PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

CFD Simulation to Optimize Depressurization of Thermal-Shock Enhanced Drill Bit

Shigemi Naganawa

School of International Resource Sciences, Akita University, 1-1 Tegata-gakuenmachi, Akita 010-8502 Japan

naganawa@mine.akita-u.ac.jp

Keywords: supercritical geothermal, thermal shock, hybrid drill bit, Venturi effect, computational fluid dynamics (CFD) simulation

ABSTRACT

For decades, utilization of the high-enthalpy supercritical geothermal resources has been pursued to improve the efficiency and capacity of geothermal power generation. However, to develop the supercritical geothermal systems, technologies that efficiently and safely drill into the hard ductile formations where the temperature exceeds 400°C are crucial. The author proposed the concept of an innovative drilling tool, named the thermal-shock enhanced drill bit in the previous study. The thermal-shock enhanced drill bit combines a Venturi mechanism with a PDC bit. There are two drilling modes; drilling mode which uses a conventional PDC bit drilling mechanism and depressurizing mode which locally reduces the pressure of drilling fluid just below the bit by the Venturi mechanism. If the depressurization is large enough to vaporize and cool the drilling fluid because of the latent heat, the rock is fractured or weakened by the thermal shock or thermal stress. The drillability of hard rocks encountered in ductile and supercritical geothermal formations might be improved. In this paper, optimization of Venturi nozzle and flow lines design to maximize the depressurization beneath the bit and feasibility of the thermal-shock enhanced drill bit are discussed on the basis of the computational fluid dynamics (CFD) simulations.

1. INTRODUCTION

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, Japan 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.

The author proposed the concept of an innovative drilling tool, named the thermal-shock enhanced drill bit that uses the Venturi depressurizing effect in the previous studies (Naganawa et al., 2017; Naganawa, 2017). In this paper, optimization of Venturi nozzle and flow lines design to maximize the depressurization beneath the bit and feasibility of the thermal-shock enhanced drill bit are discussed on the basis of the computational fluid dynamics (CFD) simulations.

2. CONCEPT OF THERMAL-SHOCK ENHANCED (TSE) DRILL BIT

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 caused by the latent heat 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 research 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; Naganawa, 2017).

As illustrated in Figure 1, 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 2. 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.

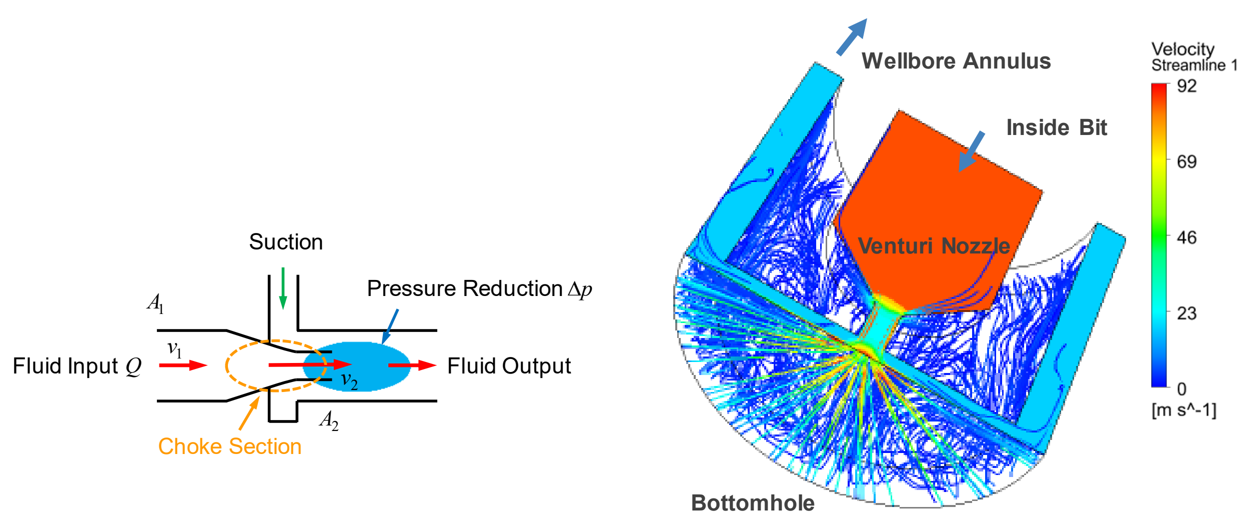

Figure 1: Principle of the Venturi effect.

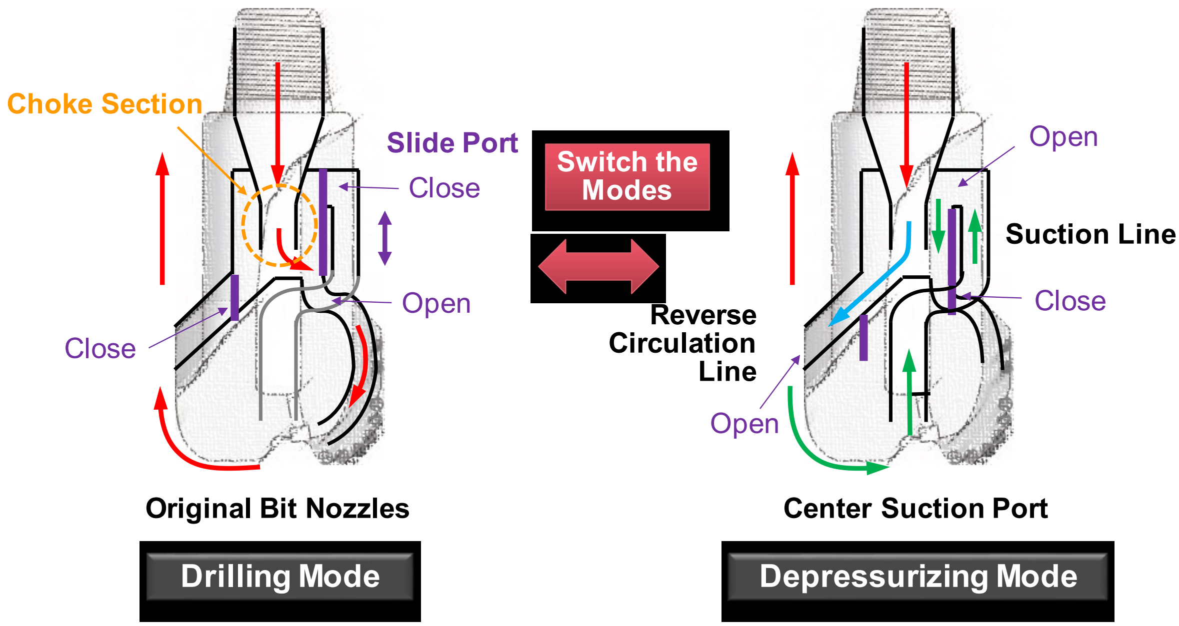

Figure 2: Concept of the thermal-shock enhanced (TSE) drill bit.

3. COMPUTATIONAL FLUID DYNAMICS SIMULATION OF VENTURI DEPRESSURIZATION MECHANISM

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. 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). Even when the inlet temperature of the drilling fluid at the surface is sufficiently low, the bottomhole temperature during drilling was estimated to 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 our preliminary consideration on phase equilibrium of pure water, P-T diagram shows that temperature reduction of 60°C requires a pressure reduction of at least 20 MPa (Naganawa, 2017). Much larger temperature reduction can be expected at the same degree of pressure reduction because the latent heat of vaporization of drilling fluid should be actually taken into account.

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 software. Figure 3 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 4. 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 and the pressure profile were simulated in depressurizing mode. 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 simulation result of fluid velocity is shown in Figure 5. The direction of the fluid flow is indicated by the white arrowhead. Reverse circulation flow and suction just below the bit were successfully achieved. The vacuum flowed through the suction line or 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 6. In the narrower Venturi nozzle case, the pressure downstream of the Venturi nozzle and in the suction line was reduced approximately 10 MPa. Further optimization of the flow line design could improve suction capability and cause much higher depressurization beneath the bit.

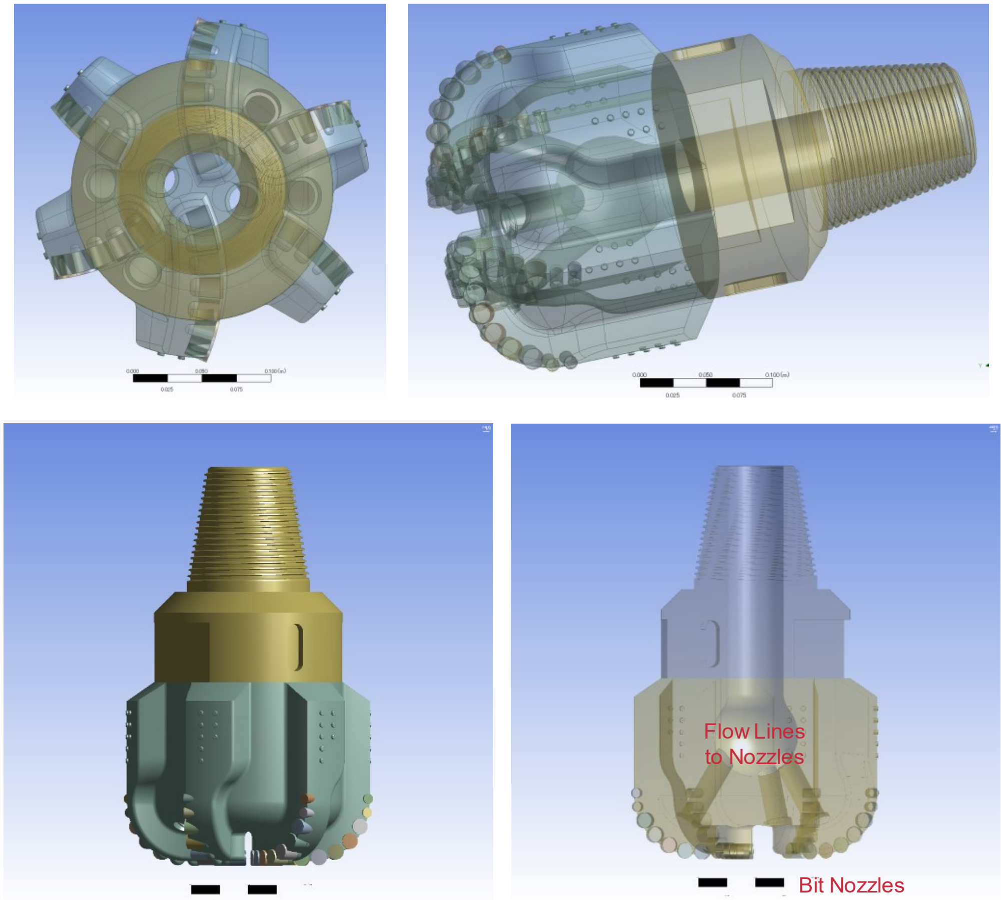

Figure 3: 3D model of 8-1/2″ PDC bit used in this study (original model was built by Ekawira K. Napitupulu).

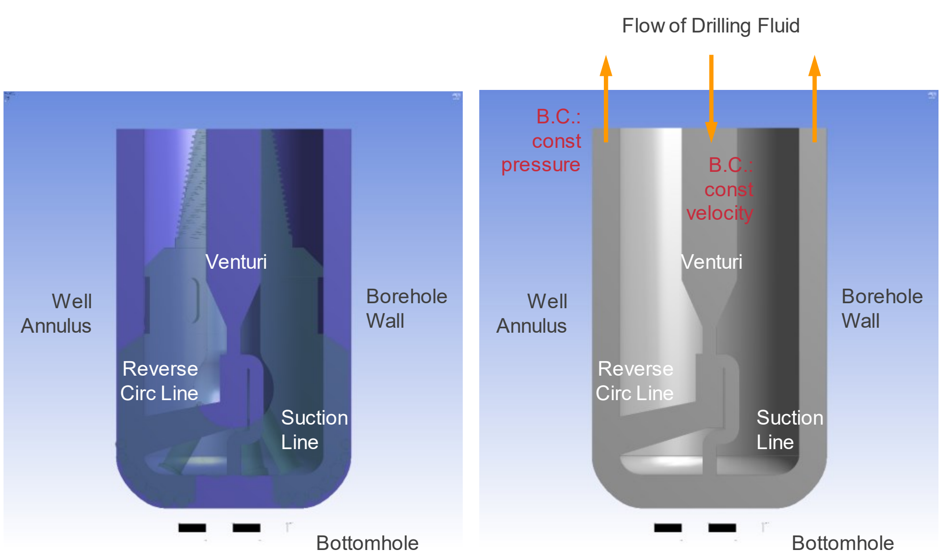

Figure 4: Simplified model settings of the flow areas inside and around the thermal-shock enhanced drill bit.

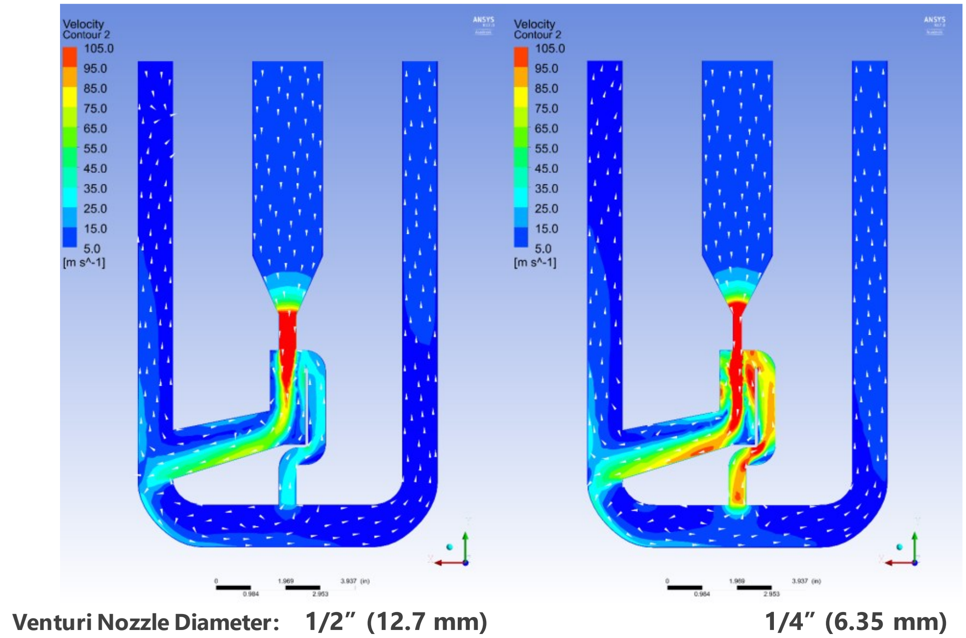

Figure 5: Simulated drilling fluid velocities in a simplified thermal-shock enhanced bit operated in depressurizing mode.

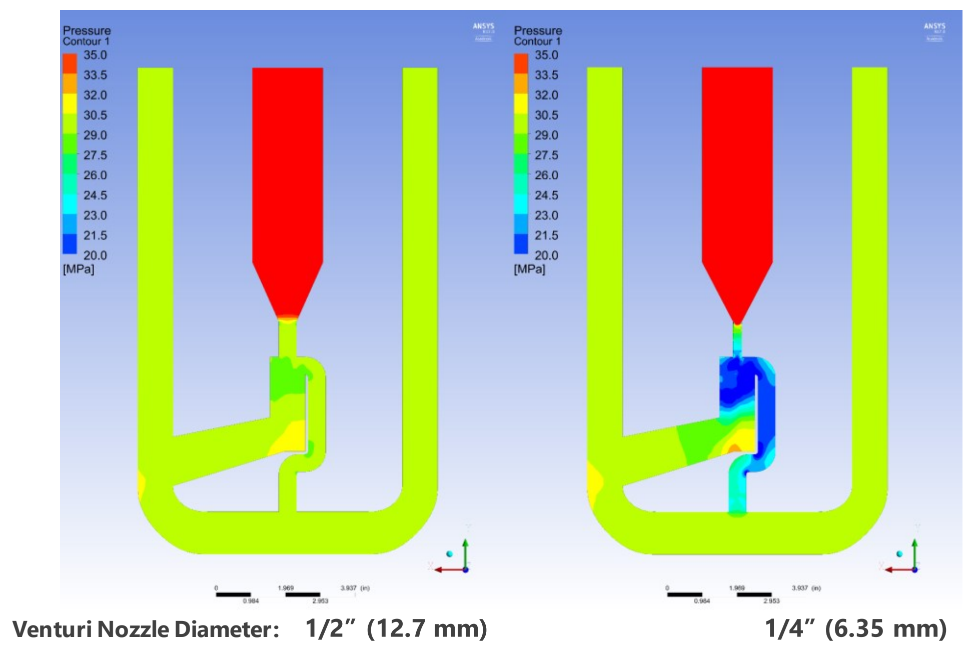

Figure 6: Simulated drilling fluid pressures in a simplified thermal-shock enhanced bit operated in depressurizing mode.

4. DISCUSSION ON THE FEASIBILITY OF THERMAL-SHOCK ENHANCED DRILL BIT

Feasibility of implementation of the Venturi mechanism, and suction and reverse circulation flow lines as discussed above was evaluated through 3D CAD (computer-aided design) modeling on a computer and 3D printing of the prototype model for the thermal-shock enhanced drill bit.

Figure 7 is a cut model of the original PDC bit showing the flow line inside the bit which was 3D printed from 3D CAD model data. Here, two sets of suction lines and reverse circulation lines (both are blue colored) as shown in Figure 8 are newly combined with the flow lines connected to the multiple jet nozzles (gray colored) originally built-in. Because the respective set of flow lines are symmetric around the bit center line, flow lines are configured to have angles of approximately 40° around the bit center line between suction lines and reverse circulation lines so as not to interfere with each other. Figure 9 shows a 3D CAD model of the above designed 8-1/2″ thermal-shock enhance drill bit which has a Venturi nozzle and two sets of suction and reverse circulation lines built-in.

Using this 3D CAD data, a prototype model of an 8-1/2″ thermal-shock enhanced drill bit was 3D printed as shown in Figure 10. It is confirmed from the real-scale 3D bit model that there are sufficient room for two or more sets of suction and reverse circulation flow lines, and the Venturi depressurization mechanism to be built-in.

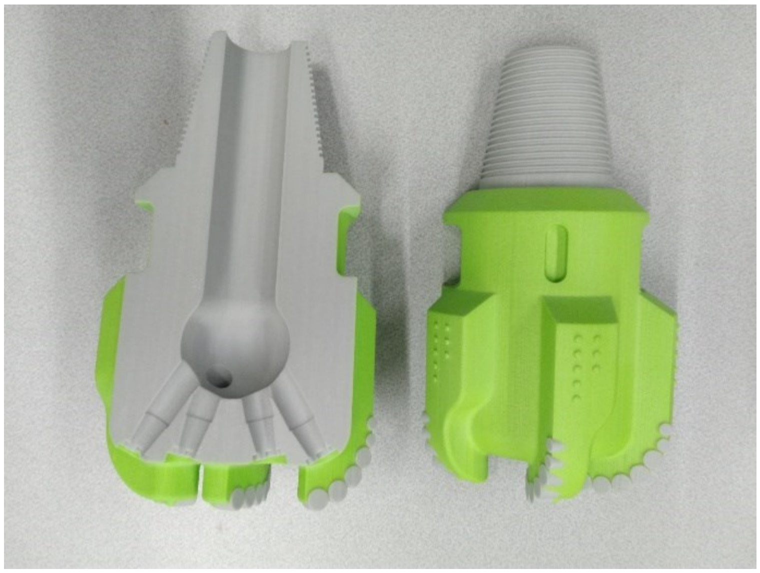

Figure 7: 1/2-scale 3D printed cut model of the original 8-1/2″ PDC bit.

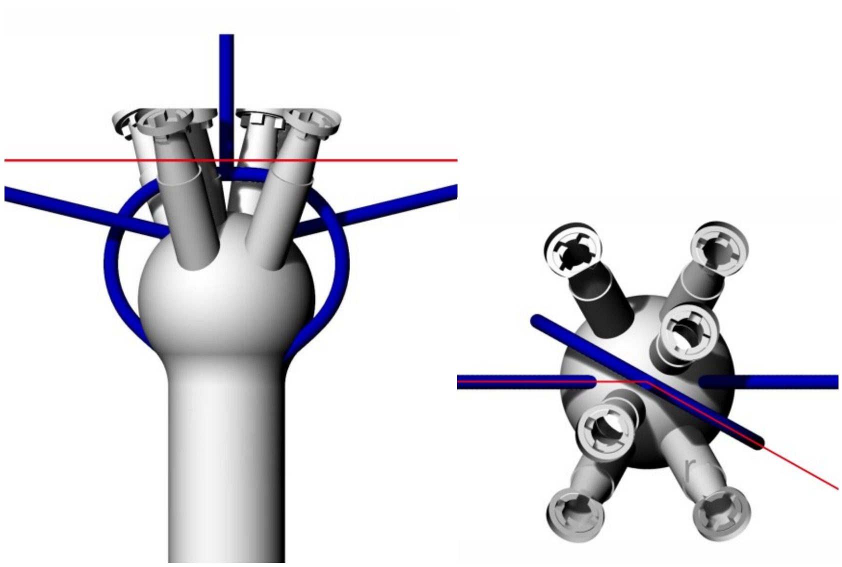

Figure 8: Configuration of two sets of suction and reverse circulation flow lines inside the thermal-shock enhanced drill bit.

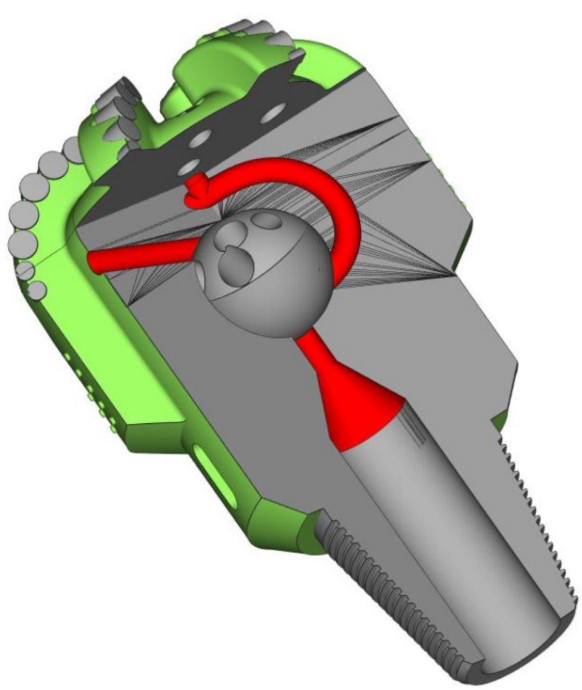

Figure 9: 3D CAD model of the thermal-shock enhance drill bit which has a Venturi nozzle and two sets of suction and reverse circulation lines built-in.

Figure 10: Prototype 3D printed model of the 8-1/2″ thermal-shock enhanced drill bit.

5. CONCLUSIONS

In this paper, design optimization of Venturi nozzle and flow lines to maximize the depressurization effect and the feasibility of the thermal-shock enhanced drill bit proposed in the previous studies are discussed on the basis of the computational fluid dynamics (CFD) simulations. The new drilling tool will generate a sufficient thermal-shock failure of rock by depressurization, boiling and consequent cooling at the bottomhole. Because the simulation results presented in this paper are still preliminary, CFD simulation study for Venturi mechanism with more complex configuration of flow lines is now going on to improve the pressure reduction.

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 National Institute of Advanced Industrial Science and Technology (AIST).

REFERENCES

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

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).

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 CO_2 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 Laboratory, Albuquerque, NM (1984).

Naganawa, S.: Concept of Thermal-Shock Enhanced Drill Bit for Supercritical Geothermal Drilling, *Geothermal Resources Council Transactions*, **41**, (2017), 406–417.

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.