Numerical Analysis of Flow Field in Multiple Hydrothermal Jet Drilling for Geothermal Wells

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ABSTRACT

This paper combines high pressure jet and thermal spallation drilling methods together and presents a new hydrothermal jet drilling method. It means striking the rock and conducting heat to it in the meantime and has the potential of being economically advantageous over conventional techniques for geothermal well drilling. Previous related studies mainly focus on numerical simulation on one hydrothermal jet flow field. This paper presents a multi-orifice nozzle model to investigate the features of flow field with multiple hydrothermal jets. Results show 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 single jet. There is a negative relationship between the maximum radial velocity and the ratio between axial distance and nozzle diameter. And the position of the maximum radial velocity moves to the side wall as the ratio increases. Second, the bottomhole temperature increases uniformly with the increase of jet temperature. The bottomhole temperature becomes less and less sensitive to the variance of pressure difference and the bottomhole pressure shows a ladder distribution. Finally, the overall rock temperature is relatively low at the beginning, and there are only three peaks, where the middle one is the highest, due to the impact of central and lateral hydrothermal jets. Besides, there is a positive relationship between the rock temperature and jet temperature. The pressure difference has little influence on the heat transfer effect on the well bottom center, while the increase of pressure difference can substantially enhance the heat transfer effect on the part around center, which means that it can be used for downhole coring. Results in this paper could guide for parameters design of hydrothermal jet drilling technology.

1. Introduction

As a renewable energy resource, geothermal energy has the advantages of 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, which are 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. In view of the high hardness and poor drillability of deep HDR, rate of penetration is limited with conventional drilling methods. A new drilling technology suitable for deep hard formations is expected to be introduced.

The newly developed technology for deep hard rock well drilling called hydrothermal jet drilling, which is expected to be more economical and efficient, has just been studied in recent years. This technology combines the advantages of both water jet (Thomas et al., 2005) and thermal spallation (J. W. Tester et al., 2006) technologies. By modulating the
temperature and pressure of fluid media, the high temperature and high velocity jet is generated to impinge and heat the rock. It leads to rock spallation and micro fractures propagation which are accelerated by the impact of high velocity jet. In the end rocks are broken by coupled jet impact and thermal spallation. Consequently, this technology can drill faster and more effectively than conventional drilling methods, which provides an applicable way for the exploitation of geothermal resources in deep formations. However, both numerical simulation and laboratory experiments have to be carried out since study on hydrothermal jet drilling technology has just started.

Studies related to hydrothermal jet drilling have just begun recently. Chad R. Augustine et al. (2009) concluded that spallation drilling had more economic advantages than conventional rotary drilling technologies. Tobias Rothenfluh et al. (2011) used Optical Schlieren method to study the penetration length of supercritical jet and found it equal to injector’s nozzle diameter. Jose Sierra-Pallares et al. (2012) studied the mixing zones between subcritical or supercritical water jets and subcritical co-flow environment. Results showed that when pressure is well above the critical point, fluid-dynamic behavior is more similar to subcritical conditions. Martin J. Schuler et al. (2013) 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. Martin J. Schuler et al. (2013) proposed a numerical model and the Prandtl number was determined in a subcritical water bath at near-critical pressures. Previous related studies mainly focus on numerical simulation on flow field with only one hydrothermal jet and there is no specific study on the thermo-physical interaction between wellbore fluid and ambient rocks. This paper presents a multi-orifice hydrothermal jet model to investigate the features of flow field with multiple hydrothermal jets.

The new technique proposed in this paper is specifically illustrated in Figure 1. The fuel, oxidizer and water are injected through respective channels via coiled tubing, and then transported to the downhole reaction chamber. Chemical reaction occurs between fuel and oxidizer in the water environment in the chamber, where they are ignited by electric spark. Thus high temperature reaction products which are mainly water is discharged from the multi-orifice nozzle in the bottomhole assembly to impinge the rock. Finally, all fluid returns to the surface from the annulus.

2. Model Building

To simplify the numerical simulation of asymmetrical circular drilling model, half of the multi-orifice model is used to represent the real 3-D situation. There are total five orifices in the multi-orifice nozzle hydrothermal jet model. The high temperature and high velocity fluid is discharged from the jet orifices in the nozzle to disintegrate the bottom rock. Since the hydrothermal jet drilling technology is designed for deep formations, the downhole hydrostatic pressure exceeds the critical pressure of water (22MPa) at depths greater than about 2km. In addition, due to the high temperature of chemical reaction (often larger than 648K), the water discharged from the orifices is in supercritical state. Therefore, the jet initial temperature is set as 700K and jet pressure is 40MPa. The thermo-physical properties of water are set according to the corresponding temperature and pressure (Peng et al., 2005). Outlet annular pressure is 25MPa. According to Hui et al. (2009), the thermal flux was set as $2W \cdot m^{-1} \cdot K^{-1}$. Gravitation (9.81m/s²) was considered in the model. The realizable $k-\varepsilon$ model (Martin J. Schuler et al., 2013), viscous heating and
energy model were also chosen to simulate 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, boundary conditions are set as follows:

Pressure inlet boundary condition: hydrothermal jet is discharged from the multi-orifice nozzle. The multiple hydrothermal jets temperature is set constant.

Pressure outlet boundary condition: all wellbore fluid flows out from the annulus with constant outlet pressure.

Stationary wall boundary condition: in the process of numerical simulation, the wellbore and the drill pipe are stationary. Thus the wall boundary condition is used to seal off the surrounding boundaries.

To guarantee the simulation results are mesh-independent, meshes with different interval sizes, including 6, 4, 3, 2, 1, etc., are computed illustrated by Figure 3. The axial temperature at 10mm down to the center nozzle is used as the indicator of mesh sufficiency. Figure 3 shows that from interval size 1, the axial temperature at the indicator becomes constant. In addition, in view of computational precision and complexity, it is acceptable to choose 1 as the final mesh interval size.

3. Results Analysis

3.1 Analysis of Downhole Transient Flow Field

Downhole temperature contours with different times of 0.0001s, 0.01s, 0.1s and 1s are shown in Figure 4. Four central normal sections are illustrated in which the area with high temperature becomes larger and larger as the time increases. At the time of 0.0001s, three hydrothermal jets are clearly distributed in the wellbore, which represent the initial stage for hydrothermal jets discharged from the multi-orifice nozzle. When the time reaches 1s, the average temperature of rocks can be about 500K.

Figure 5 shows the axial temperature distribution along the wellbore center with different times. It can be concluded that when the time reaches 0.0001s, the high temperature hydrothermal jet has not yet arrived and is in the position of 20mm to the bottom rock. And then the high temperature hydrothermal jet arrives at the bottom when the time reaches 0.1s. After that, the whole wellbore central axis keeps at the initial hydrothermal jet temperature of 700K.

Figure 6 shows the bottomhole temperature distributions with different times. It can be concluded that the average bottomhole temperature increases as the time passes by. When the time reaches 0.0001s, since the high temperature hydrothermal jet has not arrived at the well bottom, the bottomhole rock remains at the initial formation temperature. Then the whole bottomhole temperature gradually increases. However, during the whole flow process, the bottomhole central temperature is a little higher than
the other two sides because the high temperature and high velocity hydrothermal jet straightly impinges on the bottomhole center, which initiates directly heat transfer between wellbore fluid and ambient rocks. Meanwhile, the heat on the other two sides of bottomhole rock is carried away by the cross flow on the well bottom.

Figure 7 shows that, when the time reaches 0.0001s, the bottomhole center pressure is relatively low that is only 26.18MPa. Then the bottomhole center pressure increases with the increase of time and reaches 26.27MPa when the time is 1s. At each time, there are three peaks of bottomhole pressure while the middle is the highest. The bottomhole center pressure is larger than the other two sides because the high temperature and high velocity hydrothermal jet straightly impinges on the bottomhole center. And the positions close to the side wall have a little larger pressure since there are lateral hydrothermal jets discharged from the orifices which are at an angle of 45 degrees to the vertical direction.

Axial velocity and radial velocity are two important elements in reflecting the utilization efficiency of jet energy. Therefore, it is reasonable to analyze the flow field velocity distribution regularities from downhole hydrothermal jet axial velocity and radial velocity aspects.

Figure 8 shows how the axial velocity develops at the six cross sections that are 0 to 5 of dimensionless stand off distances (ratio of distance to the bottom center orifice in the nozzle and diameter of the orifice, L/D). The x-coordinate is the distance horizontally to the well bottom center. The y-coordinate is dimensionless axial velocity \( \frac{V}{V_{\text{max}}} \), which is the local velocity divided by the maximum velocity. It can be concluded from Figure 8 that the distribution of axial velocity has three peaks at cross sections, and the centerline axial velocity is the highest. At the cross section of L/D=0, the central hydrothermal jet axial velocity is the largest. The axial velocity decreases first and then increases along the wellbore radius. The flow of the central hydrothermal jet is affected by the confinement of the bottom rock, thus the axial velocity gradually decreases along the wellbore central axis. The local axial velocity increases as the position moves towards to the side wall as a result of the influence of the axial component of lateral hydrothermal jets. Afterwards, the axial velocity decreases with less and less influence of lateral hydrothermal jets. Similarly, in comparison of maximum axial velocity at different cross sections, with the influence of lateral hydrothermal jets attenuating, the maximum of axial velocity decreases, and the position of it gradually moves to the side wall.
Figure 9 shows how the radial velocity develops at the six cross sections that are 0 to 5 of dimensionless standoff distances (ratio of distance to the bottomhole center orifice and diameter of the orifice, L/D). The x-coordinate is the distance horizontally to the well bottom center. The y-coordinate is dimensionless radial velocity V/Vmax, which is the local velocity divided by the maximum velocity.

Because the high temperature and high velocity hydrothermal jet occupies the central axis of the wellbore, the radial velocity at the bottomhole center in Figure 9 is zero. The distributions of radial velocity, which increases at the first and decreases later from the bottomhole center to the side wall, are almost the same at different cross sections. The changes in the distribution of radial velocity become larger and larger closing to the bottomhole nozzle because of the influence of lateral hydrothermal jets. And there is a negative relationship between the maximum radial velocity and the ratio between axial distance and nozzle diameter (L/D). And the position of the maximum radial velocity moves to the side wall as the ratio (L/D) increases.

3.2 Analysis of Downhole Impact Flow Field With Different Jet Temperatures

In this section, in order to analyze the influence of jet temperature on the downhole impact flow field within the same period of time, the nozzle exit temperature is set as 650K, 700K, 750K and 800K, respectively.

The flow time of hydrothermal jets is 1s, and the downhole temperature field is illustrated in Figure 10. The temperature in the vicinity of orifices around the jet nozzle is slightly higher. The area of ambient rock affected by the high temperature wellbore fluid is almost the same. Besides, the wellbore temperature becomes higher as the increase of jet temperature.

Figure 11 indicates that the distributions of bottomhole temperature with different jet temperatures are conical. The temperature in the middle of bottom rock is higher, which can be up to the initial jet temperature, while the other two sides are relatively lower. However, the temperatures in the two sides of bottom rock is slightly higher than the original decreasing trend of temperature distribution from the middle to the side, due to the effect of lateral hydrothermal jets. In addition, the bottomhole temperature increases uniformly with the increase of jet temperature.

Figure 12 shows the bottomhole pressure distributions with different jet temperatures are the same, which means that the bottomhole pressure has no relevance to the jet temperature. The bottomhole pressure in the middle is the highest while the pressures in the two sides are also slightly higher due to the effect of lateral hydrothermal jets.
3.3 Downhole Impact Flow Field Analysis With Different Pressure Differences

In this section, in order to analyze the influence of pressure difference between the nozzle exit and the annulus on the downhole impact flow field. The nozzle exit pressure is set as constant 40MPa while the annular pressures are set as 25, 30 and 35MPa, respectively. Therefore, the jet pressure differences are 15, 10 and 5MPa, respectively.

For the same period of time, the downhole velocity field is illustrated in Figure 13. The major differences between different pressure differences are obviously in the vicinity of the orifice. The velocity of hydrothermal jets becomes higher and higher as the pressure difference between the nozzle exit and the annulus increases.

Figure 14 indicates the jet axial velocity distributions with 5, 10 and 15MPa pressure differences. It can be concluded that the jet axial velocity keeps almost constant at first and then decreases sharply because of the confinement of the bottom rock. The initial hydrothermal jet velocity can be up to 400m/s when the pressure difference is 15MPa. In addition, the initial velocity becomes higher and higher with the increase of pressure difference. The increasing amplitude is positively correlated with the increase of pressure difference.

For the same period of time, the downhole temperature field is illustrated in Figure 15. The whole average downhole temperature becomes higher as the pressure difference between the nozzle exit and the annulus increases. Besides, the heat transfer effect between the wellbore fluid and ambient rocks becomes better, especially for the area near to the hydrothermal jet flow orifices, with the increase of pressure difference.

Figure 16 shows the bottomhole temperature distributions with 5, 10 and 15MPa pressure differences. It can be concluded that the temperature at the bottomhole center is higher than the other two sides and the hydrothermal jet pressure difference is able to have large effect on the distribution of bot-
tomhole temperature. During the same period of time, the bottomhole central temperature gradually increases with the increase of pressure difference. However, it becomes less and less sensitive to the variance of pressure difference since the increasing amplitude gradually decreases. Moreover, the bottomhole temperature distribution tends to be almost the same with different pressure differences.

Figure 17 illustrates the bottomhole pressure distribution with pressure differences of 5, 10 and 15MPa. The pressures distributed in the middle and two sides are slightly higher because of the pattern of multiple hydrothermal jets. And the bottomhole pressure gradually increases with the increase of pressure difference. The increasing amplitude is almost the same and equal to the annular pressure, respectively.

3.4 Analysis of Influence on Heat Transfer Effect of Key Factors

The heat transfer effect between multiple hydrothermal jets and ambient rocks is influenced by many factors. In this section, three main factors, including time, jet temperature and pressure difference are investigated and compared.

Figure 18 shows axial temperature distribution in the wellbore at different times. When the time reaches 0.0001s, the axial temperature decreases to zero where it is 10mm to the bottom rock because the hydrothermal jet has not arrived at the well bottom. Then the hydrothermal jet arrives at the bottom when 0.01s and the whole wellbore axis keeps at 700K, which begins the next stage of heat transfer. The hydrothermal jet farther transfers heat to the bottom rock when 0.1s. The thickness of rock influenced by heat is 5mm. After that, 20mm rock thickness is affected when the time is 1s. Therefore, more and more bottom rock receives heat with the increase of time.

In Figure 19, the rock temperature distributed 10mm under the well bottom is illustrated as the indicator of the influences of different times. As described in Figure 18, at 0.0001s, the hydrothermal jet has not reached the well bottom. The overall rock temperature is
relatively low and there are only three peaks due to the impact of central and lateral hydrothermal jets, where the middle one is the highest. From 0.0001s to 0.1s, the rock temperature becomes higher and higher. Since 0.1s, the temperature distribution keeps the same, which indicates that the heat influx has already affected this depth of bottom rock.

Figure 20 gives the rock temperature distributions with different jet temperatures at the time of 1s. For each temperature of hydrothermal jet, the rock temperature keeps at the initial jet temperature. By comparing distributions of rock temperature with different temperatures, the higher the jet temperature is, the higher the temperature of rock is at the same depth, which means that it is much easier for the bottom rock to spall and disintegrate. Besides, there is a positive relationship between the rock temperature and jet temperature.

To analyze whether the jet pressure difference has influence on the bottom rock heat transfer, rock temperature distributions in the wellbore with different pressure differences during the same period of time of 1s are compared in Figure 21. It can be concluded that the bottom rock temperature is relatively low when the pressure difference is 5MPa. The rock temperatures in the center are almost the same when the pressure differences are 10, 15 and 20MPa, while the rock temperatures on the two sides becomes higher and higher as the increase of pressure difference. Therefore, the pressure difference has little influence on the heat transfer effect on the well bottom center, while the increase of pressure difference can substantially enhance the heat transfer effect on the part around center, which means that it can be used for downhole coring.

Figure 20. Distribution of temperature in the rock with different jet temperatures.

Figure 21. Distribution of temperature in the rock with different pressure differences.

4. Conclusions

This paper presents a multiple hydrothermal jets model to investigate the features of flow field. The following conclusions are drawn.

(1) With the increase of time, multiple hydrothermal jets gradually transfer heat to the ambient rock. After reaching the well bottom, the bottomhole central temperature and pressure are higher than the other two sides because of the jet flow patterns. The distribution of axial velocity has three peaks at cross sections, and the centerline axial velocity is the highest. Besides, there is a negative relationship between the maximum radial velocity and the ratio between axial distance and nozzle diameter (L/D). And the position of the maximum radial velocity moves to the side wall as the ratio (L/D) increases.

(2) With different jet temperatures, the temperature in the vicinity of orifices around the jet nozzle is slightly higher. Besides, the wellbore temperature becomes higher as the increase of jet temperature. The bottomhole temperature increases uniformly and the bottomhole pressure has no relevance to the jet temperature. With different pressure differences, the velocity of hydrothermal jets becomes higher and higher as the pressure difference between the nozzle exit and the annulus increases. The increasing amplitude is positively correlated with the increase of pressure difference.

(3) From the beginning, the overall rock temperature is relatively low and there are only three peaks, where the middle one is the highest, due to the impact of central and lateral hydrothermal jets. Besides, there is a positive relationship between the rock temperature and jet temperature. The rock temperatures in the center are almost the same when the pressure differences are 10, 15 and 20MPa, while the rock temperatures on the two sides becomes...
higher and higher as the increase of pressure difference. Therefore, the pressure difference has little influence on the heat transfer effect on the well bottom center, while the increase of pressure difference can substantially enhance the heat transfer effect on the part around center, which means that it can be used for downhole coring.

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