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Numerical analysis of the impact flow field of multi-orifice nozzle hydrothermal jet combined with cooling water

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ABSTRACT

Hydrothermal jet technology is a novel drilling technology and has just been studied for several years. This technology uses a high temperature and high velocity jet to break rocks and has the potential to be more efficiently advantageous than conventional techniques for deep hard formations and geothermal well drilling. This paper presents a multi-orifice hydrothermal jet model with cooling water to investigate the features of the flow field by CFD methods. First, a transient impact flow field is analyzed. Besides, influences of jet temperature, cooling water temperature and cooling water pressure on the flow field and annular cooling effect are predicted and compared. Predictions are found to be in good agreement with the published heat transfer theory for hydrothermal jet temperatures ranging from 650 K to 800 K. Results indicate that ambient cooling water envelops the high temperature hydrothermal jet in the middle. There is a second peak of bottomhole temperature and the pseudo-critical point is located. Controlling the hydrothermal jet temperature at the vicinity of the pseudo-critical point or far larger than the pseudo-critical temperature can have a better heat transfer effect. The simultaneous effect of both the hydrothermal jet and cooling water results in the non-uniform distribution of bottom temperature, which leads to higher rate of penetration. It is recommended that the cooling water pressure should be larger than the hydrothermal jet pressure, which might result in higher rate of penetration and cool the coiled tubing and borehole wall simultaneously. Results in this paper are beneficial to the parameters design for the hydrothermal jet drilling technology.

1. Introduction

1.1. Background

High pressure water jet is a method using the high velocity impact to break the bottom rock. It has been widely used in the petroleum industry over the last several decades [1–3]. One kind of enhanced water jet is the abrasive jet method. It can be used for drilling, cutting, etching, polishing and cleaning. Srikanth et al. presented the optimization of process parameters of abrasive jet machining of glass by Taguchi methodology [4]. Lu et al. designed a hard rock breaking bit and a set of hard rock drilling equipment system with abrasive water jet assistance. The experiments were conducted and compared with the conventional technique, indicating that the drilling depth has increased about 63% and the bit wear has been reduced significantly [5]. Montesano et al. investigated the influence of conventional drilling and abrasive water jet cutting on the fatigue performance of carbon fabric/epoxy plates [6]. Löschner et al. presented the effect of cutting speed on surface roughness in abrasive water jet cutting of 10 mm thick stainless steel samples [7]. Ahmed et al. carried out numerical studies to find the particle impact characteristics on the groove wall (cutting surface) as well as side walls for different radii of curvature [8]. Shukla et al. performed an experimental investigation on abrasive jet machining process for the machining of material AA631-T6 using the Taguchi methodology [9]. Nevertheless, the loss of hydraulic power at deep depths makes the water jet not suitable for breaking deep hard rocks, such as granite [10]. Thus, the necessity of breaking deep hard rocks prevents the further application of the related water jet drilling technology.

Thermal spallation technology was first applied to petroleum engineering around the 1980s [11]. 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 the thermal expansion. As a result of the stresses, thermally induced fragmentation occurs, and disk-like rock fragments are formed in the hot rock spallation zone. Its studies mainly focus on numerical simulation and small-scale experiments. Besides, about ten years ago, a method called hydrothermal spallation

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drilling (HSD) was proposed, which uses the hot fluid, such as supercritical water, to break rock in relatively deep formations. Augustine et al. verified the economic viability of the HSD [12]. Table 1 lists the previous related studies on the HSD. At the beginning, several researchers focused on the investigation of supercritical water oxidation (SCWO) to deal with the waste water and general the hydrothermal flame [13–15]. Then, HSD was studied by performing numerical simulation and experiments. The mixture of methanol/ethanol and water, and oxygen are electrically heated to the auto-ignition temperature before injected or heated at the inlets of the autoclave. The operating pressures are all above the critical pressure of water. 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.

1.2. Hydrothermal jet drilling

Hydrothermal jet drilling technology has been studied only in recent years and is expected to be more economical and efficient for deep hard formations. This technology intends to combine the advantages of both water jet and thermal spallation technologies [24,25]. First, hydrothermal jet drilling uses the 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 or geothermal energy 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.

The technique 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 (650 K, 22.1 MPa), are in 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. 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.

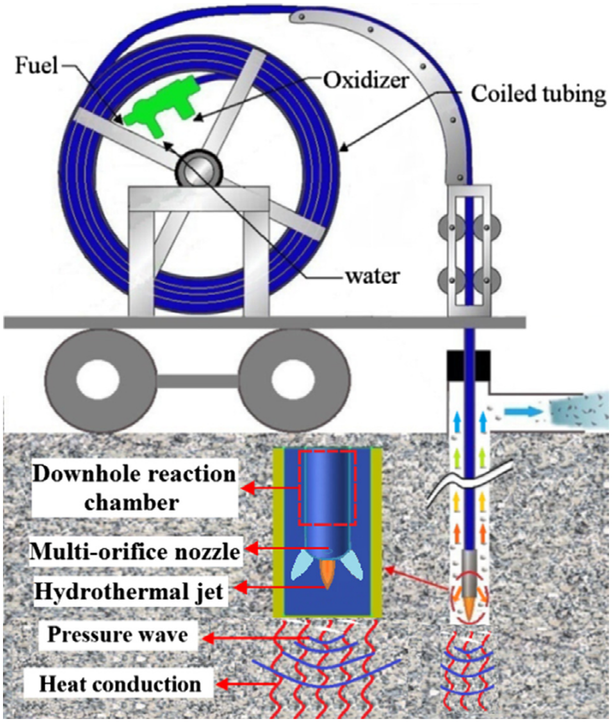

Fig. 1. Coiled-tubing-deployed multi-orifice hydrothermal jet drilling concept [15]

Computational fluid dynamics (CFD) is one of the techniques which can be used to visualize the simulated particular flow inside the wellbore under different operating conditions [26,27]. In 2016, Song et al. simulated and analyzed the downhole flow field with a single hydrothermal jet [24]. Besides, Song et al. also investigated the downhole flow field and the thermo-physical interaction

Table 1
Previous related studies on hydrothermal spallation.

Author	Topic	Temperature (°C)	Pressure (bar)	Comments
Prikopsky et al. [13]	SCWO	200–500	250	A kind of reactor set-up aimed at reactor fouling and plugging due to precipitation of salts
Welling et al. [14]	SCWO	200–1000	250	The inlet temperature of the fuel stream can be lowered below 100 °C with 27 wt.% methanol to obtain good oxidation results
Narayanan et al. [15]	SCWO	400–1200	250	Simulation of supercritical single-phase combustion has been performed for two methanol inlet mass fractions using a CFD tool
Rothenfluh et al. [16]	HSD	375–500	223	Penetration lengths of supercritical jets are determined using an optical Schlieren method
Sierra-Pallares et al. [17]	Flow field	300–800	250	It presents the evolution of subcritical to supercritical mixing, revealing the decrease of the mixing zone when temperature is increased well above the critical point
Schuler et al. [18]	Flow field	100–500	224–400	Various approaches based on a variable turbulent Prandtl number are presented to model the thermal conductivity more accurately
Stathopoulos et al. [19]	HSD	450–800	260	The influence of the bulk temperature, the fuel composition and the flow conditions on the forced ignition is presented
Schuler et al. [20]	HSD	300–1000	224	Penetration lengths of the supercritical jet plume at near-critical pressures are determined numerically and experimentally
Meier et al. [21]	HSD	0–500	260	The hot surface ignition of turbulent diffusion oxygen-ethanol hydrothermal flames is presented
Meier et al. [22]	HSD	0–1200	260	A custom made sensor with an extended service life is used to ignite and monitor a hydrothermal combustion
Schuler et al. [23]	HSD	300–485	225	Stagnation flow heat transfer under supercritical pressures of water is investigated