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Comparison of numerical analysis on the downhole flow field for multi-orifice hydrothermal jet drilling technology for geothermal wells

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ABSTRACT

Newly developed hydrothermal jet drilling technology has the potential of being economically advantageous over conventional drilling techniques for drilling deep wells in hard formations. By applying coiled tubing techniques and modulating fluid media in the bottomhole reaction chamber, there can be a high temperature and high velocity jet striking and conducting heat to break the rock. So far, there has been no specific study on the influence of nozzle structure on the flow field of multiple hydrothermal jets. This paper presents hydrothermal jet models with different numbers of orifices to investigate the features of flow field, carrying capacity, drilling ability and cooling effect. Results show that for two models in the absence of cooling water, the bottomhole center temperature and pressure are higher than the two sides under multiple hydrothermal jets conditions. This is similar to the flow pattern for a single jet. Additionally, for the five-orifice nozzle with cooling water injected, the entire high temperature region is cylindrical. Ambient cooling water envelops the inner hot water. By comparing different models, the five-orifice nozzle model without cooling water shows a circular symmetric distribution of the bottomhole temperature. With cooling water injected, the central high temperature region becomes rectangular, while the margin of the well bottom is cooled by the peripheral cooling water. The bottom rock average temperature in five-orifice model is lower than for the four-orifice model due to more drastic thermal and kinetic transfer between the hydrothermal jet and the cooling water. The five-orifice nozzle model is better than the four-orifice nozzle model in terms of bottomhole temperature, bottomhole pressure and carrying capacity. Therefore, the five-orifice nozzle should be adopted for hydrothermal jet drilling. It is also feasible to pump down relatively high temperature cooling water to guarantee the high temperature downhole environment. Meanwhile, the cooling water pressure should be controlled during the drilling process for better cooling efficiency. All results in this paper are relevant to the parameters design for multi-orifice hydrothermal jet drilling technology.

1. Introduction

In recent years, petroleum and geothermal energy in deep formations are of interest. Based on the high velocity impact to disintegrate rock, high pressure water jet technology was proposed in the 1960s and 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). However, water jet drilling has not provided satisfactory performance with respect to the breaking hard rocks, such as granite (Foldyna et al., 2005). The pressure to break these rocks is extremely high. This hinders the further application of water jet drilling.

Thermal spallation technology was first applied to petroleum engineering around the 1980s (Heard, 1980). This technology can be divided into two categories: air thermal spallation and hydrothermal spallation drilling. An air thermal spallation drilling uses high temperature media, such as hot air and flares, to heat the rock surface rapidly and cause thermal stresses in the upper rock layer due to thermal expansion. As a result of the stress, thermally induced fragmentation occurs, and disk-like rock fragments are formed in the hot rock spallation zone. Hydrothermal spallation drilling was introduced by ETH Zurich (Augustine, 2009), which aims at drilling mid-depth formations for petroleum and geothermal energy. Numerical simulation and small-scale experiments have been carried out. Augustine (2009) verified the economic viability of hydrothermal spallation drilling. However, due to widely varied rock properties encountered when drilling deep wells through multiple complex formations, a portion of rock may not spall when exposed to a high temperature flame. Therefore, unpredictable circumstances may occur, such as non-spallation of a short interval of

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Nomenclature

a	Local sound speed, m/s
C_p	Specific heat capacity, J/(kg K)
D	Nozzle diameter, m
K	Bulk modulus, Pa
L	Standoff distance, m
p_o	Total pressure, Pa
p_s	Static pressure, Pa
T	Fluid temperature, K
v	Local fluid velocity, m/s
γ	Ratio of specific heat capacity
ρ	Density, kg/m^3

rock, which can prevent the entire thermal spallation drilling operation from succeeding.

A newly developed technology for deep hard rock well drilling, called hydrothermal jet drilling, has only been studied in recent years (Song et al., 2016) and is expected to be more economical and efficient. This technology combines the advantages of water jet (Thomas, 2005) and thermal spallation (Tester, 2006) technologies. First, the hydrothermal jet drilling uses high velocity impact power to disintegrate the rock. Meanwhile, high temperature media are modulated to heat the surface of the rock, which results in heterogeneous thermal stresses and fractures in the rock. Finally, sustained heat makes thin slices leave the parent rock. Consequently, this technology enables faster and more effective drilling than conventional drilling methods, thereby making it possible to exploit deep formations. However, both numerical simulation and laboratory experiments have to be carried out because the study of hydrothermal jet drilling technology has just started.

The new technique proposed in this paper is illustrated in Fig. 1. First, the fuel, oxidizer, and water are injected into coiled tubing at the wellhead, and transported to the downhole reaction chamber. Second, a chemical reaction occurs between the fuel and the oxidizer in the chamber; they are ignited by an electric spark. The reaction products, which are mainly water (648 K, 22 MPa), are in a supercritical state due to the reaction and the hydrostatic pressure of the drilling fluid in the wellbore (exceeding 22 MPa at depths greater than approximately 2 km). In the meantime, the injected water is heated by the reaction to a supercritical state (greater than 648 K and due to the hydrostatic pressure). Thus high temperature fluid, which is mainly water, is discharged from the multi-orifice nozzle fixture in the bottomhole assembly to impinge the heat bottom rock. The rock is broken by the combined effects of thermal stresses and impact force. Finally, all fluid and cuttings return to the surface through the annulus.

In this paper, two 3D multi-orifice hydrothermal jet models are proposed. The first model has four nozzles. One nozzle is at the bottom center of the bit while the other three nozzles are uniformly distributed around bit at an angle of 45° to the vertical direction. The second concept has five nozzles. One nozzle is at the bottom center while the other four nozzles are similarly uniformly distributed. First, hydrothermal jets are discharged from all nozzles in each of the two models. For the same period of time, the flow fields of the two models are analyzed. Then, the original hydrothermal jets discharged from nozzles distributed around bit are converted to cooling water to cool the coiled tubing and wellbore. Finally, the two models are compared with respect to carrying capacity, drilling and cooling effect.

2. Model building

As shown in Fig. 2, the entire 3-D hydrothermal jet model can be divided into a fluid component and a solid component. The fluid part includes the flow of the hydrothermal jet fluid in the bottomhole and the annulus. The solid part includes the wall of the wellbore and ambient rocks. The multi-orifice nozzle is conveyed to the downhole space on the coiled tubing. The fluid discharged from the nozzle impacts on the ambient rocks and then returns to the surface up the annulus.

Two multi-orifice models are presented in this section. As shown in Fig. 3 (left panel), the first model has five orifices. One orifice (central orifice) is at the bottom center while the other four orifices (peripheral orifices) are uniformly distributed around the bit at 45° to the bit axis. The second model has four orifices. One orifice (central orifice) is at the bottom center of the bit while the other three orifices (peripheral orifices) are similarly uniformly distributed.

For the five-orifice nozzle model, half of the multi-orifice model is used to represent the real 3-D situation, to simplify the symmetric drilling model. For the four-orifice nozzle model, the entire 3-D model is established. In both of the models, the high temperature and high velocity fluid is discharged from the jet orifices in the nozzle to disintegrate the bottom rock. In deep formations (> 2 km), the downhole hydrostatic pressure exceeds the critical pressure of water (22 MPa). In addition, due to the high temperature of the chemical reaction (greater than 648 K), the water discharged from the orifices is in a supercritical state. Therefore, the jet's initial temperature is set at 700 K, and the discharged jet pressure is 40 MPa. When there is no cooling water injected, the thermo-physical properties of water are set as constant according to the corresponding temperature and pressure (Peng and Ma, 2005). Outlet annular pressure is 25 MPa. According to Hui et al. (2009), the thermal conductivity of rock is set at 2 W m^{-1} K^{-1}. Gravity (9.81 m/s^2) is considered in the model. A set of governing equations of mass, momentum and energy is used in this model. The Realizable $k-\varepsilon$ model (Martin et al., 2013a,b) and viscous heating are selected because there is heat transfer and turbulent flow. Other mathematical parameters of the model are listed in Table 1.

According to conditions for hydrothermal jet drilling, the boundary conditions are set as follows: **Pressure inlet boundary condition:** the hydrothermal jet is discharged from the multi-orifice nozzle. The temperature of the multiple hydrothermal jets is set constant. **Pressure outlet boundary condition:** all wellbore fluid returns through the

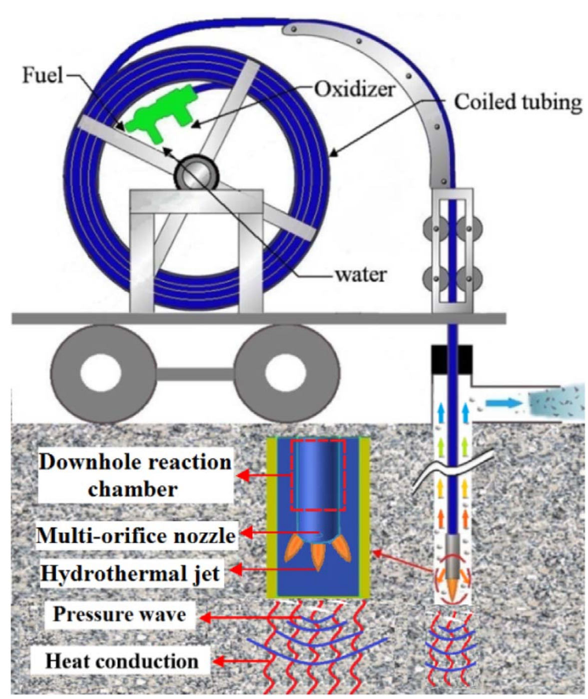

Fig. 1. Coiled-tubing-deployed multi-orifice hydrothermal jet drilling concept.