Geothermics 77 (2019) 62–74

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Numerical analysis of characteristics of reaction in hydrothermal jet drilling for geothermal energy

Zehao Lyu, Xianzhi Song*, Gensheng Li

State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing, Beijing 102249, China

ARTICLE INFO

Keywords:
Hydrothermal jet
Drilling
Numerical simulation
Reaction field

ABSTRACT

Hydrothermal jet technology is a drilling method, which is potentially suitable for the exploitation of geothermal energy in deep hard formations. The generation of a stable hydrothermal jet via combustion in the reaction chamber is an important subject for successful applications. In this paper, the Peng-Robinson equation of state and four combustion models are applied to simulate the reaction in the downhole chamber. Simulation results are compared with experimental data to obtain a suitable model. The reaction flow field and effects of several factors (i.e., fuel and oxygen flow rate, mass fraction, and wall temperature) are studied. Results show that under the conditions of this paper, the finite rate model is more suitable. It may be better to inject the maximum fraction of fuel for complete reaction to obtain the highest jet pressure and temperature simultaneously. The cooling water flow rate and temperature can be adjusted over a broad range to control the temperature of the reaction chamber within a suitable range. Results in this paper could provide guidance for further research on hydrothermal jet drilling.

1. Introduction

As a renewable energy resource, geothermal energy is usually stored in subsurface, hot, and low-permeability crystalline rocks, normally located at depths of 3–10 km (Idaho National Laboratory, 2006). However, the hardness of rock in these deep formations is high and the drill-ability is poor. For traditional rotary drilling methods, the loss of drilling mechanical energy and hydraulic energy is large along the drill string. Also, contact between the drill bit and the rock causes abrasion of the drill bit, and continual tripping and making connections lead to high drilling costs. Therefore, it is necessary to develop a new, efficient drilling method for deep formations.

Based on high velocity impact to disintegrate rock, high pressure water jet technology was proposed in the 1970s (Maurer and Heilhecker, 1969; Wa and Duncan, 2007) and has developed quickly in the past decades (Ayed et al., 2016; Chi et al., 2015; Li et al., 2012). It has been successfully applied in assisting the mechanical bit to enhance the rate of penetration in petroleum, mining, etc. However, water jet drilling has not provided satisfactory performance with respect to the breaking of hard rocks, such as granite (Foldyna et al., 2005). The threshold of pressure to break rocks is extremely high, which may hinder further application of water jet drilling.

Alternatively, thermal spallation drilling technology uses high temperature fluid to produce non-uniform expansion stresses within the rock in front of the bit (Ferré et al., 1998; Li et al., 2014). Due to these stresses, 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) (Lyu et al., 2018b, 2018c).

Research about rock spallation mainly focuses on experimental studies of the characteristics of rock under high temperature and high pressure conditions, the initiated micro-cracks in the rock and numerical simulation. Early research performed by Rauenzahn and Tester established the basis for this study and focused on characterization of fundamental mechanisms of spall formation, ejection and fluid flow, and heat transfer process modeling (Tester and Howard, 1990). In addition, Lyu et al. tried to optimize the combustion model to simulate the thermal jet more accurately with less computational cost (Lyu et al., 2017).

In the last decade, a technology referred to as hydrothermal spallation drilling was proposed by combing thermal spallation drilling with supercritical water oxidation (SCWO). SCWO is a high pressure, high temperature process, which was previously studied for the efficient destruction of an extensive diversity of aqueous organic wastes (Abelleira et al., 2013; Xu et al., 2016; Yan et al., 2016). It is based on

* Corresponding author.
E-mail address: songxz@cup.edu.cn (X. Song).

https://doi.org/10.1016/j.geothermics.2018.08.003
Received 18 April 2018; Received in revised form 1 July 2018; Accepted 9 August 2018
0375-6505/

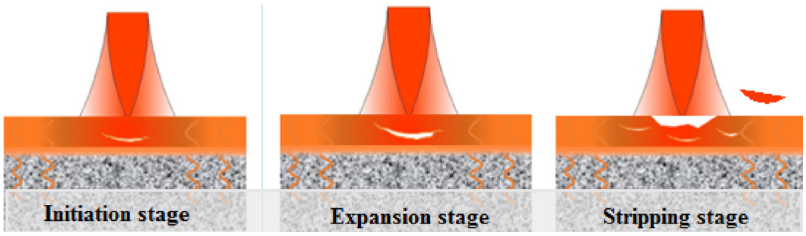

Fig. 1. Thermal spallation process.

oxidation in an aqueous medium under conditions above the critical point of pure water, usually in the range of 673–923 K and commonly at a pressure around 25 MPa. Under these conditions, water exhibits unique physical-chemical properties that make it an effective medium for oxidation. Because organics and oxygen form a homogeneous phase, mass transport limitations are minimized leading to high reaction rates and conversions close to unity in short residence times and small reactor volumes (Calzavara, 2005; Kiss et al., 2016; Onwudili and Williams, 2006; Serikawa et al., 2002).

Augustine et al. concluded that hydrothermal spallation drilling has more economic advantages than conventional rotary drilling technologies (Augustine, 2009). Rothenfluh et al. 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 (Rothenfluh et al., 2011). Sierra-Pallares et al. 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 (Sierra-pallares et al., 2012). Schuler et al. proposed a numerical model and the Prandtl number was determined in a subcritical water bath at near-critical pressures (Schuler et al., 2013a, 2013b).

In summary, recent studies have mainly used experimental and numerical methods to investigate characteristics of hydrothermal spallation drilling. These were performed under conditions where the high temperature fluid velocity is lower than the co-flow circumferential low temperature water. However, for deep wells drilling through multiple complicated formations, many rock materials do not spall. In this situation, a very short interval of non-spallable rocks can impede the advance during thermal spallation drilling.

Hydrothermal jet drilling is a technology, which combines the advantages of both the high pressure water jet and thermal spallation drilling method (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. The thermal effect leads to rock spallation and micro-fracture propagation. Meanwhile, the rock-breaking is accelerated by the impact of the high velocity jet. Thus, rocks are broken by coupled jet impact and thermal spallation. This technique can reduce the abrasion and the tripping time, and has the potential for drilling wells several kilometers deep in hard rock.

Specifically, 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. The reaction products, which are 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 the coiled tubing and returns to the surface through the annulus. This can cool the wellbore and coiled tubing simultaneously, and avoid thermal destruction of the borehole wall by the high temperature fluids. Moreover, circulation of cooling water can increase the cuttings transport efficiency. Thermal insulation is applied around the coiled tubing to keep the cooling water from influences of the reservoir or combustion (Lyu et al., 2018c; Song et al., 2017b).

Computational fluid dynamics (CFD) is one of the techniques which can be used to simulate flow inside the wellbore under different operating conditions (Gandhi et al., 2012; Zhao et al., 2013). In 2016, Song et al. investigated the downhole flow field and the thermo-physical interaction between wellbore fluid and ambient rock with a multi-orifice nozzle hydrothermal jet (Song et al., 2016). Also, Song et al. proposed and compared two cooling configurations (lateral configuration and downward configuration) for a single hydrothermal jet (Song et al., 2017a).

However, to the best of our knowledge, there has been no specific investigation related to the characteristics of reaction in the hydrothermal jet drilling. This paper shows carry out preliminary investigations on the reaction field in hydrothermal jet drilling. The Peng-Robinson equation of state is applied. Four combustion models are selected and simulation results are compared with related experimental data to obtain a suitable simulation model. The reaction field in the reaction chamber is studied and the effects of fuel and oxygen mass flow rate, methanol (i.e., fuel used in this paper) mass fraction and cooling wall temperature are analyzed.

2. Simulation model analysis

2.1. Thermo-physical properties of supercritical water

The process of SCWO mainly depends on the thermo-chemical and phase-change-related fluid properties. For each value of constant environment pressure, there is a corresponding temperature yielding the maximum value of specific heat capacity at the so-called pseudo-critical point (PCP). The corresponding temperature is called the pseudo-critical temperature (PCT). The line connecting all these PCPs is called the pseudo-critical line (PCL). In the vicinity of this PCL, all thermo-physical properties are very sensitive to temperature variations, undergoing sharp changes (i.e., increase and decrease sharply at the PCP). The water density exhibits very different, varying patterns (Wagner and Pruß, 2009). With respect to specific heat capacity, at a pressure of 25 MPa, the specific heat capacity changes sharply at a temperature about 400°C. The thermal conductivity is about an order of magnitude smaller in the gaseous and supercritical region than in the liquid region (Lieball, 2003). In the supercritical region, the thermal conductivity keeps almost constant and the water viscosity is relatively low.

2.2. Equation of state

The Peng-Robinson equation of state, which is applied in the simulation, is adopted for the SCWO process in hydrothermal jet drilling (Lieball, 2003; Peng and Robinson, 1976). Peng-Robinson is a model that is commonly used because it is relatively accurate for the prediction of vapor pressure, density and other thermodynamic properties of non-polar and slightly polar fluids (Peng and Robinson, 1976). Because water tends to be more non-polar under the supercritical condition, the Peng-Robinson equation of state may be able to describe the changing properties of supercritical material in hydrothermal jet drilling.

The general form of pressure P for this cubic equation of state model is written as: