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Numerical analysis on the impact of the flow field of hydrothermal jet drilling for geothermal wells in a confined cooling environment

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ABSTRACT

Hydrothermal jet technology is a novel drilling method expected to be suitable for the exploitation of deep geothermal resources, in which the rocks are broken coupled by thermal spallation effect with high velocity impact. Because of the high temperature return fluid, the cooling of the drill string and wellbore is one major problem in hydrothermal jet drilling. This paper presents two cooling configurations in downhole conditions: the lateral configuration and downward configuration. The investigation on the impact of the flow field of the hydrothermal jet in a confined cooling environment is estimated using CFD methods. The influences of jet velocity, jet temperature, cooling water velocity and standoff distance are analyzed. For both cooling configurations, the impact of the flow field of a hydrothermal jet in downhole conditions is divided into three zones: the jet zone, the return zone and the eddy zone. The hydrothermal jet impinges on the bottom rock, and then returns from the annulus mixed with the cooling water. The temperature in the jet zone stays constant, while it decreases in the return and the eddy zone. The temperature around the wellbore is higher due to the return flow of the cooling water. There is a high bottomhole temperature region, while the annulus is cooled by the cooling water in the lateral cooling configuration. In addition, the jet velocity, the cooling water velocity and the standoff distance have a large influence on the pressure and temperature fields, while the jet temperature has a small influence. For the downward cooling configuration, the length of the potential core of the hydrothermal jet is positively correlated to the maximum axial velocity. Finally, two cooling configurations are compared. The lateral cooling plan is suitable for reaming operation. The lateral cooling configuration is better in the cuttings carrying capacity due to the higher annular return velocity. Results in this paper could guide for parameters design of hydrothermal jet drilling technology.

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1. Introduction

As a renewable energy resource, geothermal energy offers considerable resource potential, low carbon emission, and widespread distribution. Geothermal resources can be divided into hydrothermal resources and hot dry rock (HDR) resources according to their naturally occurring states (Barbier, 2002). Hydrothermal energy can be exploited by extracting the fluid contained in a geothermal reservoir, which contains water, steam, or various gases. HDR geothermal energy is heat energy stored in subsurface hot and low-permeability crystalline rocks, normally located at depths of 3–10 km (Tester et al., 2006). HDR geothermal energy represents a considerable indigenous resource that can continuously provide baseload electric power and heat.

The successful exploitation of geothermal energy largely depends on the smooth drilling process. Conventional rotary drilling technology has been the most commonly used method to date. It uses bottom on the drill bit to crush the rock and a jointed drill string to extend to depth. However, in deep, hard formations, the contact between the drill bit and rock, continual tripping and making connections has led to the abrasion of drill bit and thus is time-consuming and has high drilling costs.

Based on high velocity impact to disintegrate rock, high pressure water jet technology was proposed in about 1970s (Maurer and Heilhecker, 1969; Pols, 1977) and has developed quickly in the past decades (Li et al., 2012; Chi et al., 2015; Ayed et al., 2016). It is a contact-free technology and utilizes the destructive energy of water (or drilling mud) jets to increase rock removal rates relative to conventional drilling techniques. It has been successfully applied in assisting mechanical action to enhance the rate of penetration in petroleum recovery, mining, etc. However, water jet drilling has not provided satisfactory performance with respect to the breaking

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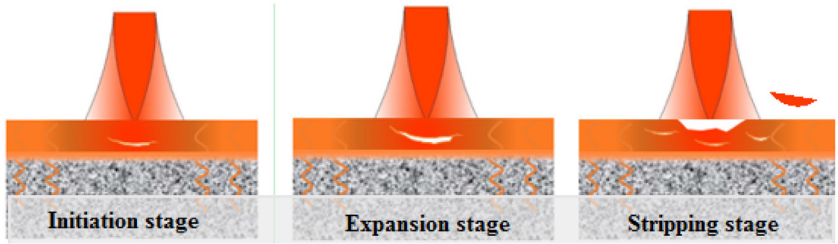

Fig. 1. Thermal spallation process.

hard rocks, such as granite (Foldyna et al., 2005). The pressure to break rocks is extremely high. This hinders the further application of the water jet drilling.

Thermal spallation drilling is an effective method for creating holes and cavities in some hard rocks that are expensive to drill using conventional mechanical drilling methods (Heard, 1980; Li et al., 2014). It uses high temperature media, such as hot air or flame via combustion, to heat the rock surface rapidly and cause high thermal stresses in the upper rock layer due to thermal expansion. Due to this stress, thermally-induced fragmentation occurs and disk-like rock fragments are formed in the heated rock's spallation zone. The entire thermal spallation process can be divided into three stages: the initiation stage, the expansion stage and the stripping stage (Fig. 1).

Recently, researchers from the Massachusettes Institute of Technology and the Swiss Federal Institute of Technology, Zurich have applied the thermal spallation rock-breaking mechanism to drilling for geothermal energy. Augustine (2009) concluded that spallation drilling has more economic advantages than conventional rotary drilling technologies. Tobias et al. (2011) experimentally used the Optical Schlieren method to study the penetration length of a supercritical jet and found it equal to the injector's nozzle diameter. José et al. (2012) numerically studied the mixing zones between subcritical or supercritical water jets and the subcritical co-flow environment. Results showed that when pressure was well above the critical point, fluid dynamic behavior was more similar to subcritical conditions. Martin et al. (2013a) proposed a numerical model and the Prandtl number was determined in a subcritical water bath at near-critical pressures. In general, recent studies have mainly used experimental and numerical methods to investigate characteristics of a hydrothermal spallation jet. These were performed under conditions where the jet velocity is relatively low (often less than 40 m/s). However, for deep wells drilling through several complicated formations, many rock materials do not spall. In this case, a very short interval of non-spallable rocks can impede advance during thermal spallation drilling.

To address the problems described above, based on high pressure water jet drilling and thermal spallation drilling technologies (Tobias, 2013), a new high temperature, high velocity hydrothermal jet drilling technique is proposed in this paper by our group (Song et al., 2016). This technique is a contact-free technology with coiled tubing used for continuous penetration (Fig. 2). By modulating the temperature and pressure of fluid media in the bottomhole assembly, a high temperature and high velocity jet is generated to impinge and heat the rock. This leads to rock spallation and microfracture propagation. These are accelerated by the impact of the high velocity jet. In the end rocks are broken by coupled jet impact and thermal spallation. This can reduce the abrasion and tripping time. The thermal spallation is especially suitable for disintegration of hard brittle rocks. This technique has the potential for drilling wells several kilometers deep in hard rock.

Fuel, oxidizer and cooling water are injected through respective channels down coiled tubing to the downhole combustion chamber. The chemical reaction between the fuel and the oxidizer in the chamber is initiated by an electric spark. Thus, the reaction products mainly water are ejected from the nozzle in the bottomhole assembly to impinge on the rock. Meanwhile, cooling water flows out from the lateral outlet or downward outlet of coiled tubing and returns to the surface through the annulus. This can cool the wellbore and coiled tubing simultaneously, and avoid the thermal destruction on the borehole wall by the high temperature fluids. Moreover, the circulation of cooling water can increase the cuttings transport efficiency. Thermal insulation is applied around coiled tubing to keep the cooling water from influences of reservoir temperature or combustion.

Two cooling configurations are presented in this paper: lateral cooling configuration and downward cooling configuration. Figs. 3 and 4 illustrate the details of the two schemes where the red region represents thermal fluid and blue region represents cooling water. Numerical simulation of the impact flow field of hydrothermal jet in downhole cooling environment was carried out. The bottomhole distributions of velocity, temperature and pressure were investigated. The influences of jet velocity, cooling water velocity, jet temperature, and standoff distance on the flow field were analyzed. In addition, the cooling effect and carrying capacity of the two cooling configurations were compared.

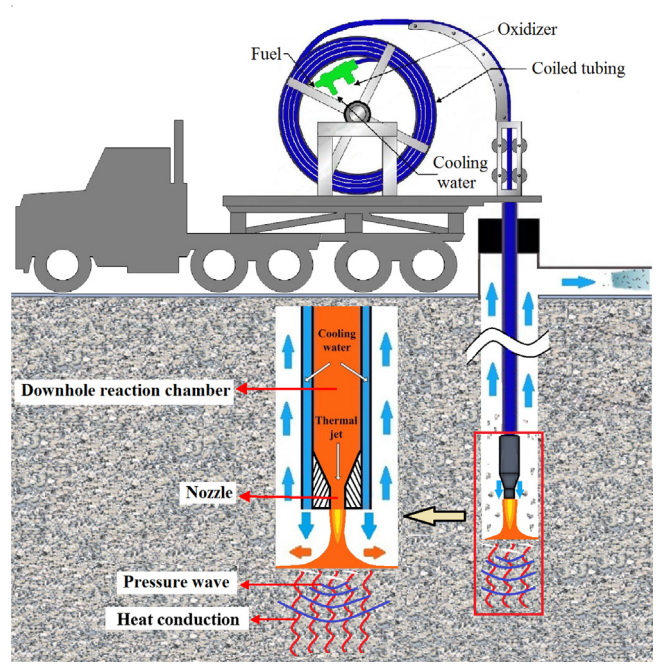

Fig. 2. Coiled-tubing-deployed hydrothermal jet drilling concept.

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