing processes, were simulated. The results demonstrate that even under continuous mud circulation, the cooling effect around the wellbore is confined to only a few meters, and bottom-hole temperatures exceed 270 °C and 390 °C in the two cases, respectively. These findings highlight the fundamental thermal challenges associated with supercritical geothermal drilling and provide quantitative insights for the design of future drilling operations.

1. INTRODUCTION

The geological structure of the Japanese archipelago, originating from subduction zones, provides abundant high-temperature geothermal resources. In addition to conventional geothermal power generation, increasing attention is being directed toward the utilization of supercritical geothermal resources characterized by extremely high temperatures and pressures. Supercritical geothermal systems are considered capable of supplying energy on the terawatt scale and may offer solutions to challenges faced by existing geothermal technologies, such as regional dependency, sustainability, scaling, and induced seismicity.

The development of supercritical geothermal resources critically depends on drilling technologies capable of operating under extreme thermal and mechanical conditions. Among various technical challenges, wellbore thermal management during drilling is one of the most decisive factors, as excessive temperatures directly affect drilling tools, drilling fluids, and casing integrity.

Conventional wellbore thermal simulators have been widely used for geothermal drilling analysis; however, their applicability is generally limited to subcritical conditions because they do not adequately account for supercritical fluid properties. To address this limitation, this study focuses on the development of an advanced wellbore hydrothermal simulator that incorporates supercritical thermophysical properties and applies it to representative deep-drilling scenarios. The objective is to quantitatively evaluate wellbore temperature behavior and cooling effectiveness during drilling under supercritical conditions.

2. OVERVIEW OF GEOTEMP2

GEOTEMP2, developed by Mondy and Duda (1984) at Sandia National Laboratories (USA), is an open-source simulator designed to model wellbore temperature during drilling operations. The system enables the input of actual well data, including casing specifications, time-dependent mud circulation rates, and measured inlet mud temperatures.

The computational framework employs a cylindrical coordinate system and applies Fourier’s heat conduction equation to represent horizontal heat transfer between discretized cells. The heat transfer model incorporates three primary components:

- Wellbore fluid (drilling mud)
- Formation
- Casing cement between the fluid and formation

For the wellbore fluid, vertical heat transport driven by fluid flow is modeled, whereas in the formation, both horizontal and vertical heat transfer processes are considered. These thermal interactions are analyzed using a finite difference approach combined with iterative calculations to determine the temperature distribution within the wellbore and the surrounding formation. Figure 1 illustrates the calculation flow and concept of wellbore drilling in GEOTEMP2 (Mondy and Duda, 1984).

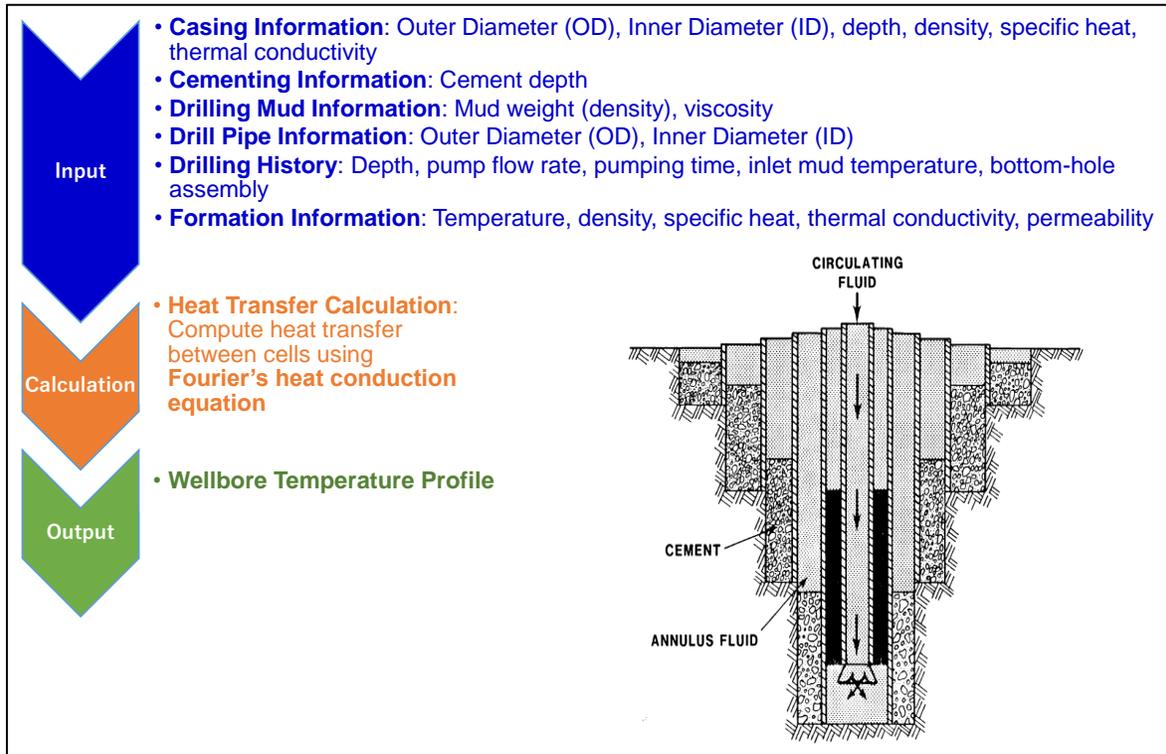


Figure 1: Calculation Steps and Concept of Wellbore Drilling in GEOTEMP2

3. DEVELOPMENT HISTORY AND IMPROVEMENTS OF THE GEOTEMP2

This section outlines the development history and subsequent enhancements of the GEOTEMP2 program.

- 1991–1995: Added functionality to enable calculations that more closely represent actual drilling operations by incorporating fluid movement through a permeable formation, calculating heat transfer due to convection within the formation and temperature changes caused by lost circulation (GEOTEMP3).
- 1996–1997: Added functionality to estimate formation equilibrium temperature through inverse analysis using actual inlet and outlet mud temperature data during drilling and bottom-hole temperature data from MWD (MWDTEMP2).

This work was carried out as part of the NEDO R&D project entitled “Development of the MWD System for Geothermal Wells.”

- 2011–2013: Enhanced to support high-angle wells (GEOTEMP4).

This work was conducted as part of the Ministry of the Environment, Government of Japan R&D project entitled “Control System for Drilling Geothermal Wells at High Angles of Deviation in National Parks.”

- 2015–2017: Added a new supercritical calculation module using the IAPWS97 formulation (Cooper and Dooley,2007) to handle supercritical fluids (GEOTEMPSC).

This work was conducted as part of the NEDO Advanced Research Program for Energy and Environmental Technologies entitled “Creation of Innovative Drilling and Completion Technologies for Realization of Supercritical Geothermal Development.”

4. CASE STUDY ASSUMING SUPERCRITICAL DRILLING

Table 1 presents the list of parameters used in case studies assuming supercritical drilling conditions. In this study, a vertical well with a depth of 5,000 m was assumed. Two scenarios were considered for bottom-hole conditions: **Case 1** (373 °C, 29.6 MPa) and **Case 2** (793 °C, 23.6 MPa). The bottom-hole pressure for Case 2 is lower due to the lower fluid densities of the higher temperature fluid.

The final hole section diameter was set to 8-1/2". The rate of penetration was defined as 70 m/day for depths up to 1,000 m, 60 m/day for 1,000–2,400 m, 50 m/day for 2,400–3,500 m, and 40 m/day for depths exceeding 3,500 m. Circulation flow rates were specified as 2,700 L/min down to 2,400 m, 2,300 L/min for 2,400–3,500 m, and either 2,000 L/min or 3,000 L/min beyond 3,500 m. The inlet mud temperature was maintained at 50 °C down to 3,500 m and at 60 °C for greater depths. The inlet mud temperature and formation conditions were generally assumed to correspond to those from the Kakkonda deep well WD-1.

Table 1: List of Parameters for Case Studies Assuming Supercritical Drilling Conditions

Well Depth	5000m (vertical well)
Bottom-Hole Pressure and Temperature	[Case 1] Temperature:373°C, Pressure: 29.6MPa [Case 2] Temperature:793°C, Pressure: 23.6MPa
Hole Diameter	8-1/2" Bit (use of 5-1/2" Drill Pipe)
ROP	0~1000m : 70m/day, 1000~2400m : 60m/day, 2400~3500m : 50m/day, 3500~5000m : 40m/day
Pump Rate	0~2400m : 2700L/min, 2400~3500m : 2300L/min, 3500~5000m : 2000L/min, 3000L/min
Inlet Mud Temperature	0~3500m : 50°C 3500~5000m : 60°C
Rock Properties	Permeability: 1.0e-14 m ² Density: 2640 kg/m ³ Specific Heat: 1250 J/(kg·K) Thermal Conductivity: 3.5 W/(m·K)

4.1 Drilling Specifications

Figure 2 illustrates the drilling specifications applied in both supercritical drilling case studies.

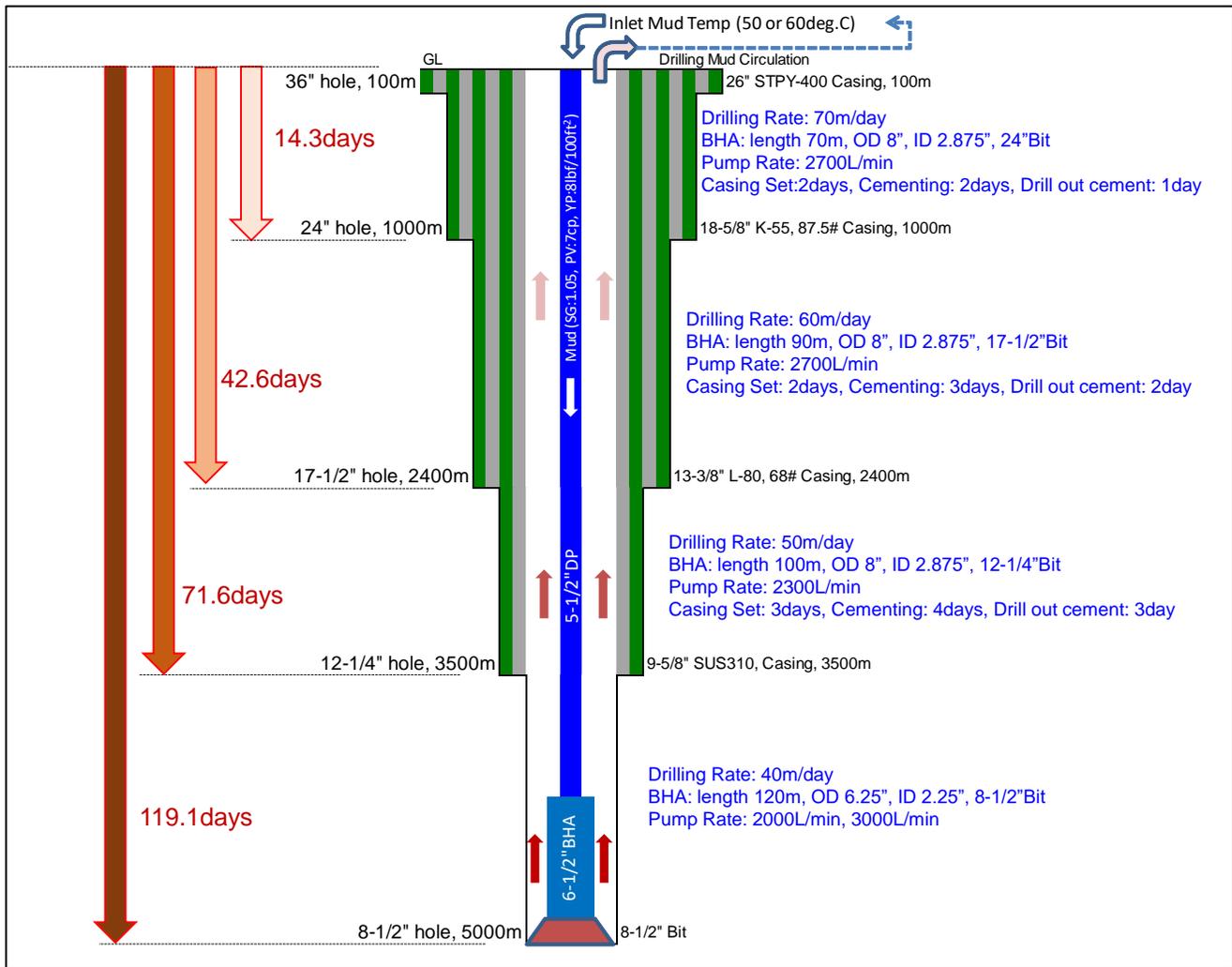


Figure 2: Drilling Specifications for Supercritical Drilling Case Studies

4.2 Assumed Drilling Schedule

Figure 3 illustrates the drilling schedule assumed in the simulation.

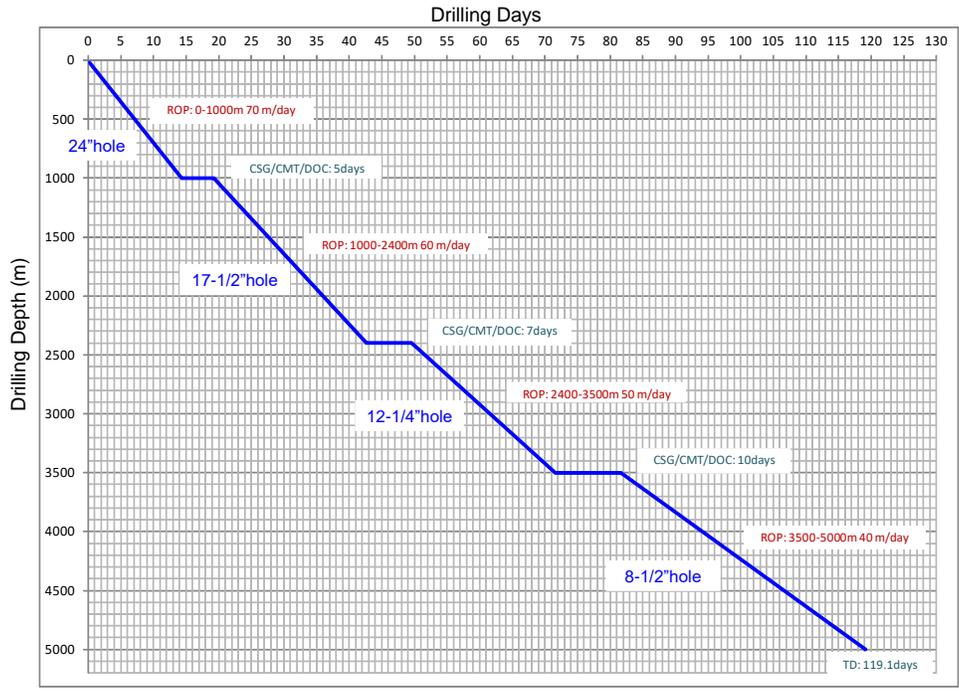


Figure 3: Assumed Drilling Schedule for Simulation

4.3 Initial Temperature and Pressure Distribution

Figure 4 illustrates the assumed formation temperature and pressure profiles for the two case studies. Below the critical temperature, a boiling point for depth profile was assumed, with a linear temperature profile and hydrostatic pressures below this.

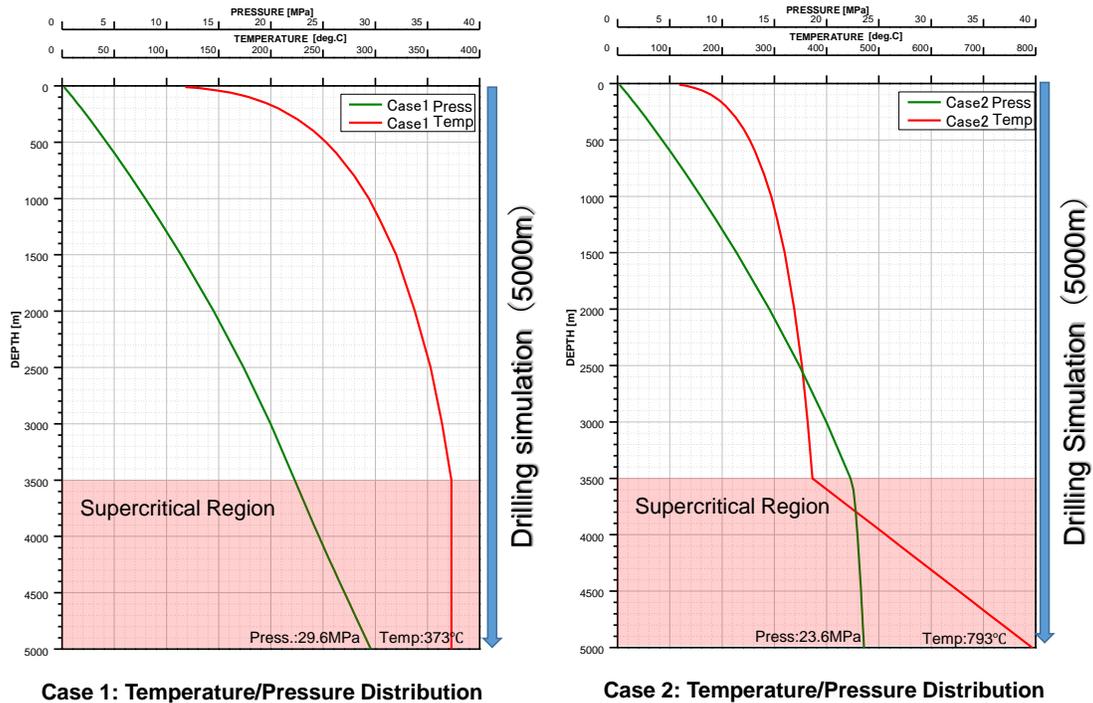


Figure 4: Formation Temperature and Pressure Profiles for Case 1 and Case 2

4.4 Simulation Model

Figure 5 shows the simulation model used in this study. The simulation model was configured with a vertical spacing of 20 m, 20 divisions in the circumferential direction, and 15 divisions in the radial direction, corresponding to a radial extent of 20 m.

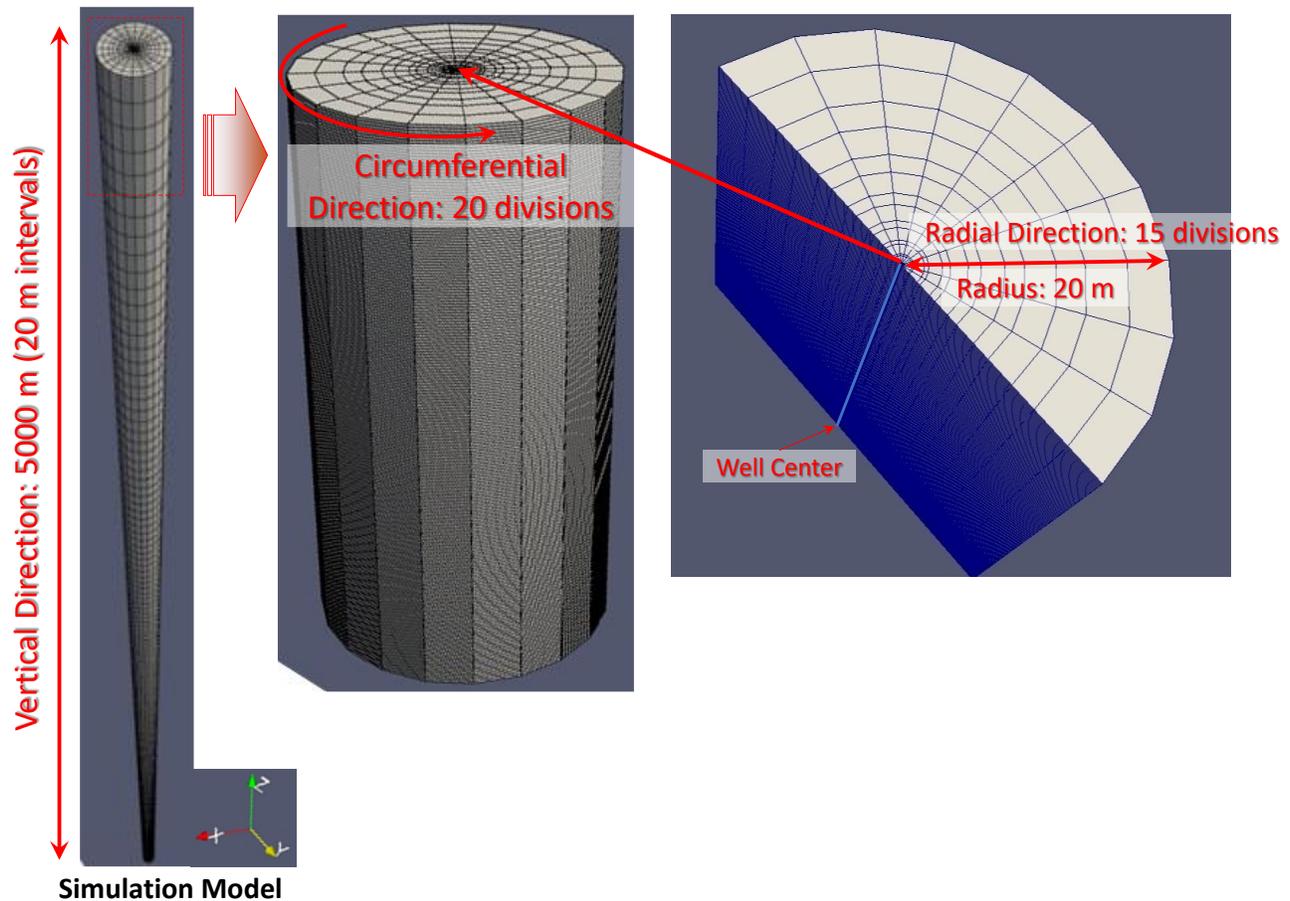


Figure 5: Simulation Model Configuration (Vertical and Radial Grid Layout)

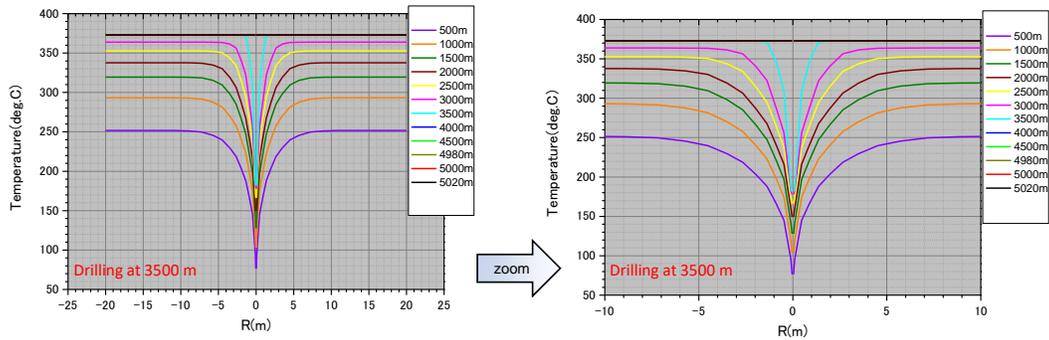
5. SIMULATION RESULTS

The results of the drilling simulations conducted using the assumed parameters for Case 1 and Case 2 are presented below.

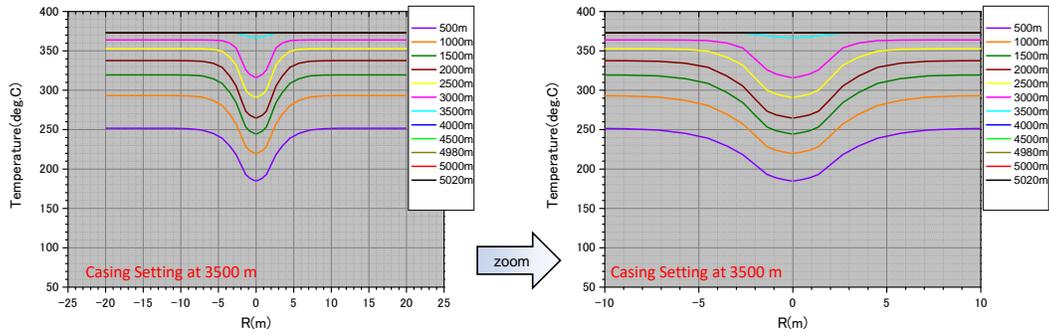
For Case 1, the temperature distribution along slice lines at various depths at days 71.6 and 74.6 when the casing is set() is presented in Figure 6 and Figure 7. The cooling effect inside the well is illustrated by showing the temperature distribution in the drill pipe and annulus during drilling at depths of 3,500 m and 5,000 m (Figure 8). Furthermore, Figure 9 compares the cooling effect at a depth of 5,000 m under different circulation flow rates. Note that below 3,500m the reservoir temperatures are constant.

For Case 2, the temperature distribution along slice lines at various depths is presented in Figure 10 and Figure 11. The cooling effect inside the well is illustrated by showing the temperature distribution in the drill pipe and annulus during drilling at depths of 3,500 m and 5,000 m (Figure 12). Furthermore, Figure 13 compares the cooling effect at a depth of 5,000 m under different circulation flow rates.

Also, Figure 14 shows the cooling effect inside the well during drilling for Case 1 and Case 2.

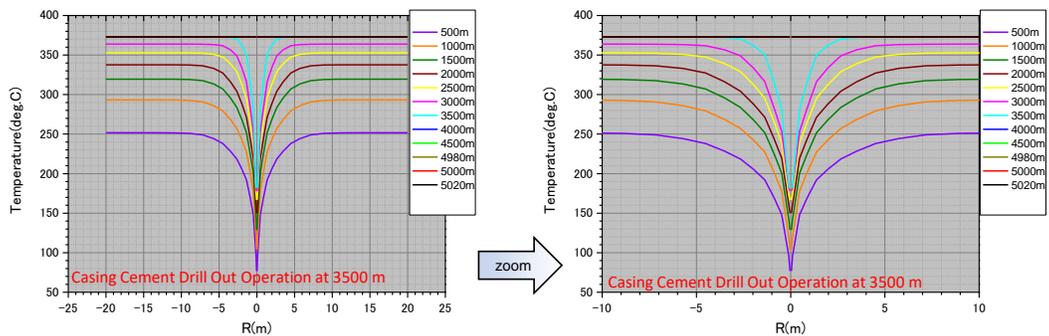


Temperature Profile on Slice Line (71.6 days, total well depth 3500 m)

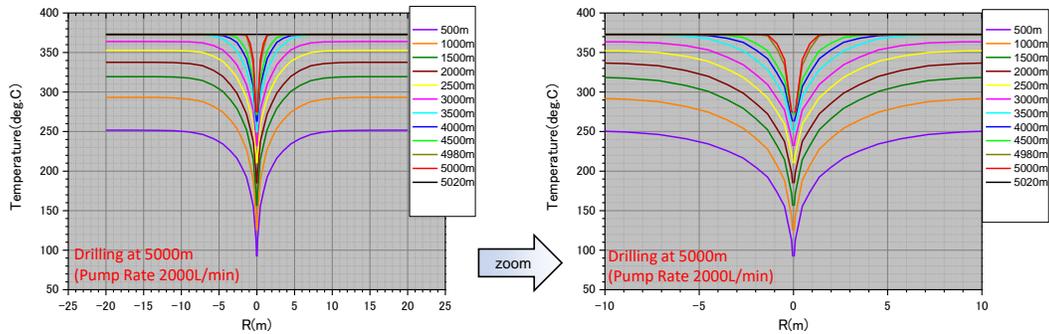


Temperature Profile on Slice Line (74.6 days, total well depth 3500 m)

Figure 6: Temperature Distribution During Drilling – Case 1 (71.6 and 74.6 Days)



Temperature Profile on Slice Line (81.6 days, total well depth 3500 m)



Temperature Profile on Slice Line (119.1 days, total well depth 5000 m)

Figure 7: Temperature Distribution During Drilling – Case 1 (81.6 and 119.1 Days)

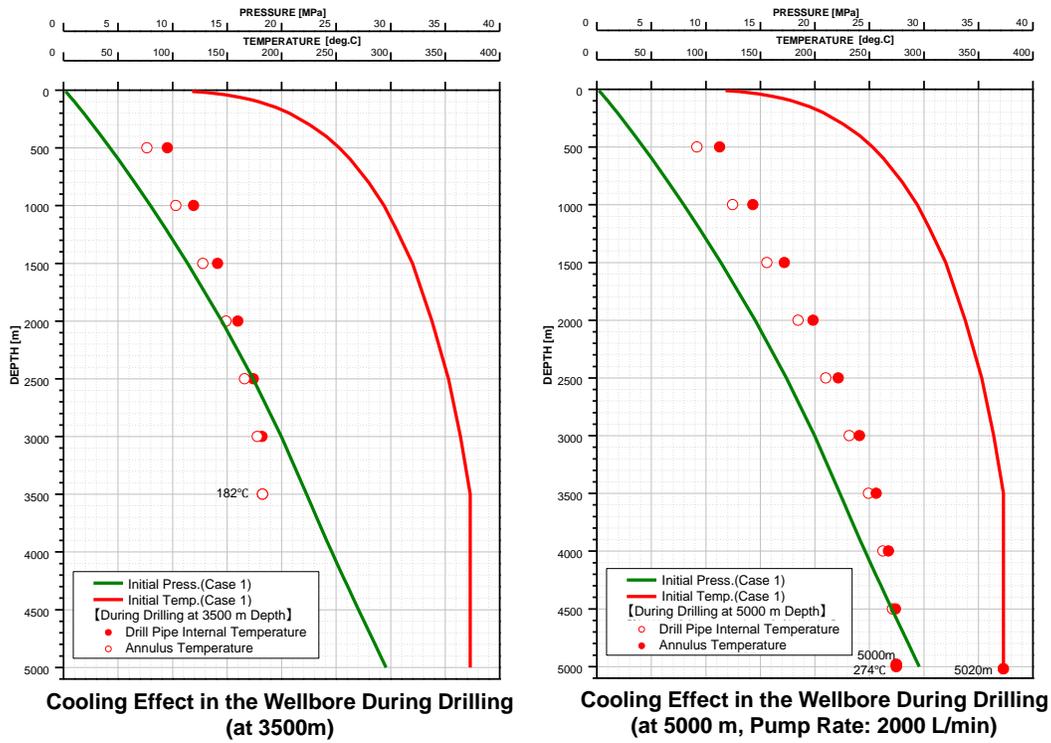


Figure 8: Wellbore Cooling Effect at Depths of 3,500 m and 5,000 m – Case 1

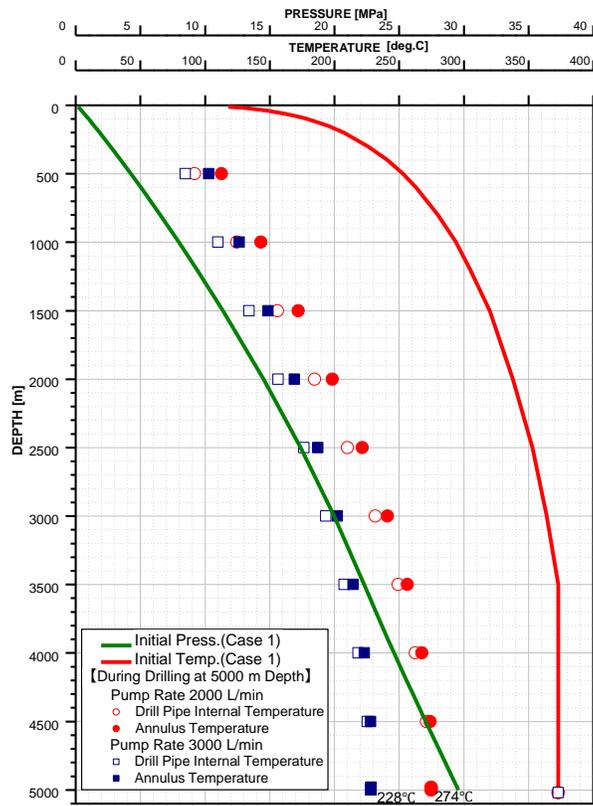
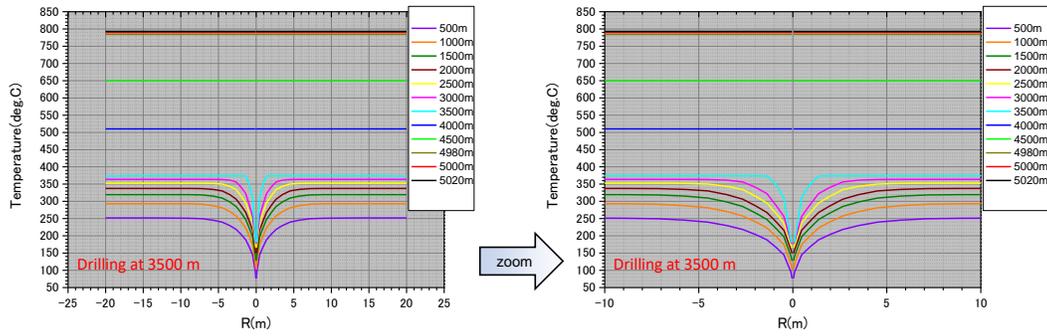
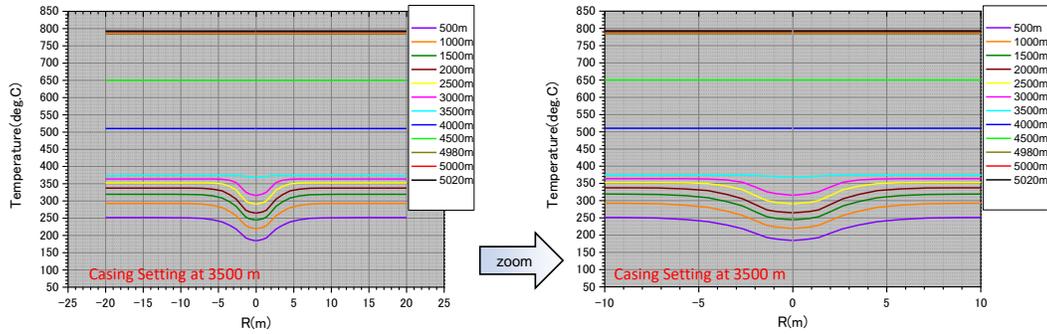


Figure 9: Comparison of Cooling Effects at 5,000 m Under Different Flow Rates – Case 1

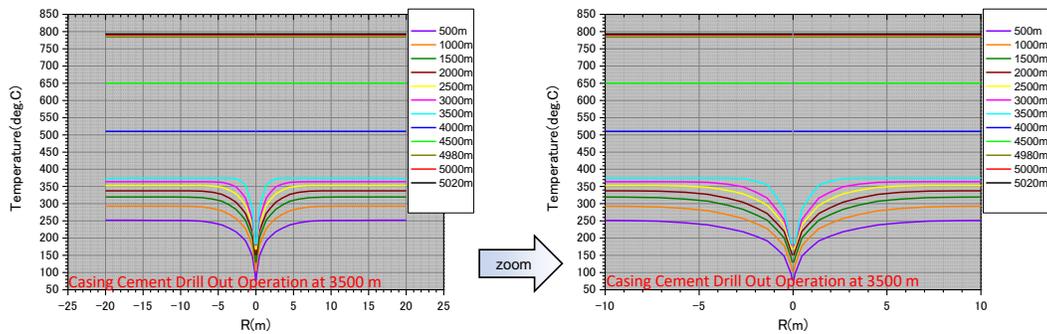


Temperature Profile on Slice Line (71.6 days, total well depth 3500 m)

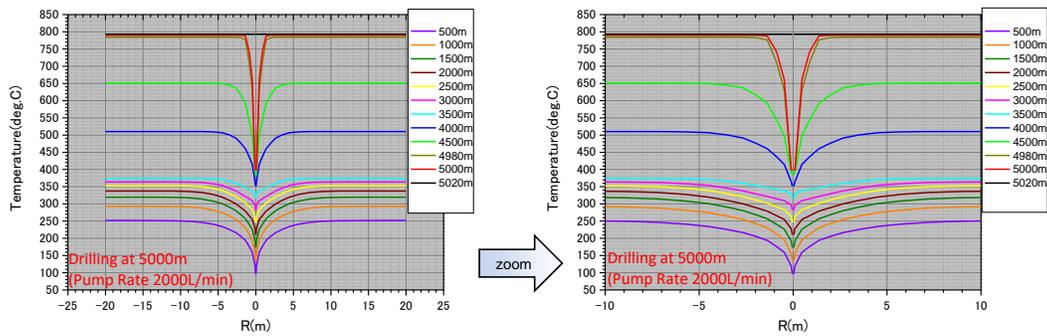


Temperature Profile on Slice Line (74.6 days, total well depth 3500 m)

Figure 10: Temperature Distribution During Drilling – Case 2 (71.6 and 74.6 Days)



Temperature Profile on Slice Line (81.6 days, total well depth 3500 m)



Temperature Profile on Slice Line (119.1 days, total well depth 5000 m)

Figure 11: Temperature Distribution During Drilling – Case 2 (81.6 and 119.1 Days)

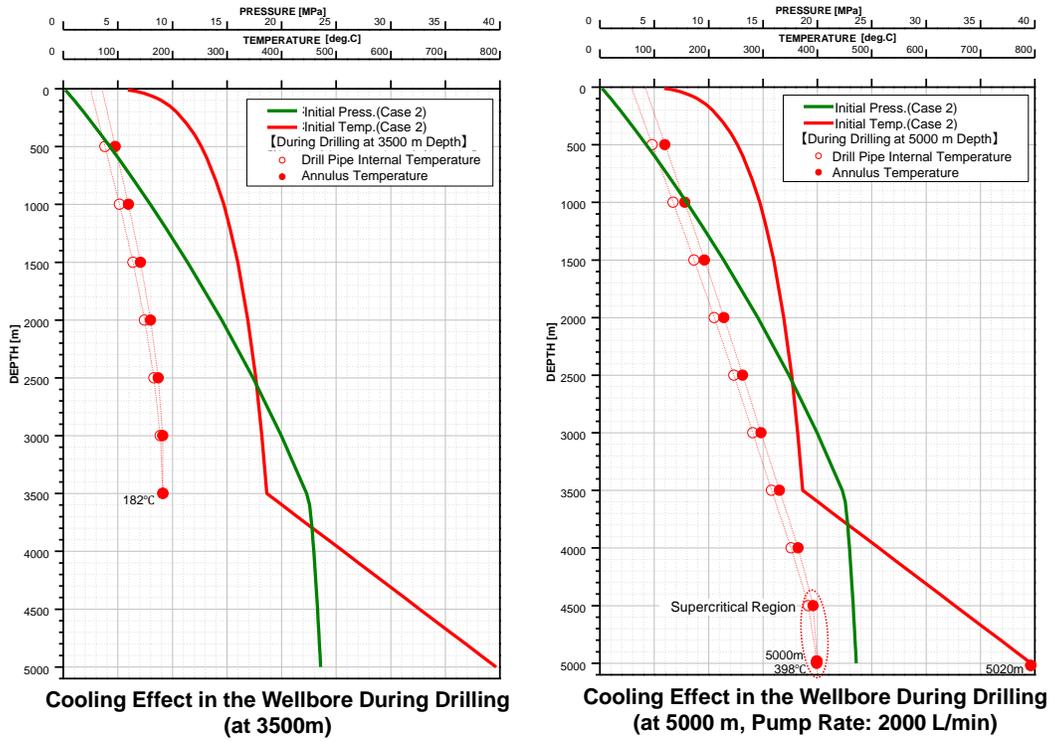
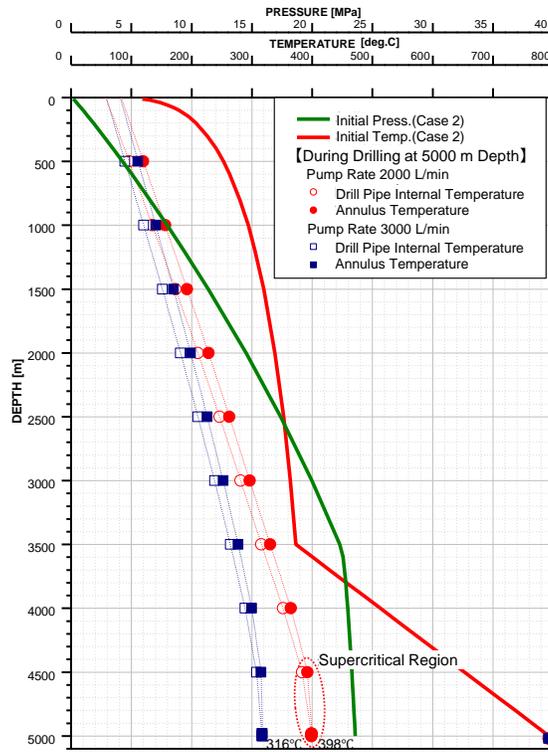


Figure 12: Wellbore Cooling Effect at Depths of 3,500 m and 5,000 m – Case 2



Cooling Effect in the Wellbore During Drilling (Case 2)

Figure 13: Comparison of Cooling Effects at 5,000 m Under Different Flow Rates – Case 2

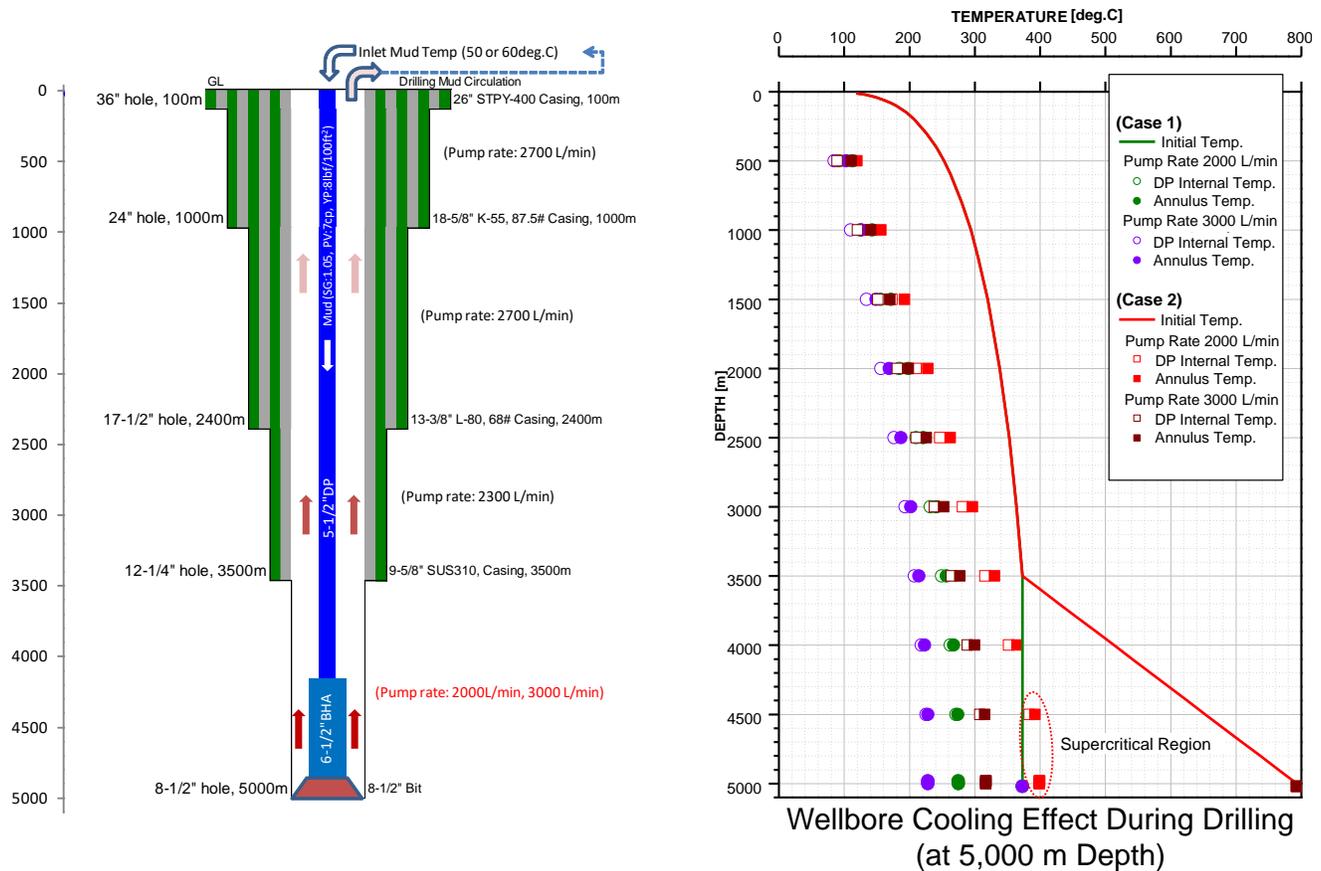


Figure 14: Comparison of Wellbore Cooling Effects for Case 1 and Case 2 (Flow Rates: 2,000 L/min and 3,000 L/min)

6. SUMMARY

The key insights derived from this study, along with the remaining challenges for future research, are outlined below.

6.1 Key Findings

Using the supercritical-capable wellbore hydrothermal simulator GEOTEMPSC, drilling simulations were performed for two representative deep geothermal scenarios. The results quantitatively demonstrate the inherent limitations of mud-circulation cooling under supercritical conditions and provide practical insights into temperature management strategies for future supercritical geothermal drilling projects. The main findings are as follows:

- The cooling effect near the wellbore during drilling was limited to only a few meters when drilling to a depth of 5,000 m with a circulation rate of 2,000 L/min (Cases 1 and 2).
- In Case 1, the bottom-hole temperature reached 182 °C at 3,500 m depth and 274 °C at 5,000 m depth (2,000 L/min).
- In Case 2, the bottom-hole temperature was 182 °C at 3,500 m depth and 398 °C at 5,000 m depth (2,000 L/min), indicating a supercritical condition.
- For both cases, temperatures exceeded 150 °C below 1,500 m even during continuous circulation.
- During casing operations (casing setting, cementing, and cement washing), temporary suspension of circulation resulted in rapid temperature recovery.
- Increasing the circulation rate from 2,000 L/min to 3,000 L/min during the final drilling stage produced a similar cooling range near the wellbore:
- In Case 1, the bottom-hole temperature at 5,000 m decreased to 228 °C at 3,000 L/min (compared to 274 °C at 2,000 L/min).
- In Case 2, the bottom-hole temperature decreased to 316 °C at 3,000 L/min (compared to 398 °C at 2,000 L/min).

6.2 Future Work

To enhance the efficiency of simulations, improvements to the simulator's user interface will be considered. Furthermore, if the drilling of a supercritical demonstration test well is planned in the future, preliminary simulations and comparative evaluations with actual drilling data will be conducted. These efforts will provide fundamental data for optimizing drilling technology and contribute to improving the accuracy of thermal-hydraulic calculations.

ACKNOWLEDGMENT

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REFERENCES

- Mondy, L. A. and Duda, L. E.: Advanced Wellbore Thermal Simulator GEOTEMP2 USER Manual, SANDIA REPORT, UC-66C. (1984).
- Cooper J.R., Dooley R.B.: Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam. Publication of the International Association for the Properties of Water and Steam, Lucerne, Switzerland, IAPWS97. (2007).