GRC Transactions, Vol. 41, 2017

Concept of Thermal-Shock Enhanced Drill Bit for Supercritical Geothermal Drilling

Shigemi Naganawa

Frontier Research Center for Energy and Resources, The University of Tokyo, Japan

Keywords

Innovative drilling method, supercritical geothermal systems, thermal-shock rock failure, Venturi effect, bottomhole cooling by depressurization

ABSTRACT

Supercritical geothermal systems are unconventional high-temperature geothermal systems in which the reservoir fluid exists in the supercritical condition in excess of 374°C and 22.1 MPa. For decades, utilization of these high-enthalpy supercritical geothermal resources has been pursued to improve the efficiency and capacity of geothermal power generation. However, to develop supercritical geothermal systems, technologies that efficiently and safely drill into the deep ductile formations where the temperature exceeds 400°C are required.

In this paper, development of a new innovative drilling tool, named the "thermal-shock enhanced drill bit," through computational fluid dynamics (CFD) simulations is presented. The drilling tool aims to generate a thermal-shock failure of rock by depressurization, boiling and cooling at the bottomhole, and to fracture or weaken the formation rock. The depressurization is achieved by the Venturi mechanism installed in a PDC bit. A preliminary simulation study demonstrated that the pressure reduction could be improved by further optimization of the bit design and configuration of the flow paths.

1. Introduction

Supercritical geothermal systems are unconventional high-temperature geothermal systems in which the reservoir fluid exists in the supercritical condition. Under the saline conditions of typical reservoir fluids, the critical point of pure water (374°C and 22.1 MPa) may shift to higher temperature and pressure. In the 1980s, supercritical conditions were discovered in deep geothermal drillings in the Larderello geothermal field, Italy and The Geysers geothermal field in the United States (Dobson et al., 2017). In 1995, the hottest geothermal exploration well then known, the Kakkonda WD-1a, was drilled in Japan. The formation temperature of this system was estimated to exceed 500°C. In the latest well of the Iceland Deep Drilling Project at the Reykjanes geothermal field, IDDP-2, completed only in January 2017, the measured bottomhole temperature was 427°C (Friðleifsson et al., 2017). For decades, utilization of these high-enthalpy supercritical geothermal resources has been pursued to improve the efficiency and capacity of geothermal power generation.

After the Great East Japan Earthquake and the subsequent Fukushima Nuclear Power Disaster in March of 2011, Japanese researchers proposed a new concept for engineered geothermal systems (EGSs) called the "Japan Beyond-Brittle Project (JBBP)" in which the reservoirs are created in ductile basement formations. The proposed project aims to overcome the known defects in conventional EGSs, and is expected to offer the following advantages: simpler control design for the reservoir, near-full recovery of injected water, sustainable energy production, potentially large-scale EGSs in the widely distributed ductile zones at relatively shallow depth in the tectonic belt, universal site-independent design/development/control methodologies, and suppression of induced/triggered earthquakes (Asanuma et al., 2012; Muraoka et al., 2014). Supercritical geothermal systems originated in the Japan Trench subduction zone (Figure 1) are estimated to contain slab-derived geothermal fluid, and might deliver terawatt-scale energy. Recently, Watanabe et al. (2017) reported high-enthalpy supercritical fluids trapped in the 375–500°C temperature formations. Potentially exploitable geothermal resources exist even in the nominally ductile crust of these formations (Watanabe et al., 2017). To develop supercritical geothermal systems, however, technologies that efficiently and safely drill into the deep ductile formations where the temperature exceeds 400°C are required. Wells with sufficient integrity for long-term power generation are also indispensable.

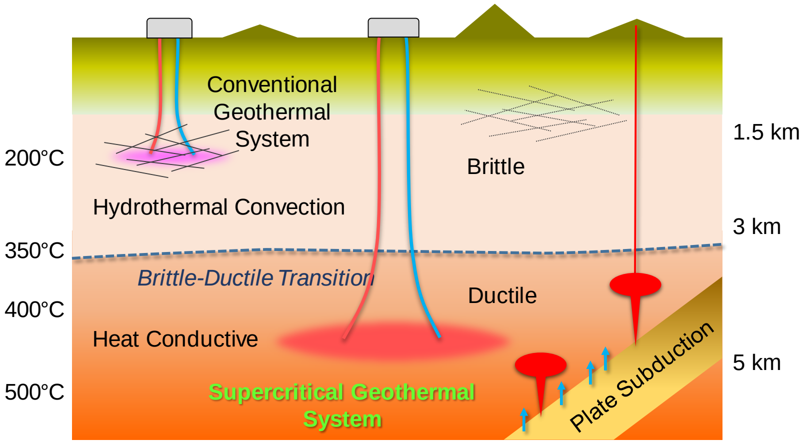

Figure 1: Supercritical geothermal system containing slab-derived geothermal fluid originated in the Japan Trench subduction zone.

2. Innovative Drilling Technologies for High-Temperature and Hard Formations

Depending on their structure and drilling mechanism, conventional rotary drilling bits are classified as roller bits or fixed cutter bits. The most popular and widely used bits are milled tooth bits, tungsten carbide insert bits, and polycrystalline diamond compact (PDC) bits. PDC bits generally provide higher rate of penetration but are more expensive than roller bits. With no elastomer-seal rolling components, PDC bits offer long life and high heat resistance. Although these properties are advantageous for geothermal drilling, PDC bits demonstrate poor performance when drilling hard, abrasive, and inhomogeneous volcanic formations in typical geothermal fields. Therefore, hard formations in geothermal well drilling are usually drilled with insert bits.

In the 1960s, various ideas or concepts of novel drilling systems were presented aiming to replace conventional rotary drilling bits (Maurer, 1966). Whereas conventional drill bits operate by a mechanical rock breaking mechanism, these novel drilling systems employ non-mechanical rock failure mechanisms, including non-contact mechanisms such as thermal spalling, melting, electric, laser, microwave, and nuclear energy techniques. Among these innovative drilling systems, laser drilling have been revived since 2000, and was researched and developed by institutes such as the Colorado School of Mines and the Argonne National Laboratory (Parker et al., 2003). Funded by the US Department of Energy, Ezzedine et al. (2015) presented a prototype laser-PDC hybrid bit. A laser-drilling research project was also conducted in Japan (Kobayashi et al., 2009). Other recent ongoing studies on novel or innovative drilling technologies, mostly conducted in Europe, include hydrothermal spalling (Potter et al., 2010; Kant et al., 2016), plasma (Kocis et al., 2013), laser jet (Jamali et al., 2016), flame jet (Meier and von Rohr, 2016), and electric impulses (Lehr et al., 2016). However, these drilling systems require high power generation from large and heavy equipment that is difficult to install in downhole tools. Consequently, none of these novel drilling systems have become commercially viable.

Tsuchiya et al. (2012) proposed a new concept of well stimulation method, called decompression drilling, which creates fracture clouds by exploiting the rock failure phenomena induced by thermal shock or thermal stress. The thermal shock are generated by decompression, boiling and consequent rapid cooling of the completion fluid in the wellbore. Their research group at Tohoku University has conducted subsequent experiments on hydrothermal rock failure in which a granite core sample with a small internal borehole was placed in a water-saturated supercritical condition, and rapidly depressurized to atmospheric conditions. During the rapid pressure drop of approximately 42 MPa in the high-pressure cell, the temperature rapidly reduced by approximately 130°C because of the latent heat of vaporization of water (Hirano et al., 2015; Naganawa et al., 2017). Moreover, X-ray computed tomography images revealed a considerable number of thermal-stress microfractures generated by the thermal shock.

An idea of exploiting thermal shock or thermal stress in the drilling of hard rock formations was already presented over 60 years ago (Blood, 1951). The drilling mechanism of this system was designed to alternately heat and cool the hard formations in oil well drilling operations, eventually fracturing the hard formations. The downhole drilling equipment constituted a fishtail bit with drilling fluid-circulation nozzles, passageways with nozzles for combustible gases, e.g., oxygen and acetylene, and an ignition mechanism that alternately cooled and heated the bottomhole. However, this system may require special and probably expensive drill pipes to introduce the combustible gases to the downhole, and an additional mechanism to prevent downhole fires. Considering the total energy efficiency and drilling cost, this thermal-shock drilling system seems to offer few advantages.

3. Thermal-Shock Enhanced Drill Bit

3.1 Concept of Thermal-Shock Enhanced Drill Bit using the Venturi Effect

According to the experimental results of hydrothermal rock failure obtained by Tohoku University, if the drilling or completion fluid can be effectively depressurized locally at the bottomhole, the rapid cooling can fracture or weaken the formation rock in deep boreholes, where the pressure and temperature conditions are high. The drillability of hard rocks encountered in ductile and supercritical geothermal formations might be improved. Based on the above hypothesis, our group proposed a new innovative drilling method that locally depressurizes the rock at the bottomhole by the Venturi effect, thereby inducing thermal-shock failure of the rock (Naganawa et al., 2017).

As illustrated in Figure 2, the Venturi effect reduces the pressure in the choke section of the flow path. The volume flow rate of the fluid Q is related to the pressure reduction through the Venturi nozzle Δp as follows:

$$\frac{Q}{A_1} = v_1 = C\sqrt{\frac{2}{\rho}\cdot\frac{\Delta p}{\left(\frac{A_1}{A_2}\right)^2 - 1}}, \tag{1}$$

where A_1 and A_2 are the cross-sectional areas at the inlet and choke section respectively, v_1 is the drilling fluid velocity at the inlet, ρ is the density of the drilling fluid, and C is the discharge coefficient of energy loss, which generally ranges from 0.96 to 0.99. Rearranging Eq. (1) the pressure reduction by the Venturi effect is obtained as

$$\Delta p = \frac{\rho v_1^2}{2C^2}\left[\left(\frac{A_1}{A_2}\right)^2 - 1\right] = \frac{\rho v_1^2}{2C^2}\left[\left(\frac{d_1}{d_2}\right)^4 - 1\right], \tag{2}$$

where d_1 and d_2 are the diameters at the inlet and choke section respectively.

The Venturi effect is commercially exploited in downhole tools such as vacuum-type junk basket fishing tools and hydraulic jet pumps for artificial oil production. The proposed tool combines a Venturi mechanism with a PDC bit. The Venturi-PDC hybrid bit, named “thermal-shock enhanced drill bit,” is shown in Figure 3. There are two drilling modes; “drilling mode,” which uses a conventional PDC bit drilling mechanism, and “depressurizing mode,” which reduces the rock strength by the Venturi depressurizing mechanism. In the depressurizing mode, the pressure is reduced downstream of the Venturi nozzle, thus vacuuming the drilling fluid from the suction line that leads the center suction port. The fluid flow through the Venturi nozzle is diverted to the reverse circulation line, establishing a reverse circulation of the drilling fluid beneath the bit. Thus, the depressurized zone is considered to locate just below the bit.

The two modes can be alternately switched by operating the sliding sleeve, which opens and closes the port valves. The port switching mechanism can be realized by a commercially available innovative cam mechanism activated by mud pump flow rates (Lima et al., 2014), or by sliding sleeve installed with conventional drop ball activation system. The latter are widely used in multistage hydraulic-fracturing tools for shale oil and gas development.

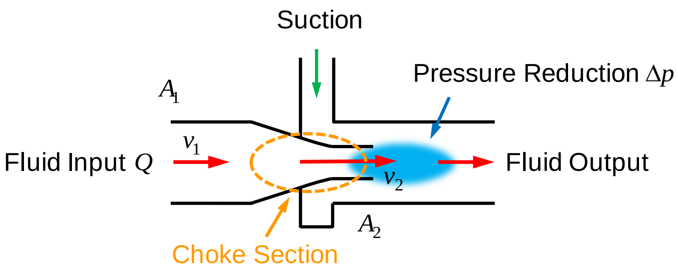

Figure 2: Principle of the Venturi effect.

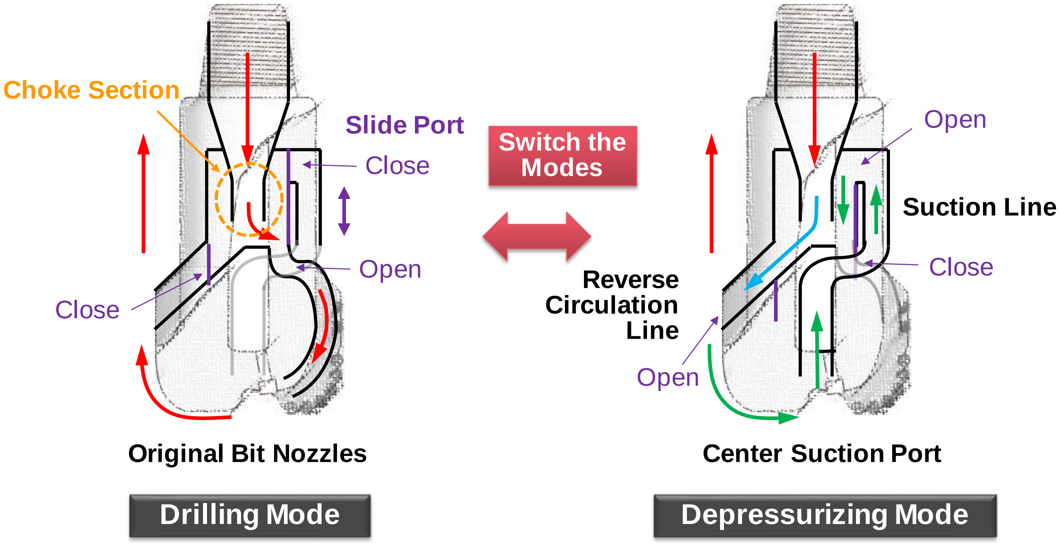

Figure 3: Concept of the thermal-shock enhanced drill bit.

3.2 Preliminary Simulation Study of Venturi Depressurization

Before developing the thermal-shock enhanced drill bit, we must estimate the required pressure reduction at the bottomhole for boiling and vaporizing the drilling fluid. Here, the target temperature and pressure profile of supercritical geothermal drilling is assumed to follow the boiling point at the depth condition above the critical point of pure water, which corresponds to an approximately depth of 3500 m (see Figure 4). Below 3500 m, the formation pressure depends on the density of the supercritical formation fluid and the formation temperature elevates in a heat conductive manner with a certain geothermal gradient.

Supposing the above formation temperature, the bottomhole temperature when drilling around transition depth to the supercritical condition was roughly estimated by the wellbore thermal simulator “GEOTEMP2” (Mondy and Duda, 1984). The result is shown in Figure 5. Even when the inlet temperature of the drilling fluid at the surface is sufficiently low, the bottomhole temperature during drilling might exceed 200°C. Given the temperature limitations of the applied downhole tools and materials, the downhole should be cooled to below 200°C. Conversely, a relatively high bottomhole temperature is advantageous for thermal-shock enhanced drilling. From the pressure-temperature diagram of Figure 6, a temperature reduction of 60°C requires a pressure reduction of at least 20 MPa.

The next consideration is whether the Venturi mechanism achieves sufficient pressure reduction below the bit. Although the pressure reduction by the Venturi effect can be calculated from Eq. (2), the actual pressure reduction should be estimated through more accurate flow simulations. As a preliminary study, the steady-state flow through the Venturi depressurization mechanism implemented inside the PDC bit was simulated by ANSYS® Fluent CFD. Figure 7 shows the 8-1/2″-diameter PDC bit model used in this study. Considering the model dimensions, a simple Venturi mechanism was implemented inside the bit. A simplified model of the flow area inside and around the thermal-shock enhanced drill bit was combined with a borehole wall model, as shown in Figure 8. This simple model has one suction line and one reverse-circulation line.

The Venturi nozzle diameter was varied as 1/2″ (12.7 mm) and 1/4″ (6.35 mm), and the drilling fluid velocity was simulated in depressurizing mode. The simulation result is shown in Figure 9. The direction of the fluid flow is indicated by the white arrowhead. The outlet of the annulus was subjected to a constant-pressure boundary condition (30 MPa), and a constant fluid velocity (8 m/s) was assumed at the inlet of the bit interior. The drilling fluid was assumed as water. The vacuum flowed through the suction line and the fluid velocity in the suction line was higher in the narrower Venturi nozzle than in the wider nozzle. The simulated pressure profile in the flow area is shown in Figure 10. In the narrower Venturi nozzle case, the pressure downstream of the Venturi nozzle and in the suction line was reduced approximately 10 MPa.

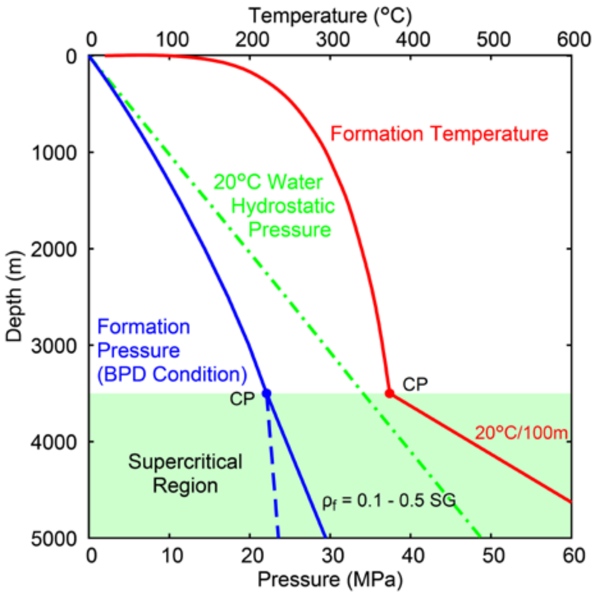

Figure 4: Assumed pressure and temperature profile of supercritical geothermal drilling.

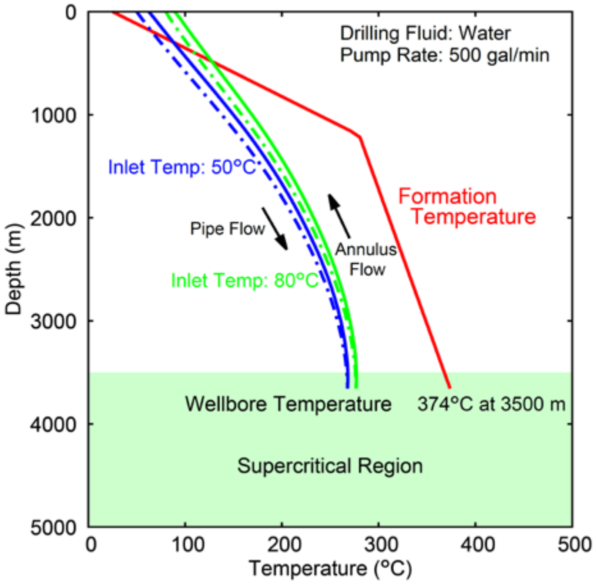

Figure 5: Estimation of bottomhole circulation temperature when drilling around transition depth to supercritical condition by GEOTEMP2.

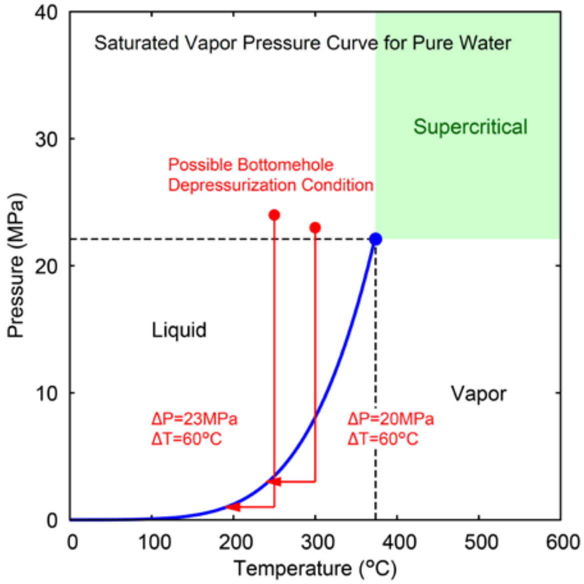

Figure 6: Pressure-temperature diagram of pure water for determining the pressure reduction required for cooling the downhole.

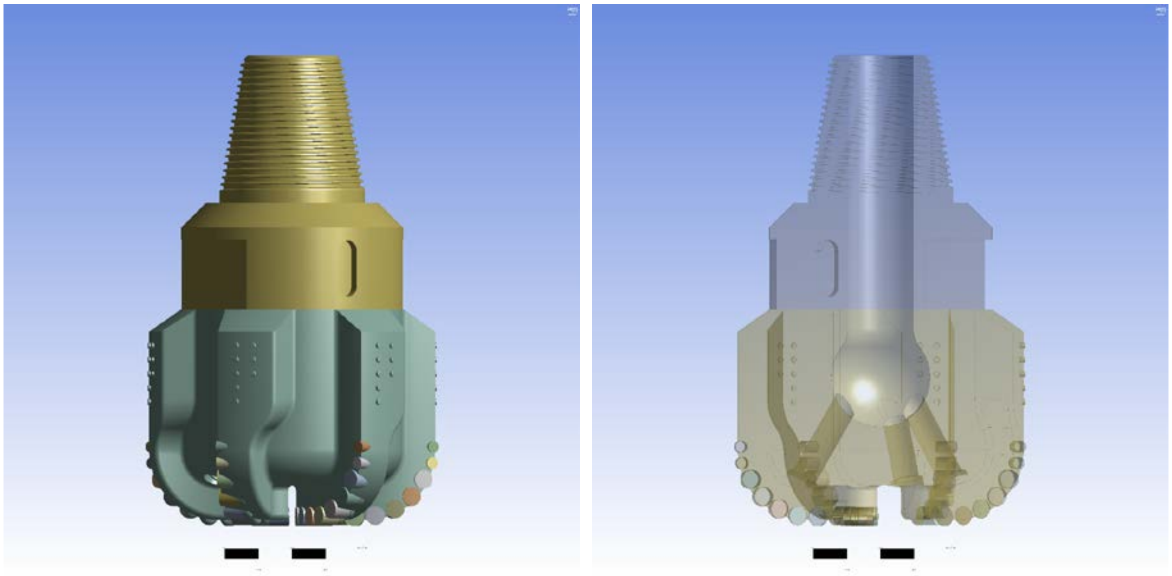

Figure 7: 3D model of the 8-1/2″ PDC bit used in this study (original model was built by Ekawira K Napitupulu).

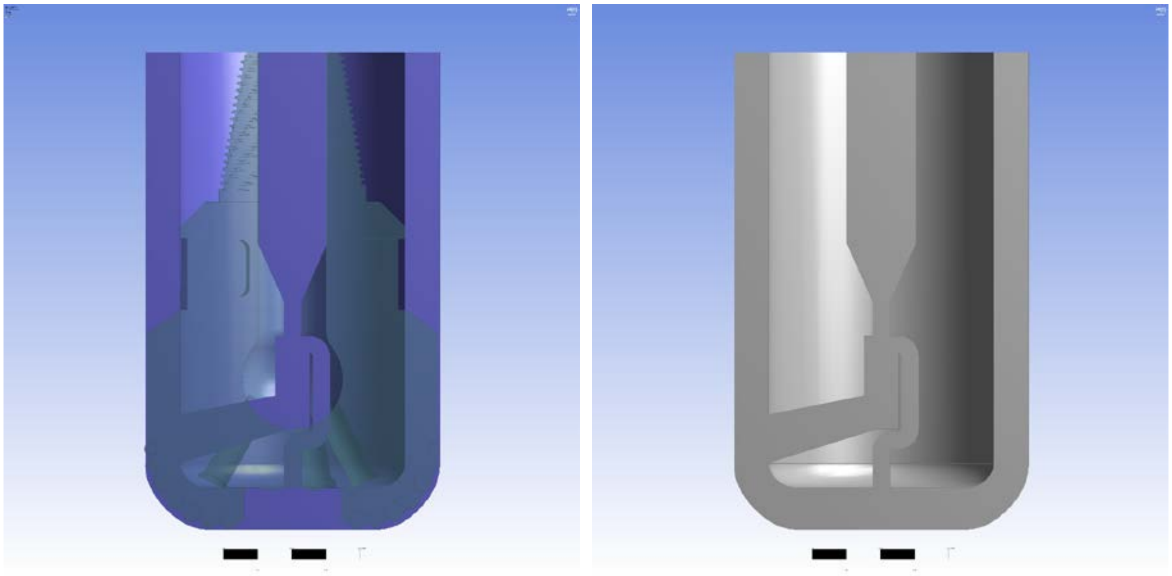

Figure 8: Simplified model settings of the flow areas inside and around the thermal-shock enhanced drill bit.

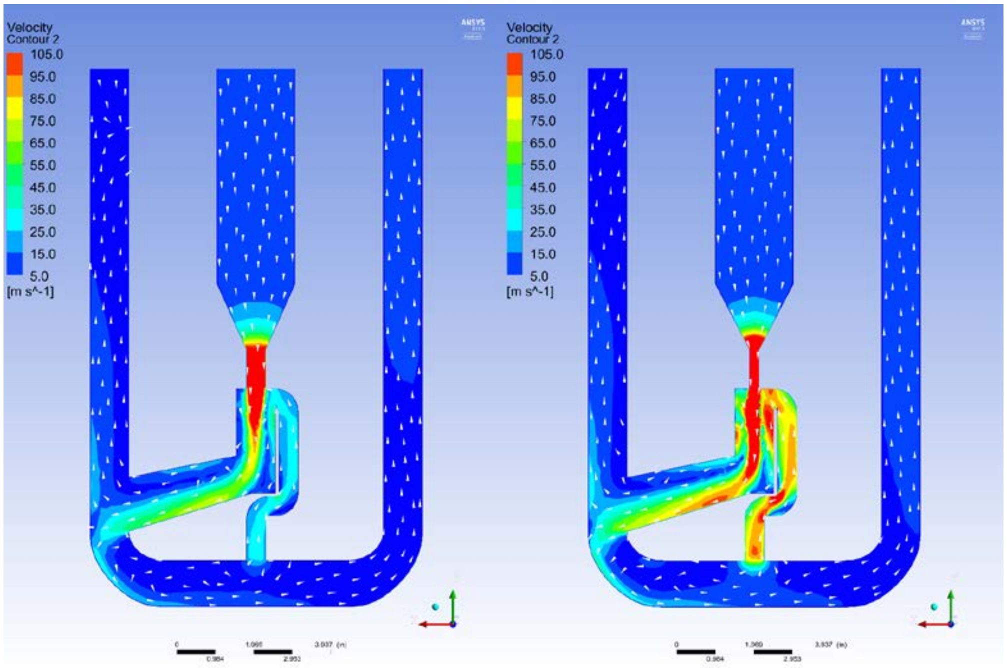

Figure 9: Simulated drilling fluid velocities in a simplified thermal-shock enhanced bit operated in depressurizing mode. The diameters of the Venturi nozzle are 1/2″ (left) and 1/4″ (right).

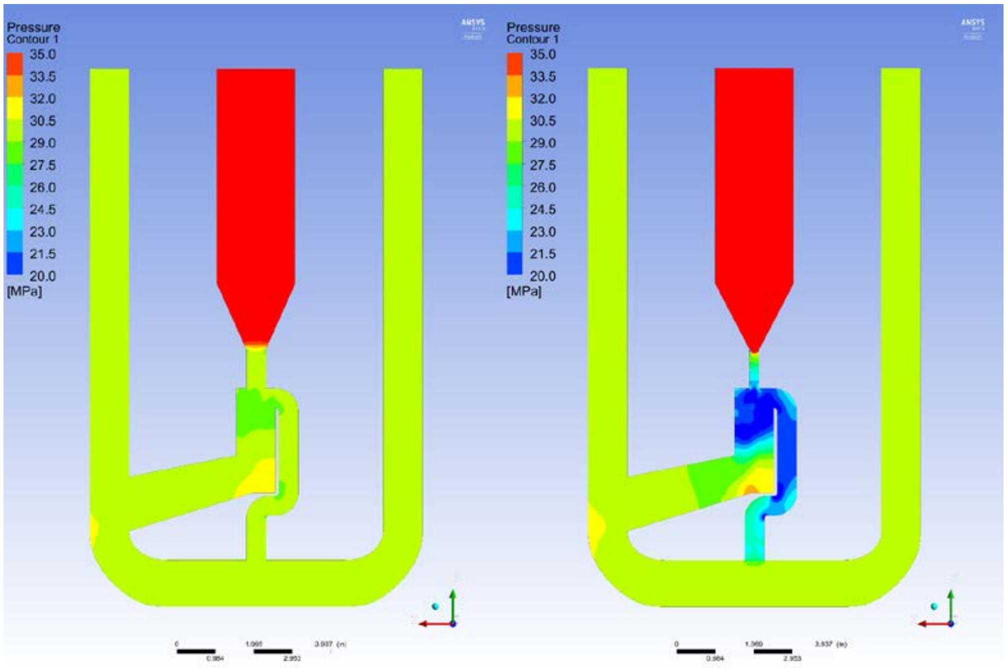

Figure 10: Simulated drilling fluid pressures in a simplified thermal-shock enhanced bit operated in depressurizing mode. The diameters of the Venturi nozzle are 1/2″ (left) and 1/4″ (right).

5. Concluding Remarks

In this paper, development of a new drilling tool, named the “thermal-shock enhanced drill bit,” through CFD simulations was presented. The drilling tool will generate a sufficient thermal-shock failure of rock by depressurization, boiling and cooling at the bottomhole. Because the simulation results presented in this paper are only preliminary, the pressure reduction can be improved. To this end, the bit design and configuration of the flow paths will be optimized in future work.

The thermal-shock enhanced drilling system is currently being developed as a collaborative research project between industrial, government, and academic institutions. To improve the possibility of realizing for the system, the project also includes the following subtasks on the related technologies:

- Experimental and simulation studies on the mechanism of hydraulically induced thermal-shock failure of high temperature rocks.
- Development of a wellbore thermal simulation technology applicable to supercritical formation conditions. The design of the developing bit and packer well be optimized based on the wellbore thermal simulations.
- Experimental evaluation of the mechanism of a newly conceived, thermally activated casing packer.
- Study of acid-, corrosion-, and fatigue failure-resistant materials in supercritical environments, particularly the resistance of casing pipes.

Acknowledgments

This paper is based on the results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO), Japan. The author gratefully acknowledges the project collaborator Tohoku University, Geothermal Energy Research & Development Co., Ltd., Geothermal Engineering Co., Ltd., Teiseki Drilling Co., Ltd., and Fukushima Renewable Energy Institute (FREA), AIST. The author especially thanks Dr. Nobuo Hirano and Prof. Noriyoshi Tsuchiya at Tohoku University who contributed in the experimental work that was fundamental to this paper.

REFERENCES

Asanuma, H., Muraoka, H., Tsuchiya, N., and Ito, H. “The Concept of the Japan Beyond-Brittle Project (JBBP) to Develop EGS Reservoirs in Ductile Zones.” *Geothermal Resources Council Transactions*, **36**, (2012), 359–364.

Blood, R.H. “Thermal Shock Drilling Bit.” US Patent No. 2,548,463 (1951).

Dobson, P., Asanuma, H., Huenges, E., Poletto, F., Reinsch, T., and Sanjuan, B. “Supercritical Geothermal System—A Review of Past Studies and Ongoing Research Activities.”

Proceedings: 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2017).

Ezzedine, S., Rubenchik, A., and Yamamoto, R. "Laser-Enhanced Drilling and Laser Assisted Fracturing for Subsurface EGS Applications." *Proceedings: 40th Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, CA (2015).

Friðleifsson, G.Ó. et al. "The Drilling of the Iceland Deep Drilling Project Geothermal Well at Reykjanes has been Successfully Completed." Report assembled by the IDDP on-site science team. http://iddp.is/wp-content/uploads/2017/02/IDDP-2-Completion-websites-IDDP-DEEPEGS.pdf (accessed 29 May 2017).

Hirano, N., Kasahara, N., Aoshima, S., and Tsuchiya, N. "Fundamental Study of Fracturing in the Mineral by Rapid Decompression-Boiling under 400°C, 20 MPa Hydrothermal Condition." *Proceedings: Annual Meeting of Geothermal Research Society of Japan,* Beppu, Japan (2015).

Jamali, S., Wittig, V., and Bracke, R. "Innovative Thermal Drilling Technologies based on Mechanically Assisted Laser Jet Drilling (LJD) for Hard Rock (Geothermal) Applications." *Proceedings: European Geothermal Congress 2016*, Strasbourg, France (2016).

Kant, M., Höser, D., Schuler, M., Rossi, E., and von Rohr, P.R. "Thermal Spalling Drilling—An Alternative Drilling Technology for Hard Rock Drilling." *Proceedings: International Conference and Exhibition for Advanced Drilling Technology,* Celle, Germany (2016).

Kobayashi, T., Nakamura, M., Kubo, S., and Ichikawa, M. "Drilling a 2-inch in Diameter Hole in Granites Submerged in Water by CO2 Lasers." *Proceedings: SPE/IADC Drilling Conference and Exhibition*, Amsterdam, Netherlands (2009), SPE-119914-MS.

Kocis, I., Kristofic, T., and Kocis, I. "Plasmabit—Innovative Drilling and Casing System." *Proceedings: European Geothermal Congress 2013*, Pisa, Italy (2013).

Lehr, J., Oppelt, J., Krueger, S., Anders, E., Voigt, M., Reich, M., Lehmann, F., and Mezzetti, M. "Advanced Evaluation and Research of Electric Impulse Drilling Technology." *Proceedings: International Conference and Exhibition for Advanced Drilling Technology*, Celle, Germany (2016).

Lima, A., Oliveira, D., and Benton, M. "Efficiently Delivering Difficult Tortuous Well Profile Deepwater Brazil Ream-on-Demand System Saves Operator Trip for Tool Change-Out." *Proceedings: SPE Latin American and Caribbean Petroleum Engineering Conference*, Maracaibo, Venezuela (2014).

Maurer, W.C. "The State of Rock Mechanics Knowledge in Drilling." *Proceedings: 8th U.S. Symposium on Rock Mechanics (USRMS)*, Minneapolis, MN (1966), ARMA-66-0355.

Meier, T., and von Rohr, P.R. "Flame-Jet Drilling—An Assessment of the Technique in a Borehole Environment at Fluid Pressure up to 26 MPa and Vertical Stress up to 100 MPa." *Proceedings: International Conference and Exhibition for Advanced Drilling Technology*, Celle, Germany (2016).

Mondy, L.A. and Duda, L.E. "Advanced Wellbore Thermal Simulator GEOTEMP2 User Manual." SAND-84-0857, Sandia National Labs, Albuquerque, NM (1984).

Muraoka, H., Asanuma, H., Tsuchiya, N., Ito, T., Mogi, T., Ito, H., and the Participants of the ICDP/JBBP Workshop. "The Japan Beyond-Brittle Project," *Scientific Drilling*, **17**, (2014), 51–59.

Naganawa, S., Tsuchiya, N., Okabe, T., Kajiwara, T., Shimada, K., and Yanagisawa, N. "Innovative Drilling Technology for Supercritical Geothermal Resources Development." *Proceedings: 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA (2017).

Parker, R.A., Gahan, B.C., Graves, R.M., Batarseh, S., Xu, Z., and Reed, C.B. "Laser Drilling: Effects of Beam Application Methods on Improving Rock Removal." *Proceedings: SPE Annual Technical Conference and Exhibition*, Denver, CO (2003), SPE-84353-MS.

Potter, R.M., Potter, J.M., and Wideman, T.W. "Laboratory Study and Field Demonstration of Hydrothermal Spallation Drilling." *Geothermal Resources Council Transactions*, **34**, (2010), 249–252.

Tsuchiya, N., Yamamoto, K., and Hirano, N. "Experimental Approach for Decompression Drilling in High Temperature Geothermal Conditions." *Geothermal Resources Council Transactions*, **36**, (2012), 561–564.

Watanabe, N., Numakura, T., Sakaguchi, K., Saishu, H., Okamoto, A., Ingebritsen, S.E., and Tsuchiya, N. "Potentially Exploitable Supercritical Geothermal Resources in the Ductile Crust." *Nature Geoscience*, **10**, (2017), 140–144.