Numerical Simulation on the Performance of Thermal-Shock Enhanced Drill Bit for Supercritical Geothermal Drilling

Jumpei Nanao and Shigemi Naganawa

School of International Resource Sciences, Akita University, Japan

Keywords

geothermal well drilling, supercritical geothermal, thermal shock, hybrid bit, Venturi effect, computational fluid dynamics simulation

ABSTRACT

Supercritical geothermal systems haves now been attracting attention as a future promising renewable energy in which a potential of hundreds of giga-watts power generation is expected in Japan as a whole. Because the heat-resistant performance of roller cone bits that are conventionally used in geothermal drilling is naturally limited by the sealed bearing mechanism and its materials, PDC bits are considered suitable for supercritical geothermal drilling where the formation temperature is estimated to exceed 400°C. In Japan, however, hard and complex formations make it difficult to utilize the PDC bit in most geothermal fields.

The authors have proposed the concept of an innovative drilling tool named the thermal-shock enhanced (TSE) drill. The TSE bit is a hybrid PDC bit that has an internal Venturi depressurization mechanism. Drilling fluid pressure can be rapidly reduced just below the TSE bit by the mechanism. In addition to the prevention of chip hold-down effects caused by the drilling fluid pressure, the rapid deduction of pressure would favorably induce the vaporization of drilling fluid, subsequent cooling by the latent heat of vaporization, and consequently thermal shock or thermal stress failure of hard formation rock that enhancing the drillability of the formation by the TSE bit.

In this study, a computational fluid dynamics simulation was performed to evaluate the pressure reduction performance and to optimize the design of Venturi nozzle and flow lines of the TSE bit. Based on the numerical simulation, feasibility of the TSE bit for supercritical geothermal drilling is discussed.

1. Introduction

In the ductile area of the subduction zone including Japan, it is thought that water derived from the seawater drawn into the ground by the plate tectonics exists at a high temperature and high pressure (supercritical state) around the magma. It is supercritical geothermal power generation that is trying to utilize this geothermal resource. In Japan, a national research project on supercritical geothermal resources development, originally known as the Japan Beyond-Brittle Project (JBBP), is in progress. The project plans to drill for the actual proof of an engineered geothermal system of enhanced geothermal system (EGS) in or below the brittle-ductile transition zone underground (Asanuma et al., 2012).

The drilling conditions at JBBP are assumed to be 3000 to 5000 m deep, the predicted formation temperature is between 350 and 500 degrees C, and the predicted formation pressure 30 to 100 MPa, and it can be said that it is very hard compared to ordinary oil and natural gas wells (Naganawa, 2013). Because the heat resistance performance of the roller cone bits conventionally used in geothermal well drilling is naturally limited by the sealed bearing mechanism and its materials, PDC bits are considered to be suitable for supercritical geothermal drilling. Although PDC bits for geothermal drilling have been developed in Japan, drilling is difficult in Japan's hard and complex formation, and many solutions are required (Imaizumi et al., 2017). To efficiently excavate hard granite layers at ultra-high temperatures in JBBP, there is a need to develop a new drilling technology to replace roller cone bits.

The authors proposed the concept of an innovative drilling tool called a thermal-shock enhanced drill bit in previous research (Naganawa et al., 2017; Naganawa, 2017). In this study, a computational fluid dynamics simulation was further performed to evaluate the pressure reduction performance and to optimize the design of Venturi nozzle and flow lines of the TSE bit. Based on the numerical simulation, feasibility of the TSE bit for supercritical geothermal drilling is discussed.

2. Concept of Thermal-Shock Enhanced (TSE) Drill Bit

According to the research by Tsuchiya et al. (2012), 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 considerably high. This effect might improve the drillability of hard rocks encountered in ductile and supercritical geothermal formations. Based on the above hypothesis, the drilling tool that locally decompresses the rock at the bottomhole by the Venturi effect, thereby inducing thermal-shock failure of the rock, was proposed as the thermal-shock enhanced (TSE) drill bit.

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:

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

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.

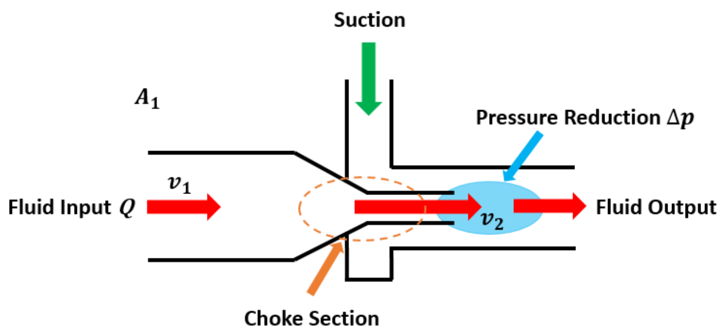

Figure 1: Principle of the Venturi effect.

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. It can be used with a depth of 300 m to 5500 m. It is an existing technology used all around the world. The tool proposed in our previous study is a combination of Venturi-PDC hybrid bit, named “thermal-shock enhanced drill bit,” is shown 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 be just below the bit. The two modes can be alternately switched by operating a sliding sleeve, which opens and closes the port valves.

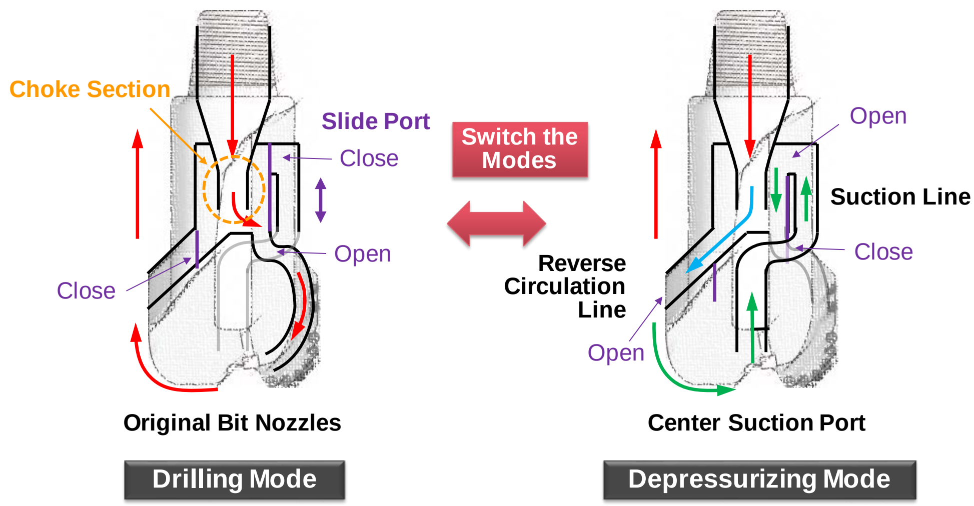

Figure 2: Concept of the Thermal-Shock Enhanced (TSE) Drill Bit (Naganawa, 2018).

3. Computational Fluid Dynamics Simulation of Venturi Depressurization Mechanism

3.1 Basic Model Setup

In this study, a computational fluid dynamics (CFD) simulation was performed to evaluate the pressure reduction performance, and to optimize the design of Venturi nozzle and flow lines of TSE bit.

Here, as in the previous studies, the target temperature and pressure profiles of supercritical geothermal drilling are assumed to follow the boiling point at the depth condition above the critical point of pure water, which corresponds to an approximate depth of 3500 m (Figure 3).

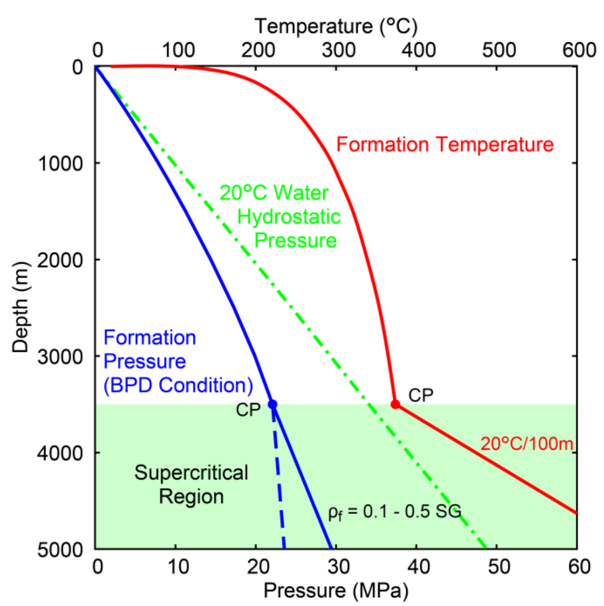

Figure 3: Assumed pressure and temperature profiles of supercritical geothermal drilling (Naganawa, 2017).

Below 3500 m, the formation pressure depends on the density of the supercritical formation fluid and the formation temperature increases conductively with a certain geothermal gradient. Supposing the above formation temperature, the bottomhole temperature, 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 (Naganawa, 2017). The relatively high bottomhole temperature would be advantageous for thermal-shock enhanced drilling.

Our previous studies have simulated steady-state flow through the Venturi decompression mechanism implemented in PDC bits by ANSYS® Fluent CFD software as a preliminary study. In the previous simulation, one suction line and one reverse circulation line were implemented in an 8 1/2-in. diameter PDC bit model (Figure 4). The Venturi nozzle diameter was varied as 1/2 in. (12.7 mm) and 1/4 in. (6.35 mm) and drilling fluid velocity and 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 bit interior. The drilling fluid was assumed to be water.

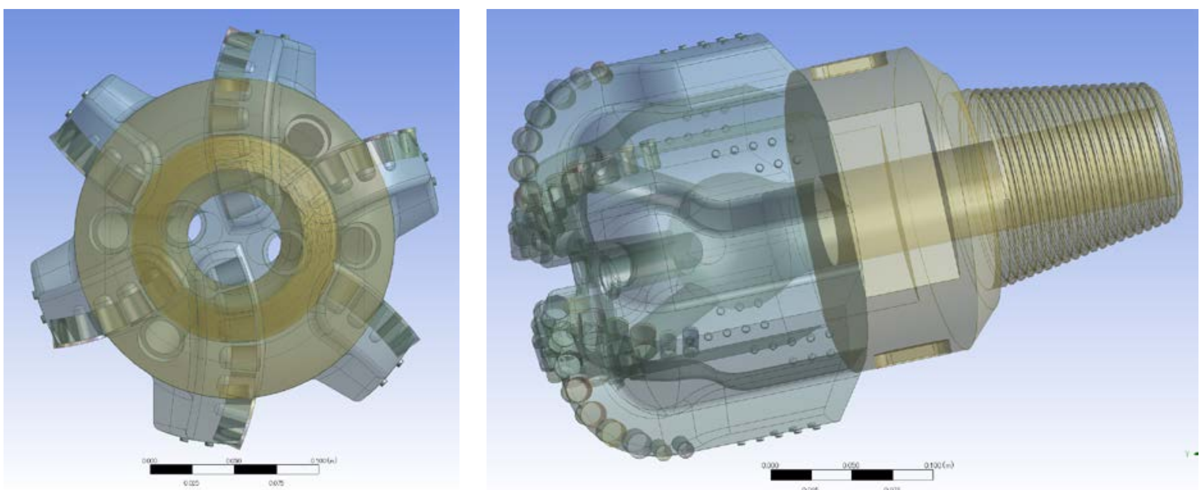

Figure 4: Original 3D model of 8 1/2-in. PDC bit used in this study.

3.2 Modification of the Model to Multiple Nozzle and Suction Configuration

In this study, the boundary conditions were set in the same manner as the previous one, and a modified model in which three suction lines and three reverse circulation lines were implemented in an 8 1/2-in. diameter PDC bit was constructed. By increasing the number of the suction lines and reverse circulation lines, it is expected to improve the amount of pressure reduction at the bottomhole. 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 5.

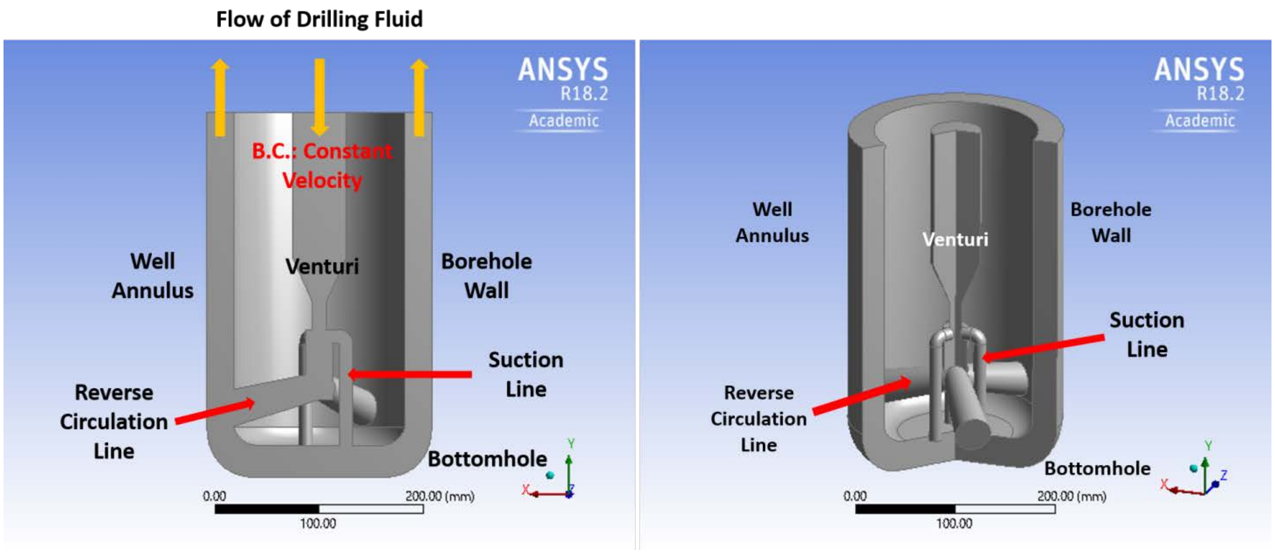

Figure 5: Simplified model setting of the flow areas inside and around the thermal-shock enhanced drill bit.

4. Discussion on CFD Simulation Results for Thermal-Shock Enhanced Bit

A comparison was made between single and triple flow line cases to assess the effect of increasing the number of flow lines. The diameter of the Venturi nozzle was varied as in two patterns for 1/2 in. (12.7 mm) and 1/4 in. (6.35 mm) respectively. The simulation results of the fluid velocity are shown in Figure 6. The velocity of the fluid through the suction lines was higher for the narrow Venturi nozzle in both single and triple flow line cases than the wider nozzle. The simulated pressure profile in the flow area is shown in Figure 7.

The amount of pressure reduction downstream of the Venturi nozzle and suction lines was greater for the narrow Venturi nozzle in both flow line cases than for the wider nozzle. Initially, an increase in the amount of pressure reduction was expected by increasing the suction line and the reverse circulation line. However, from the simulation results, it was found that simply increasing the number of flow lines, on the contrary to the expectation, does not cause an increase in the amount of decompression. In the case of the narrow Venturi nozzle, because the amount of pressure reduction downstream of the Venturi nozzle and the suction line is improved, it can be said that the diameter of the Venturi nozzle greatly affects the improvement of the suction capability. Moreover, in this model, it was a simple shape that connected the suction line vertically to the bottomhole. Further optimization of the flow line design may improve the suction capacity and may result in an increase in the amount of depressurization, which needs further study.

5. Conclusions

In this study, a CFD simulation was performed to evaluate the pressure reduction performance and to optimize the design of the Venturi nozzle and flow lines of the thermal-shock enhanced drill bit. By increasing the number of suction lines and the reverse circulation lines, an increase in the amount of depressurization was expected. From the simulation results, however, it was found that the increase in the amount of depressurization did not occur simply by increasing the number of flow lines which was contrary to the expectations. In this simulation, a simplified model of the flow area around and inside the thermal-shock enhanced drill bit was used. Therefore, to estimate the amount of depressurization more accurately, it is necessary to carry out simulations in the state where the flow lines are incorporated in the detail PDC bit model in the future. At the same time, we will optimize the flow lines, and improve suction capacity and depressurization performance further.

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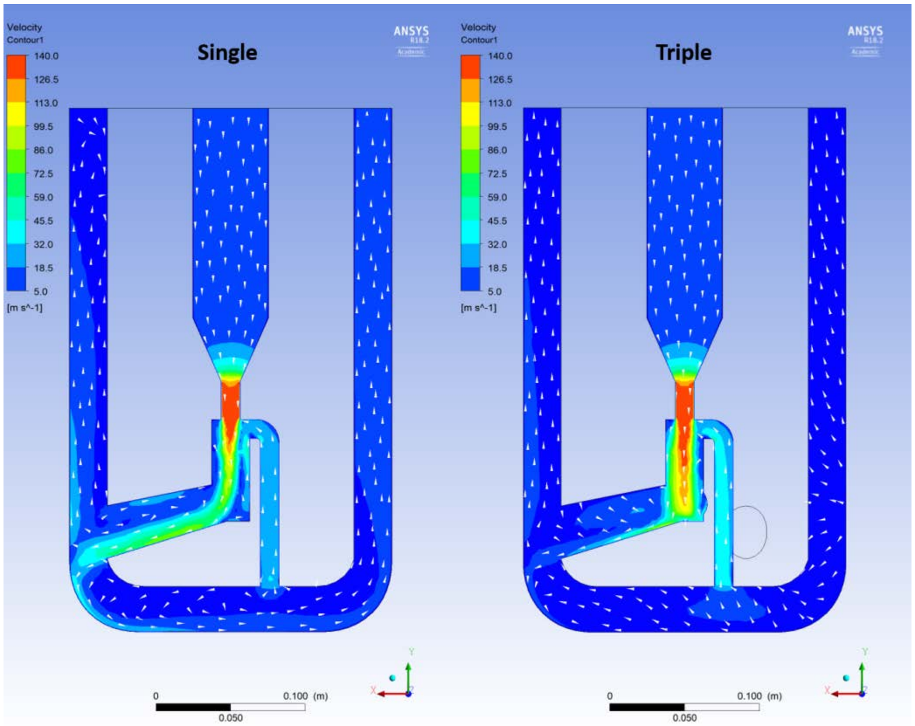
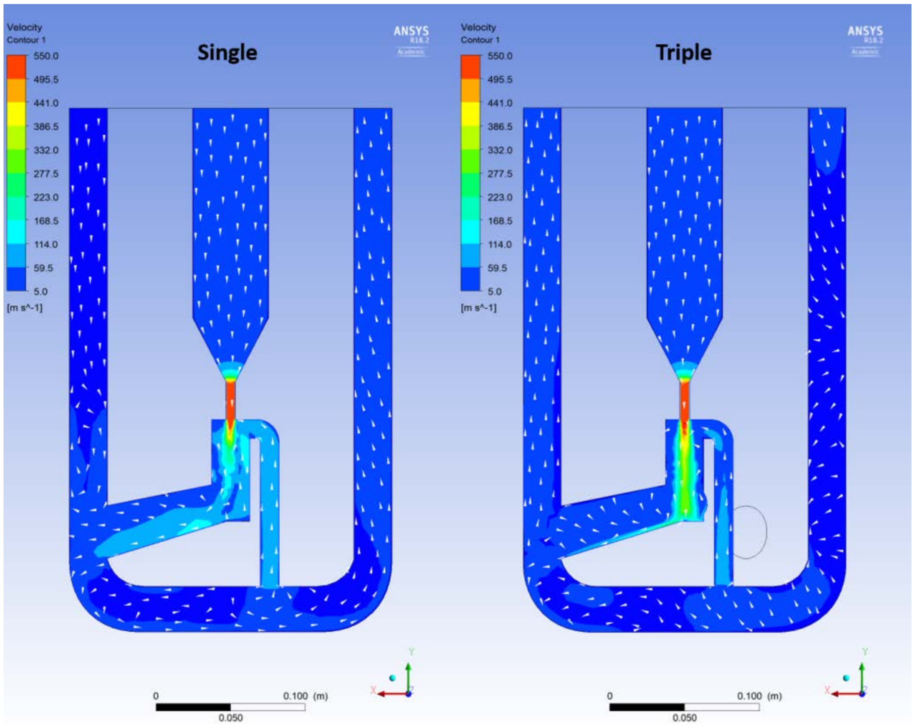
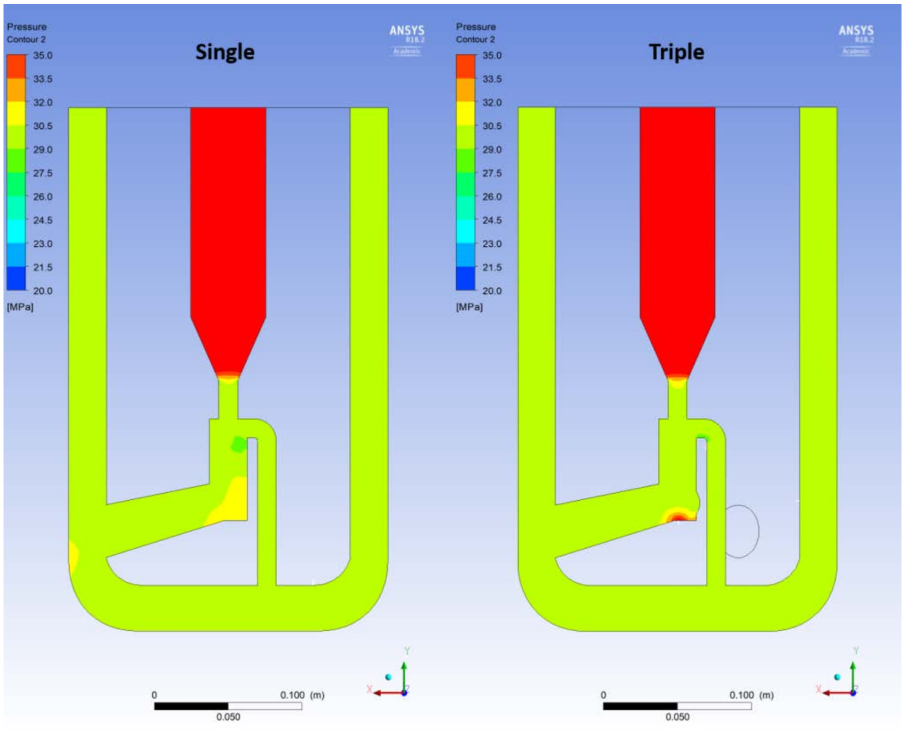


(a) Venturi Nozzle Diameter: 1/2” (12.7 mm)

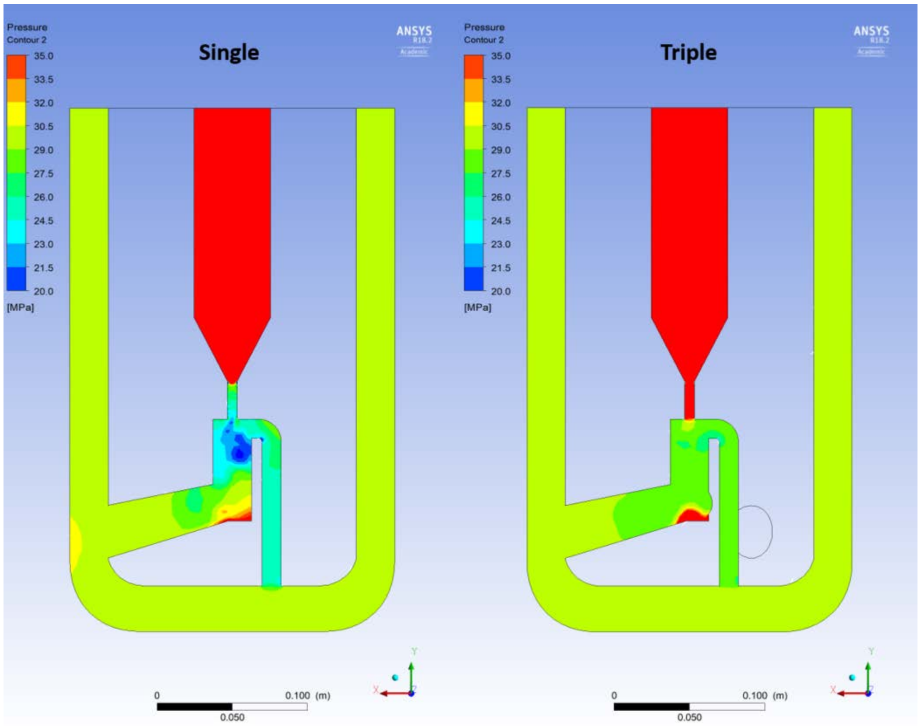


(b) Venturi Nozzle Diameter: 1/4” (6.35 mm)

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



(a) Venturi Nozzle Diameter: 1/2” (12.7 mm)



(b) Venturi Nozzle Diameter: 1/4” (6.35 mm)

Figure 7: Simulated drilling fluid pressures in a simplified thermal-shock enhanced bit operated in depressurizing mode.