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Analysis of temperature simulation in downhole reaction chamber of hydrothermal jet drilling

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ABSTRACT

Hydrothermal jet is an alternative drilling method for the exploitation of oil and geothermal energy in deep hard formations. For the application of this novel technology, the successful generation of hydrothermal jet is very important. This paper focuses on investigating applications of different reaction, turbulence and radiation models to the supercritical water oxidation process in downhole reaction chamber of hydrothermal jet drilling. The objective is to identify the pros and cons of each model and determine a set of models that are the most appropriate for the reaction. Simulation models are tested and optimized through two different operating conditions. Simulation results are compared with experimental data. Results show that the entire space of the reaction chamber is in a high temperature state using the laminar finite rate model. The finite rate model is suitable for the simulation compared with other reaction models discussed. The Magnussen constant *A* and *B* in the finite rate model can be modified to be 7 and 0.5 to further reduce the error. In addition, the high temperature areas in k-omega model and SAS model are more concentrated, while they are more uniform in RNG k-epsilon model and standard k-epsilon model. The RNG k-epsilon model and DO or DTRM are the most appropriate turbulence and radiation models through comparison. Results in this paper can provide implications for the reaction simulation of hydrothermal jet drilling.

1. Introduction

Massive resource, such as petroleum and geothermal energy, is stored in deep hard formations, normally located at depths of 3–10 km [1]. The rocks in these deep formations are usually very hard, which makes the drill-ability is poor. The loss of drilling mechanical energy and hydraulic energy is large along the drill string for conventional rotary drilling methods. In addition, the contact between the drill bit and rock, continual tripping and making connections result in the abrasion of drill bit, which is also time-consuming [2]. Therefore, it is necessary to develop a new efficient drilling method for deep formations.

A drilling method called hydrothermal spallation drilling was proposed about a decade ago, which uses the thermal effect to break the bottom rock [3]. The generation of the hydrothermal fluid is based on supercritical water oxidation (SCWO) in the downhole reaction chamber. The SCWO process is a kind of reaction, in which organic materials react with oxidizer in a supercritical environment (temperature and pressure higher than 650 K and 22.1 MPa, respectively) [4,5]. During the process, the organic materials, oxidizer and water are in a single phase, which makes the oxidation proceeds rapidly by an elimination of potential interface mass transport limitation [6,7]. The main advantage of the SCWO is that it is a very efficient reaction process and the products are non-toxic [8,9]. Many researchers have investigated the SCWO process. In 2007, Prikopsky et al. studied the reactor set-up about fouling and plugging due to the precipitation of salts [10]. Wellig et al. concluded that the inlet temperature of the fuel stream can be lowered below 100 °C with 27 wt% methanol to obtain good oxidation results [11]. Marrone et al. reviewed the status of full-scale commercial SCWO facilities and focused on the related challenges [12].

Meanwhile, some investigations have been carried out about hydrothermal spallation drilling. Rothenfluh et al. studied the penetration lengths of supercritical jets using an optical Schlieren method [13]. Sierra-Pallares et al. focused on the investigation on the transition from subcritical to supercritical mixing [14]. Schuler et al. presented various approaches based on a variable turbulent Prandtl number to model the thermal conductivity [15]. Other researchers have studied the feasibility of ignition under such harsh conditions. Stathopoulos et al. studied the influences of bulk temperature the fuel composition and the flow conditions on the forced ignition [16]. Schuler et al. determined penetration lengths

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Nomenclature

A and B	magnussen empirical constants
A_r	pre-exponential factor, s^{-1}
a_λ	spectral absorption coefficient, m^{-1}
C	coefficient of the linear phase heterogeneous phase function
$C_{j,r}$	molar concentration of species j in reaction r
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ and C_μ	constants
C^ε	volume proportion constant
C_τ	time scale constant
D and c_μ	constants for SAS model
E_r	reaction activation energy, J/mol
F_1	blending function
f	mixing fraction
f_{fuel}	value at the fuel flow inlet
f_{ox}	value at the oxidant flow inlet
f_{sec}	value at the second flow inlet
G	incident radiation, W/m^2
G_k	turbulence kinetic energy due to the mean velocity gradients, $m^2\ s^2$
G_b	turbulence kinetic energy due to buoyancy, $m^2\ s^2$
G_ω	generation of ω
I	radiative intensity, $W\ m^{-2}\ sr^{-1}\ Hz^{-1}$
$I_{b\lambda}$	black body intensity, W/m^3
J_k	energy that is given off (or radiosity) of surface k
k	turbulence kinetic energy, $m^2\ s^2$
$k_{f,r}$	forward constant for reaction r
L	length scale of the modeled turbulence, m
$L_{\upsilon\kappa}$	von Karman length scale, m
$M_{w,i}$	molecular weight of the component i, kg/kmol
N	number of chemical components
n	refractive index
P	absolute pressure, MPa
P_c	critical pressure, MPa
R	universal gas constant
$R_{i,r}$	net rate of species i caused by reaction r, $kmol/m^3/s$
$\vec{r}$	position vector
r and z	spatial coordinates in radial and axial direction, respectively
$\vec{s}$	direction vector
$\vec{s}'$	scattering direction vector
s	path length, m
S	modulus of the mean rate-of-strain tensor
S_k, S_ε and S_ω	user-defined source terms
T	temperature, K
T_c	critical temperature, K
t	time, s
u_i	velocity component, m/s
V	specific molar volume, m^3
V_c	critical volume, m^3
$\upsilon'_{i,r}$ and $\upsilon''_{i,r}$	reactants of the component i in the chemical reaction r and the chemical correctness coefficient of the product
υ	kinematic viscosity, m^2/s
Y_M	contribution of the fluctuating dilatation
Y_P	mass fraction of the product P
Y_R	mass fraction of the reactant R
Y_ω	dissipation of ω due to turbulence
z_i	elemental mass fraction of the element i
Greek letter	
α, η_2 and σ_Φ	constants for SAS model
α_1, b, c, δ and τ	coefficients for each equation of state
α_k and α_ε	inverse effective Prandtl numbers
β	absorption coefficient, 1/m
β_r	temperature index
β_1	constants for SAS model
$\eta'_{j,r}$	rate of exponent for reactant species j in reaction r
$\eta''_{j,r}$	rate of exponent for product species j in reaction r
κ	von Karman constant
ε	rate of dissipation, m^2/s^3
ζ	acentric factor
λ	wavelength, m
μ	molecular viscosity, kg/m/s
μ_t	turbulent viscosity, kg/m/s
μ_{eff}	effective viscosity
ρ	density of the mixture, kg/m^3
ρ_k	reflectivity of surface k
σ	Stefan-Boltzmann constant, $W\ m^{-2}\ K^{-4}$
σ_k, σ_ε and σ_ω	turbulent Prandtl numbers
σ_s	scattering coefficient, 1/m
Ω'	solid angle
ω	turbulence specific dissipation rate, 1/s

of the supercritical jet plume at near-critical pressures numerically and experimentally [17]. Meier et al. used the hot surface to ignite the hydrothermal flames and monitored the combustion [18,19]. Schuler et al. studied the stagnation flow heat transfer under supercritical pressures of water [20]. However, in these studies, the generated hot fluid velocity is lower than the peripheral cooling water. In addition, for deep wells drilling through several complicated formations, many rock materials do not spall. In this case, a very short interval of non-spallable rocks can impede advance during thermal spallation drilling.

Hydrothermal jet drilling intends to combine the advantages of both water jet and thermal spallation technologies, which is expected to be more economical and efficient for deep hard formations [2]. Fuel, oxidizer and cooling water are injected through respective channels down coiled tubing to the downhole combustion chamber (Fig. 1). The chemical reaction between the fuel and the oxidizer in the chamber is initiated by an electric spark. Thus, 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 coiled tubing and returns to the surface through the annulus. This can cool the wellbore and coiled tubing simultaneously, and avoid the thermal destruction on the borehole wall by the high temperature fluids. Song et al. investigated and compared the downhole flow field and the thermo-physical interaction between wellbore fluid and ambient rock of multi-orifice nozzle hydrothermal jet [21,22]. In addition, Song et al. proposed and compared two kinds of cooling configurations (Lateral configuration and downward configuration) for a single hydrothermal jet drilling [2]. Lyu et al. tried to optimize the combustion model to simulate the thermal jet more accurately with less computational costs [23].

In hydrothermal jet drilling, the successful generation of the hydrothermal jet is of great importance. Therefore, investigations on the reaction in the downhole chamber are necessary. However, there is no specific and systematic study on the applicability of different simulation models to the reaction in hydrothermal jet drilling. This paper investigates and optimizes three kinds of models, including reaction model, turbulence model and radiation model, to determine the most appropriate models for the reaction in the