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Numerical analysis of characteristics of multi-orifice nozzle hydrothermal jet impact flow field and heat transfer

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A B S T R A C T

Hydrothermal jet technology is a new drilling method in which the rocks are broken by the combination of thermal spallation and high velocity impact effect. This technology uses a high temperature and high velocity jet to break rocks and has the potential to be more economically advantageous than conventional techniques for geothermal well drilling. Previous related studies primarily examine numerical simulation on one hydrothermal jet flow field, and to the best of our knowledge, no specific study addresses the thermo-physical interaction between wellbore fluid and ambient rock. This paper presents a multi-orifice nozzle model to investigate the features of a flow field with multiple hydrothermal jets and the heat transfer to ambient rocks. A transient impact flow field with multiple hydrothermal jets is analyzed in terms of axial temperature, bottomhole temperature, and bottomhole pressure. Also, downhole velocity field is specifically investigated. Next, influences of time, jet temperature, and jet pressure difference on the flow field and heat transfer between wellbore fluid and ambient rocks are predicted and compared. The results indicate that the bottomhole central temperature and pressure are higher than the two sides under multiple hydrothermal jets conditions, which is similar to the flow pattern with a single jet. Moreover, the distribution of axial velocity has three peaks at cross-sections, and the centerline axial velocity is the highest. There is a negative relationship between the maximum radial velocity and the ratio between axial distance and nozzle diameter (L/D). Also, the position of the maximum radial velocity moves to the side wall as the ratio (L/D) increases. Second, the bottomhole temperature increases uniformly with increase in jet temperature. The bottomhole temperature becomes decreasingly sensitive to the variance of pressure difference, and the bottomhole pressure exhibits a ladder distribution. Finally, while an increase in either jet temperature or pressure difference can enhance the multiple hydrothermal jets heat transfer effect, increasing the jet temperature is considerably more effective. All of these results are beneficial to the parameters design for the hydrothermal jet drilling technology.

1. Introduction

The use of high velocity impacts from high pressure water jets to enhance the penetration rate of a mechanical bit in petroleum has increased quickly over the last several decades (Li et al., 2012a,b; Chi et al., 2015; Y. Ayed et al., 2016). Nevertheless, water jet drilling is not suitable for breaking hard rocks, such as granite (Foldyna et al., 2005). The necessity of breaking hard rocks prevents the further application of the water jet drilling technology.

Thermal spallation technology was first applied to petroleum engineering around the 1980s (Heard, 1980). This technology 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. However, due to the widely varied rock properties encountered when drilling deep wells through several complicated formations, a portion of rock may not spall when met with high temperature flame. Therefore, unpredictable circumstances may occur, such as the non-spallation of a short interval of rock, which can prevent the whole thermal spallation drilling from succeeding.

A newly developed technology for deep hard rock well drilling, called hydrothermal jet drilling, has been studied only in recent years and is expected to be more economical and efficient. This technology combines the advantages of both water jet (Thomas,

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2005) and thermal spallation (J. W. Tester, 2006) technologies. First, hydrothermal jet drilling uses high velocity impact power to disintegrate the rock. Meanwhile, high temperature media are modulated to heat the surface of rock, which results in heterogeneous thermal stresses and fractures in the rock. Finally, lasting 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 petroleum in 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.

Studies related to hydrothermal jet drilling mainly focus on numerical simulation and small-scale experiments. Chad R. Augustine (2009) verified the economic viability of the technology called hydrothermal spallation drilling. Tobias et al. (2011) used the optical schlieren method to study the penetration length of a supercritical jet and found it equal to the injector's nozzle diameter. Jose et al. (2012) studied the mixing zones between subcritical or supercritical water jets and subcritical co-flow environment. The results showed that when pressure is well above the critical point, fluid-dynamic behavior is more similar to subcritical conditions. Martin et al. (2013a,b) determined the Prandtl number in a subcritical water bath at near-critical pressures via establishing a numerical model and validated it through a laboratory experiment. Previous related studies mainly focus on numerical simulation on a flow field with only one hydrothermal jet and no specific study addresses the thermo-physical interaction between wellbore fluid and ambient rocks. This paper presents a multi-orifice hydrothermal jet model to investigate the features of a flow field with multiple hydrothermal jets and the heat transfer to ambient rocks.

The new technique proposed in this paper is specifically illustrated in Fig. 1. First, the fuel, oxidizer, and water are injected through their respective channels via coiled tubing in the wellhead, and then transported to the downhole reaction chamber. Second, a chemical reaction occurs between the fuel and the oxidizer in the chamber, where they are ignited by an electric spark. Next, the reaction products, which are mainly water (648K, 22 MPa) and carbon dioxide (304K, 7.4 MPa), are in a supercritical state due to the reaction (larger than 1000K) 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 (larger than 648K), which is also due to the hydrostatic pressure. Thus high temperature fluid, which is mainly water, is discharged from the multi-orifice nozzle in the bottomhole assembly to impinge on the heat bottom rock. Rocks are broken by the combined effects of thermal stresses and impact force. Finally, all fluid and cuttings return to the surface from the annulus (see Fig. 2).

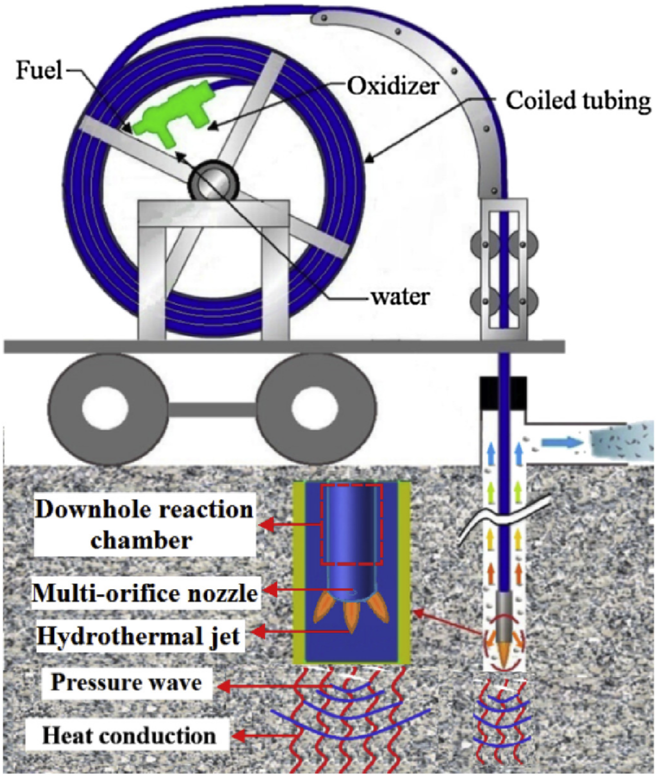

Fig. 1. Coiled-tubing-deployed multi-orifice hydrothermal jet drilling concept.

In this paper, a 3-D multi-orifice nozzle hydrothermal jet model is proposed. Based on previous studies on one hydrothermal jet, five hydrothermal jets are applied in this model. To study the process of hydrothermal jets discharged from a multi-orifice nozzle to the bottom rock, the hydrothermal jet flow field, including axial temperature, bottomhole temperature, and bottomhole pressure, is analyzed over various time periods. The downhole velocity field is highlighted by investigating the effect that multiple hydrothermal jets have on the axial and radial velocity. Next, the influences of jet temperature and pressure difference on the downhole flow field are obtained. Finally, comparison of the heat transfer effect between hydrothermal jets and ambient rocks with different jet temperatures and pressure differences is performed.

2. Model building

To simplify the numerical simulation of an asymmetrical circular drilling model, half of the multi-orifice model is used to represent the real 3-D situation. The whole 3-D hydrothermal jet model can be divided to the fluid part and the solid part. The fluid part includes the flow of hydrothermal jet fluid in the bottomhole and annulus. The solid part represents the wall of the wellbore and ambient rocks.

There are total five orifices in the multi-orifice nozzle hydrothermal jet model. One orifice is at the bottom center of the bit while the other four orifices are uniformly distributed around the bottom center at an angle of 45° to the gravitational direction. The high temperature and high velocity fluid is discharged from the jet orifices in the nozzle to disintegrate the bottom rock. Because hydrothermal jet drilling technology is designed for deep formations, the downhole hydrostatic pressure exceeds the critical pressure of water (22 MPa) at depths greater than approximately 2 km. In

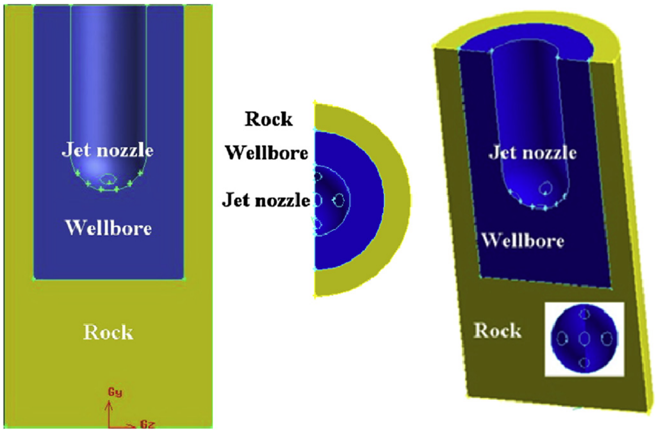

Fig. 2. 3-D multi-orifice nozzle hydrothermal jet model.