Comparative simulation research on the stress characteristics of supercritical carbon dioxide jets, nitrogen jets and water jets

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ABSTRACT

In previous studies it has been shown that supercritical carbon dioxide (SC-CO\textsubscript{2}) jets are more efficient at rock breaking than water jets, but the corresponding systematic mechanism explanations were not available. Therefore, this paper conducts an in-depth analysis of the fluid properties with equations suggested by the American National Institute of Standards and Technology (NIST), establishes the fluid-solid-heat coupling model with the support of ANSYS, and reveals the stress responding mechanism of SC-CO\textsubscript{2}, water and nitrogen jets. When the rock is at room temperature, the jets increase the temperature of the rock and generate thermal stress. Furthermore, the temperature elevation effect decreases in the sequence of water at 70°C, nitrogen at 70°C, carbon dioxide at 70°C and water at 27°C. In comparison with water jets at 27°C, jets at 70°C in carbon dioxide increase the maximum stress range and the high stress range of rock, accounting for the low threshold pressure and large volumes of rock breaking in the current literature. For jets at the same temperature (70°C), the stress in rock decreases in the sequence of water, nitrogen and carbon dioxide, indicating that previous studies have not taken the effects of the temperature into consideration, leading to the incorrect conclusion that carbon dioxide is more efficient for rock breaking. In addition, this paper also analyzes the jet field and the stress field with respect to the formation temperature and finds a decrease in thermal stress generated by jets produced at rock temperature. Both the temperature decreasing effect and the rock breaking stress decrease in the sequence of carbon dioxide, nitrogen and water. When the difference in jet pressure decreases or the elastic modulus of the rock increase, SC-CO\textsubscript{2} jets boast more palpable advantages over nitrogen and water jets in rock breaking. This shows that SC-CO\textsubscript{2} jets boast the potential of effectively breaking rock in deep formations.

1. Introduction

Supercritical carbon dioxide (SC-CO\textsubscript{2}) has a low viscosity but strong fluidity and high permeability in rock, which can decrease the circulating pressure loss and reduce the requirements of circulating equipment on the ground in deep rock breaking. In addition, it can easily create high-pressure jets at the well bottom, which does less harm to reservoirs than water-based drilling fluid and can increase the recovery ratio of oil and gas (Al-Advani, Langlinais, & Hughes, 2009; Street, Tesche, & Guigard, 2009). As a result, it has potential as a new type of rock-breaking method.

Researchers outside of China have highlighted the rock-breaking efficiency of SC-CO\textsubscript{2}. The first indoor test conducted in the United States (US) in 2000 proved that the efficiency of SC-CO\textsubscript{2} jets for Mancos shale breaking is 3.3 times greater than that of water jets, and that the energy per unit volume is 20% of that of water jets (Kolle, 2000; Kolle & Marvin, 2000). In the current work, the feasibility of both coiled tubing and underbalanced drilling by SC-CO\textsubscript{2} is analyzed (Al-Advani, 2007; Gupta, Gupta, & Langlinais, 2005).

In order to better understand rock-breaking mechanisms, Chinese researchers carried out systematic experiments and theoretical studies on the rock-breaking properties of SC-CO\textsubscript{2}. Du et al. (2012) carried out experiments of SC-CO\textsubscript{2} rock breaking, from which influential laws of fluid parameters and jet structures on the rock breaking properties of jets were derived. In addition, they demonstrated that the effects of SC-CO\textsubscript{2} jets in rock breaking are superior to those of water jets and rock breaks mainly in large volumes (Du et al., 2012). Wang, Li, Shen et al. (2015) and Tian et al. (2016) carried out indoor experiments, from which influential laws of the confining pressure and rotating speed of the core on the rock breaking of jets were derived. Huang, Lu, Tang,
Ao, and Jia (2015) applied tools like computed tomography and scanning electron microscope and found that after being impacted by SC-CO₂, the end surface of the shale had ‘reticulated’ cracks and the whole had bulky layered cracks. When it comes to SC-CO₂ jets, pressure loss has proved to be smaller than that of water jets according to current experiments and simulated studies. In addition, a temperature decrease is generated by jets (Du et al., 2012; Li, Ni, & Wang, 2014; Wang, Li, Tian et al., 2015).

However, the above studies are primarily explorative studies focused on macroscopic rock-breaking laws, and fail to provide a qualitative and quantitative account of why SC-CO₂ jets have better rock-breaking effects than water jets. On the basis of some related theories, the small pressure loss of SC-CO₂ jets coupled with strong permeability in cracks speak volumes for their advantages over water jets. Nevertheless, comparative studies on experimental results show that the rock has large-scale cracks on its surface with SC-CO₂ jets, while it has bowl-shaped cracks with water jets (Figure 1; see Du et al., 2012; Huang et al., 2015; Kolle, 2000; Tian et al., 2016). Yet, the above theories fail to fully explain this difference. The density of SC-CO₂ is close to that of water, and its viscosity is close to that of air – but there have not been any relevant studies on the rock-breaking effects of SC-CO₂ in comparison with nitrogen jets. In order to further delve into the rock-breaking mechanisms of SC-CO₂, this paper presents a comparative analysis on the rock stress of SC-CO₂, water and nitrogen jets through establishing a heat-fluid-solid above coupling simulation model using ANSYS (Knaust, 2016). By revealing the effect of thermal stress on rock breaking, this paper offers systematic answers to the current experimental results that SC-CO₂ jets are better at rock breaking than water jets, and reveals the advantages of SC-CO₂ jets over nitrogen jets in well drilling.

2. Computational modeling

2.1. Physical model and mesh generation

Based on the indoor experimental equipment (Du et al., 2012), a simplified 3D 1/4 plane symmetrical physical model was established, which primarily consists of the jet entrance, the rock at the well bottom and the exit. The radius of the jet nozzle (R₁) is 1.15 mm, and the standoff distance (D₁) is 4.6 mm – that is, two times the diameter. The radius of the rock (R₂) is 50 mm with a length (D₂) of 50 mm. The specific parameters of the model are shown in Figure 2.

In order to capture both the thermal and velocity boundary layers, the entire model was discretized using hexahedral mesh elements which are accurate and involve less computation effort for the solver. The mesh elements and nodes are 1,500,000 and 1,700,000, respectively. The mesh average element quality reaches a high level of 0.98468. With the intense flow around the nozzle wall and rock surface, a local mesh densification method was used to generate the mesh of the boundaries. The mesh generation is shown in Figure 3.

2.2. Basic hypotheses

It is extremely difficult to accurately simulate experimental processes, so a decision was made to focus on the main factors and ignore the secondary factors. The following basic assumptions were made regarding the simulation processes:

1. The fluid in the jets travel at high speeds and thus the process can be regarded as a heat-insulated one.
2. In a previous study, it was proved through calculation that the influence of the inside permeability of rock on rock breaking is small (Ni & Wang, 2004). Additionally, because most current rock-breaking experiments involve non-permeable shale, the influence of rock permeation is not taken into consideration.
The deformation of the rock caused by the jet pressure field is small, as are the influences on the flow field. Therefore, it was hypothesized that there was no rock deformation when the flow field was calculated.

To more directly observe the influences of the flow field on the stress of the rock, it was assumed that the rock is a homogeneous solid and that changes in the inside stress conform to a linear and elastic constitutive relation. The influences of the differences in thermal expansibility among different mineral grains inside the rock are not taken into consideration.

2.3. Governing equations of fluid mechanics

The flow field was calculated using ANSYS Fluent (Kim, Choudhury, & Patel, 1999). The governing equations of fluid mechanics selected in the simulation areas follow.

Equation of continuity:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0,
\]

(1)

where \( \rho \) is the density, \( t \) is the time, \( u_i \) is the velocity along the \( i \) direction, and \( S_m \) is the mass added to the continuous phase from the dispersed second phase.

Momentum equation:

\[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i,
\]

(2)

\[ \tau_{ij} = \mu \left[ \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right], \]

(3)

where \( p \) is the static pressure, \( \tau_{ij} \) is the stress tensor, \( \rho g_i \) and \( F_i \) are the gravitational and other body force, respectively, and \( \mu \) is the molecular viscosity.

Energy equation:

\[
\frac{\partial}{\partial t} (\rho E) + \frac{\partial}{\partial x_i} (\rho u_i E) = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_e} \right) \frac{\partial T}{\partial x_i} \right] + k_{\text{eff}} \frac{\partial T}{\partial x_i} - \sum_j h_j f_j' + u_j (\tau_{ij}^\text{eff}) + S_h,
\]

(4)

where \( k_{\text{eff}} \) is the effective conductivity, \( f_j' \) is the diffusion flux of the species, and \( S_h \) is the volume heat source.

Turbulence equations:

The realizable \( k-\varepsilon \) model proposed by Shih, Liou, Shabbir, Yang, and Zhu (1995) was used to control the jet flow. This model has been extensively validated by a wide array of flows, including rotating homogeneous shear flows, free flows such as jets and mixing layers, channel and boundary layer flows, and separated flows (Kim, Choudhury, & Patel, 1999; Mohan, Yang, & Chou, 2014; Shih et al., 1995; Wasewar & Sarathi, 2008). It is especially noteworthy that the realizable \( k-\varepsilon \) model resolves the round-jet anomaly; that is to say, it predicts the spreading rate for axisymmetric jets as well as that for planar jets.

The transport equations of \( k \) and \( \varepsilon \) in the realizable model are

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k,
\]

(5)

and

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_{\varepsilon},
\]

(6)

where \( C_1 = \max[0.43, (\eta/\eta + 5)], \eta = S(k/\varepsilon), \) and \( S = \sqrt{2 S_j k S_j}, \) \( G_b \) is the generation of turbulence kinetic energy.
due to the mean velocity gradients, $G_b$ is the generation of turbulence kinetic energy due to buoyancy, $Y_M$ is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, $C_2$ and $C_{1f}$ are constants, $\sigma_k$ and $\sigma_\varepsilon$ are the turbulent Prandtl numbers for $k$ and $\varepsilon$, and $S_k$ and $S_\varepsilon$ are user-defined source terms.

### 2.4. Governing equations of fluid properties

To better simulate the flow field, the model of fluid properties recommended by the American National Institute of Standards and Technology (NIST) was defined in Fluent using user-defined functions (UDFs).

The model recommended by the NIST was used to accurately describe the density and isobaric heat capacity of carbon dioxide (Span & Wagner, 1996), nitrogen (Span, Lemmon, Jacobsen, Wagner, & Yokozeki, 2000) and water (Wagner & Pruß, 2002).

The implicit equations are presented in the following form:

$$P(\delta, \tau) = \rho RT(1 + \delta \Phi_0^')$$

where the dimensionless reduced density is given as $\delta = \rho / \rho_c$, and $\tau = T_c / T$ is the inverse reduced temperature. Dimensionless $\Phi_0^'$ is the partial derivative of the Helmholtz energy $\Phi(\delta, \tau)$.

The equation for the isobaric heat capacity is given by

$$\frac{M \cdot c_p}{R} = -T^2(\phi_{\tau \tau}^\rho - \phi_{rr}^\rho) + \frac{(1 + \delta \phi_0^\rho - \delta \tau \phi_x^\rho)^2}{1 + 2 \delta \phi_y^\rho + \delta^2 \phi_{\delta \delta}^\rho}.$$ (8)

In finite elements, numerical algorithms are employed to calculate the density $\rho$ and heat capacity $c_p$ when the pressure $P$ and temperature $T$ are obtained.

The models cited by NIST for the viscosity and thermal conductivity of carbon dioxide (Fenghour, Wakeham, & Vesovic, 1998) and nitrogen (Leamon & Jacobsen, 2004) are presented as

$$\eta(T, \rho) = \eta_0 + \Delta \eta(T, \rho) + \Delta \eta_c(T, \rho).$$ (9)

The equations for thermal conductivity are in a form similar to that of viscosity:

$$\lambda(T, \rho) = \lambda_0 + \Delta \lambda(T, \rho) + \Delta \lambda_c(T, \rho).$$ (10)

The first terms on the right-hand side of Equations (9) and (10) are contributed by the diluted gas; the second terms are the contribution to the transport coefficients of the moderately dense gas; and the third terms are the contribution of the dense gas.

The models of viscosity and thermal conductivity of water (Kestin, Sengers, Kamgar-Parsi, & Sengers, 1984) are presented as

$$\eta(T, \rho) = \eta_0(T) \times \eta_1(T, \rho) \times \Delta \eta_2(T, \rho),$$ (11)

$$\lambda(T, \rho) = \lambda_0(T) \times \lambda_1(T, \rho) + \lambda_2(T, \rho).$$ (12)

The first terms on the right-hand side of Equations (11) and (12) are the viscosity or thermal conductivity of fluid in the ideal-gas limit; the second terms can be calculated by defined equations; and the third terms account for the enhancement of the viscosity or thermal conductivity in the critical region.

### 2.5. Governing equations of rock mechanics

The stress field was calculated using ANSYS’s Static Structural component. The governing equations of rock mechanics used in the simulation are shown as follows.

Equilibrium equations:

$$\sigma_{ij} + F_{bi} = 0.$$ (13)

Geometric equations:

$$\varepsilon_{ij} = \frac{(u_{ij} + u_{ji})}{2}.$$ (14)

Stress and strain relationship:

$$\varepsilon_{ii} = \alpha(T - T_0) + E \frac{\sigma_{ii}}{E} - \nu \frac{\sigma_{kk}}{E} - \frac{\nu \sigma_{kk}}{G};$$

$$\varepsilon_{ij} = \frac{\sigma_{ij}}{G}; \quad G = \frac{E}{2(1 + \nu)}.$$ (15)

In the above equations, $\sigma_{ij}$ is the stress, $\varepsilon_{ij}$ is the strain, $F_{bi}$ is the body force, $u_{i}$ is the displacement, $T_0$ and $T$ are the initial and changed temperatures of the rock, respectively, $\alpha$ is the thermal expansion coefficient, $E$ and $G$ are the Young and shear moduli, respectively, and $\nu$ is Poisson’s ratio. Heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \frac{\lambda}{\partial x} \frac{\partial T}{\partial x} + \frac{\partial}{\partial y} \left( \frac{\lambda}{\partial y} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\lambda}{\partial z} \frac{\partial T}{\partial z} \right) + q_v \right.$$ (16)

where $c$ is the heat capacity, $\lambda$ is the thermal conductivity, and $q_v$ is the heat generation rate.

### 2.6. Boundary conditions

With regard to the boundary conditions of fluids, because the controllable parameters in the experiment are the entrance pressure, temperature and exit back pressure of the fluid, the entrance conditions include the pressure and the temperature, and the exit condition is the exit pressure. The jet wall was set under the heat insulation condition, and the other fluid walls were set under the ambient temperature condition.
The boundary conditions of the rock sidewalls are as follows:

\[ T_R = T_S; \quad \sigma_R = \sigma_S; \quad \tau_R = 0. \]

And the boundary conditions of the rock bottom are as follows:

\[ T_R = T_S; \quad u_R = 0; \quad \tau_R = 0. \]

When it comes to the interface between the fluid and the rock, the following coupling conditions are adopted:

\[ P_L = \sigma_R; \quad T_L = T_R; \quad \tau_R = 0. \]

In reference to the above expressions, \( T_S \) is the ambient temperature, \( \sigma_S \) is the confining pressure of the rock, \( P_L \) and \( T_L \) are the pressure and the temperature of the fluid close to the wall, respectively, \( \sigma_R, \tau_R, \) and \( T_R \) are the positive stress, shearing stress and temperature of the rock surface, respectively, and \( u_R \) is the displacement.

### 2.7. Rock mechanics and thermodynamic variables

In spite of a growing body of research on rock breaking, there are no descriptions of the mechanical or thermodynamic properties of the rock. The mechanical and thermodynamic properties of cement rock, sandstone, shale and marble were investigated (Brandt, 2009; Clauser & Huenges, 1995; Fjar, Holt, Raane, Risnes, & Horsrud, 2008; Kraft, Engqvist, & Hermansson, 2004; Lama & Vutukuri, 1978; Q. Li, Yuan, & Ansari, 2002) and the results are presented in Table 1, where it can be seen that the variation of the same kind of rock is great. Based on the shale parameters, the physical parameters of rock used in the simulation were obtained (Table 2).

### 2.8. Solving process

The solving process was split into two parts. The flow field of the fluid and the temperature field of the rock were calculated in Fluent, and then the rock stress field was calculated in the static structural model of ANSYS using the results from Fluent as the boundary conditions. The details are as follows:

1. The initial temperature and pressure values were assigned to the boundary of the fluid and inside the fluid. The heat conduction between the fluid and the rock was not taken into consideration. The pressure field and the temperature field of the fluid in the steady state flow were calculated by the coupled scheme and second-order discretization of Fluent (equivalent to the process of adjusting the jet pressure and temperature in the experiment).

2. The coupling heat conduction between the fluid and the rock was taken into consideration and the stable flow field in step 1 was taken as the zero point of time. The pressure field and temperature fields of the rock surface were calculated at the jet time of \( t_j \) with the transient simulation model of Fluent (equivalent to the process of jetting after opening the baffle in the experiment).

3. The boundary conditions of the pressures and internal temperatures obtained from step 2 at the jet time of \( t_j \) were applied to the rock impacted surface and rock interior, respectively. The axial displacement restriction was applied to the bottom of the rock and the confining pressure was applied to the rock sidewalls. The tensile stress and shear stress in the rock were calculated at the jet time of \( t_j \).

### 3. Results and discussion

#### 3.1. Analysis of the jet field and stress field at room temperature and validation of the simulation

Simulation analysis of the flow fields and stress fields of water, carbon dioxide and nitrogen were carried out under the following conditions: the jet pressure \( P_{in} = \)

| Rock type       | Density (1000 kg/m³) | Heat capacity (kJ/kg.K) | Thermal conductivity (W/m.K) | Poisson’s ratio | Young’s modulus (GPa) | Thermal expansion coefficient \(10^{-6}°C^{-1}\) |
|-----------------|----------------------|--------------------------|-------------------------------|----------------|-----------------------|--------------------------------------------|
| Cement stone    | 1.1–2.5              | 0.8–1.1                  | 0.5–1.7                       | .12–.18        | 7.0–15.0              | 10–20                                      |
| Sandstone       | 2.0–2.7              | 0.8–1.0                  | 1.4–2.4                       | .00–.45        | 0.1–70.0              | 13–17                                      |
| Shale           | 2.3–2.8              | 0.9–1.1                  | 1.3–2.3                       | .00–.30        | 0.4–60.0              | 11–20                                      |
| Marble          | 2.7–3.2              | 0.7–0.9                  | 2.7–3.2                       | .00–.30        | 5.0–75.0              | 8–12                                       |

| Simulation factors | Density (1000 kg/m³) | Heat capacity (kJ/kg.K) | Thermal conductivity (W/m.K) | Poisson’s ratio | Young’s modulus (GPa) | Thermal expansion coefficient \(10^{-6}°C^{-1}\) |
|--------------------|----------------------|--------------------------|-------------------------------|----------------|-----------------------|--------------------------------------------|
| Stress analysis at room temperature | 2.55              | 1                        | 1.8                           | 0.15           | 30                    | 15.5                                       |
| Stress analysis at earth temperature  | 2.55              | 1                        | 1.8                           | 0.15           | 30                    | 15.5                                       |
| Stress analysis at earth temperature  | 2.55              | 1                        | 1.8                           | 0.15           | 70                    | 15.5                                       |
30 MPa, the back pressure $P_{\text{out}} = 10$ MPa, the entrance temperature $T_{\text{in}} = 27^\circ$C and $T_{\text{in}} = 70^\circ$C, and the rock ambient temperature $T_a = 27^\circ$C (room temperature).

The pressure field and temperature field at the jetting time period ($t_j$) of $0.001$ s are shown in Figures 4 and 5. $D_{ra}$ and $D_{ver}$ in Figures 4 and 5 are defined as the radial distance to the jet center above the rock surface diameter and the vertical distance to the jet center along the rock axis, respectively. It can be seen in Figure 4 that the pressure of $1.5$ mm outside the center quickly decreases to the $P_{\text{out}}$ of $10$ MPa. Basically, the central jet pressure of carbon dioxide is tantamount to the pressure for $27^\circ$C water and $70^\circ$C water. In comparison, the central jet pressure of nitrogen is small, and is $94\%$ of that of carbon dioxide. Figure 5 exhibits the changes in the temperature field. It can be seen that the jets increase the temperature of rock. The differences in the temperature field are larger than those in the pressure field and the changes decrease in the sequence of $70^\circ$C water $>$ $70^\circ$C nitrogen $>$ $70^\circ$C carbon dioxide $>$ $27^\circ$C water. Current comparative studies on rock breaking draw upon carbon dioxide heated up to a supercritical status and unheated water (Du et al., 2012; Kolle, 2000), which conforms to temperature fields of water jets at $27^\circ$C and carbon dioxide jets at $70^\circ$C. This reveals that the temperature stress generated by the temperature field influences the rock-breaking effects to a great extent.

In order to further study the influences of the temperature stress quantitatively the surface stress and the inside stress of rock were analyzed, as this is required for determining references based on explaining rock breaking by jets through the stress distribution of rock breaking. Currently, there are few studies that focus on rock-breaking theories of supercritical fluids or gases. Even rock-breaking mechanisms of water jets have received little attention, and the rock-breaking theories of water jets can be divided into water wedge tensile failure, quasi-static elastic fracture, pulse loading fatigue failure, impact stress wave failure and cavitation effect failure (Wang & Ni, 2002). This paper mainly analyzes the matter from the perspective of quasi-static elastic fracture theory, which posits that rock mainly undergoes tensile failure and shear failure when exposed to jets.

Rock has a lower thermal conductivity than metal and a higher heat capacity than air. In comparison with changes in the flow field of the rock surface, the inside temperature transfer of rock is a slow process. Figures 6 to 9 show changes in the stress field at different jet times ($t_j$). In all relevant figures, $F-P$ denotes the effect of the pressure field only and $F-P&T$ denotes the combined effect of the pressure and temperature fields. It can be seen that the jet temperature field exerts a relatively small influence on the inside stress of rock but serves to increase the tensile stress and shearing stress of the rock surface. The tensile stress is over four times the shearing stress.
The collapsing stresses of rock decrease in the sequence of the compressive stress, the shearing stress and the tensile stress. Consequently, the tensile stress of the rock surface can be employed as the standard by which rock-breaking effects can be assessed. Figures 10, 11 and 12 show the changes in the tensile stress of the rock surface in 27°C water, 70°C water and 70°C nitrogen jets, respectively. It can be seen that at 0.1 s, the tensile stress reaches its maximum, and changes are regarded as the standard of whether the rock-breaking effects are good (as shown in Figure 13). It can be seen that the tensile stress of the rock decreases in the sequence of 70°C water > 70°C nitrogen > 70°C carbon dioxide > 27°C water, which is consistent with the temperature field analyses. At the same time, this shows that since the influence of the temperature is not taken into consideration, it is inappropriate to compare water jets at room temperature and SC-CO₂ jets in the present study.

To ensure the validation of the simulation, a comparative analysis was conducted on the current simulation...
Figure 12. The tensile stress along $D_{ra}$ with an N$_2$ jet over time ($T_{in} = 70°C$, $T_a = 27°C$).

Figure 13. The tensile stress along $D_{ra}$ with various jets ($t_j = 0.1s$, $T_a = 27°C$).

and the experimental results. In previous studies it was proved by simulation that the temperature of an SC-CO$_2$ jet above the impacted surface rises at first and then drops with the increasing distance to the jet center, and that the lowest temperature occurs at a distance of the nozzle diameter (Long, Liu, Ruan, Kang, & Lyu, 2016; Lv, Long, Kang, Xiao, & Wu, 2013). From the temperature of the 70°C carbon dioxide jet showed in Figure 5, it can be seen that the temperature change with the distance varies from 0 mm to 5 mm and is a good fit with the above results. Figures 14 and 15 show the inside tensile stress distribution cloud chart of 27°C water and 70°C carbon dioxide jets. It can be seen that SC-CO$_2$ jets can improve the maximum stress and enlarge the functional range of the stress, which is consistent with the experimental results that the impacted rock has a low rock-breaking threshold pressure and a large rock-breaking area (Du et al., 2012; Kolle & Marvin, 2000). Thus, these comparisons verify the models by showing good agreement with previous experimental data and previous simulation results, and it is indicated that the current numerical model can predict both the flow field of the fluid and the stress field of the rock.

3.2. Analysis of the jet fields and stress fields at formation temperature

In actual oil and gas drilling, the temperature of the carbon dioxide increases as the formation temperature increases, and can be regarded as approximately tantamount to the formation temperature, which is counter to the situation at room temperature ($T_a = 27°C$). The jet temperature field decreases the temperature of rock, and the temperature stress is mainly the result of the temperature decrease. According to Figure 5, it can be found that the decrease in temperature when using the SC-CO$_2$ jet
is larger than the decrease when using the water or nitrogen jets, indicating that carbon dioxide drilling may have better rock-breaking effects when the rock is at formation temperature.

As a result, at the jet temperature and the ambient temperature of the formation rock of 70°C, simulation analyses were carried out on the flow fields and stress fields of water, carbon dioxide and nitrogen under a jet pressure of 30 MPa and an exit back pressure of 10 MPa. Figures 16 and 17 demonstrate the distribution of the surface pressure and the temperature of the rock, respectively, indicating that the changes in the pressure field of water, carbon dioxide and nitrogen are basically the same. The decrease in the temperature of the rock is mainly ascribed to the jets and the decrease range is in the sequence of carbon dioxide > nitrogen > water.

The tensile stress field and the shearing stress field with carbon dioxide jets were analyzed (Figures 18 to 21).

**Figure 16.** The pressure distribution along Dra ($T_{in} = 70°C$, $T_a = 70°C$).

**Figure 17.** The temperature distribution along Dra ($T_{in} = 70°C$, $T_a = 70°C$).

**Figure 18.** The tensile stress along Dra with an SC-CO$_2$ jet over time ($T_a = 70°C$).

**Figure 19.** The tensile stress along D$_{ver}$ with an SC-CO$_2$ jet over time ($T_a = 70°C$).

**Figure 20.** The shear stress along Dra with an SC-CO$_2$ jet over time ($T_a = 70°C$).
It can be seen that the jet temperature field does not exert a significant influence on the tensile stress of the rock surface, but can more than double the shearing stress on the rock surface and enlarge the damage area of the shearing stress from the jet center to the whole rock surface. With the passage of time, the jet temperature field makes growing contributions to the tensile stress and the shearing stress inside the rock.

From Figures 18 to 21, it can be seen that changes in the shearing stress on the rock surface and the tensile stress inside the rock reach their maximum at the jet times of 1 s and 60 s, respectively, which are taken as the standard of rock-breaking effects for jets of carbon dioxide, water and nitrogen. Figures 22 and 23 show the distribution of the shearing stress and the tensile stress of carbon dioxide, water and nitrogen at the jet times of 1 s and 60 s, respectively. It can be seen that the rock-breaking stress decreases in the sequence of carbon dioxide, nitrogen and water, which is consistent with analytic results of the flow field.

At present, jet-aided rock breaking is the commonly-used drilling method. Limited by the performance of pump, high jet pressure difference can hardly be realized. As a reaction, jet fields and stress fields with the decrease in jet pressure of 10 MPa were analyzed. Figure 24 and Figure 25 show distribution of rock surface pressure and temperature, respectively. It can be seen that variation trend in the pressure field are the same as those with jet pressure difference of 20 MPa. However, differences of the temperature field increased, indicating that differences of rock breaking stress resulting from the jet temperature field would increase. Figure 26 and Figure 27 exhibit distribution of the shearing stress and the tensile stress. It can be seen that rock breaking stress decreased in the sequence of carbon dioxide, nitrogen and water while their differences increased. Therefore, advantages of carbon dioxide jets were more prominent.

When drilling, rock in deep formations boasts a high level of hardness and abrasiveness, resulting in low
drilling speeds and rapid drill bit abrasion. In general, the hardness and the elastic modulus of rock are proportionally related. As a result, the elastic modulus of rock was set as 70 GPa to simulate the rock-breaking effects of jets on hard rock. Figures 28 and 29 show the stress distribution of carbon dioxide, nitrogen and water. It can be seen that after the elastic modulus of the rock increases to 70 GPa, differences in the stress of carbon dioxide, nitrogen and water jets become larger, implying that compared with nitrogen and water jets, carbon dioxide jets have the potential for efficiently breaking rock in deep strata.

4. Conclusions

According to the relevant literature, SC-CO$_2$ jets are more efficient at rock breaking compared to water jets. However, its mechanisms have not been systematically examined. Compared with nitrogen jets, there have not been any studies relevant to the rock-breaking effects of SC-CO$_2$ jets. By virtue of the established fluid-solid-heat coupling model, this paper offers the following conclusions:

(1) This paper analyzes the jet fields and rock stress distribution of carbon dioxide, nitrogen and water jets at room temperature. The results show that the
jet pressure fields of carbon dioxide, nitrogen and water are basically consistent, while their jet temperature fields differ greatly. The jet temperature fields increase the temperature of rock, and the increase of temperature decreases in the sequence of 70°C water, 70°C nitrogen, 70°C carbon dioxide and 27°C water. Taking the influence of temperature stress into consideration, according to the stress comparison analysis jet temperature fields increase the tensile stress and shearing stress of rock. Compared to water jets at 27°C, the temperature field of SC-CO2 jets increases the maximum stress and the high stress distribution range of rock, accounting for problems of low threshold pressure and large volumes in rock breaking in current studies. This paper also found that for jets at the same temperature (70°C) and pressure (30 MPa), the stress in rock breaking decreases in the sequence of water, nitrogen, and carbon dioxide, showing that the current experimental studies have not taken the effect of temperature into consideration and that the experiments lack comparability. As a result, the wrong conclusions have been drawn.

(2) In actual drilling, the jet temperature is close to that of the formation. The results of this study show that the jet pressure fields of carbon dioxide, water and nitrogen are basically consistent, while their respective jet temperature fields greatly differ. The jet temperature field decreases the temperature of the rock, and the decrease in temperature occurs in the sequence of carbon dioxide, nitrogen and water. The temperature stress is generated as the temperature decreases, indicating that there are differences in the rock-breaking stress of carbon dioxide, water and nitrogen. The stress analyses show that the rock-breaking stress at formation temperature decreases in the sequence of carbon dioxide, nitrogen and water, which is consistent with the analysis of the flow fields. When the jet pressure is reduced or the elastic modulus increases, carbon dioxide jets boast palpable advantages over nitrogen and water jets for rock breaking. In actual drilling, jet-aided drill-bit rock breaking is the main mode. The decrease in jet pressure is not too great, while the drilling speed is slow due to the high level of hardness in deep strata. The aforementioned characteristics show that SC-CO2 jet-aided drill-bit rock breaking has proved to be an efficient deep-stratum drilling method.

(3) The limitations of this paper include the fact that the rock is considered as a homogeneous media and thus the effect of the thermal stress of the jets is underestimated. The thermal stress is produced by two reasons in reality – the thermal gradient of the rock and the different coefficient of thermal expansion of different rock minerals. Therefore, a rock model considering the thermal expansion differences of real types of rock is needed in order to generate more accurate results and conclusions.

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**Nomenclature**

- $R_1$: Radius of the nozzle, mm
- $R_2$: Radius of the rock, mm
- $D_1$: Standoff distance between the nozzle and the rock, mm
- $D_2$: Length of the rock, mm
- $D_{ra}$: Radial distance to the jet center above the rock surface diameter, mm
- $D_{ver}$: Vertical distance to the jet center along the rock axis, mm
- $T_{in}$: Fluid temperature of the nozzle inlet, °C
- $t_j$: Jet time, s
- $T_a$: Rock ambient temperature, °C
- $P_{in}$: Fluid pressure of the nozzle inlet, MPa
- $P_{out}$: Fluid pressure of the outlet, MPa
- $P_{con}$: Rock confining pressure, MPa
- $F-P$: Effect of the pressure field only
- $F-P&T$: Combined effect of the pressure and temperature fields
- $\Delta P$: Difference between the inlet and outlet pressures, MPa
- $\rho$: Density of the fluid or rock, kg/m$^3$
- $t$: Time, s
- $u_i, u_j$: Velocity along the $i$ or $j$ displacement coordinates, m/s
- $S_m$: Mass added to the continuous phase from the dispersed second phase, kg/(m$^3$.s)
- $x_i, x_j$: Displacement of the mass point along the $i$ or $j$ coordinate, m
- $\rho g_i, F_i$: Gravitational or other body force, kg/(m$^2$.s$^3$)
- $\mu$: Molecular viscosity, Pa.s
- $\delta_{ij}$: Kronecker delta function, dimensionless
- $E$: Internal energy of the fluid, J/kg
- $p$: Pressure, Pa
- $k_{eff}$: Effective conductivity, W/(m.K)
\( J_f \)  
**Diffusion flux of the species, dimensionless**

\( S_h \)  
**Volume heat source, J/(m^3.s)**

\( T \)  
**Temperature, K**

\( k \)  
**Turbulent kinetic energy, dimensionless**

\( \varepsilon \)  
**Turbulent dissipation rate, dimensionless**

\( \delta \)  
**Dimensionless reduced density**

\( \tau \)  
**Inverse reduced temperature, dimensionless**

\( \rho_c \)  
**Density at the supercritical point, kg/m^3**

\( T_c \)  
**Temperature of the fluid at the supercritical point, K**

\( M \)  
**Molecular weight, kg/mol**

\( c_p, c \)  
**Specific heat capacity, J/(kg.K)**

\( \eta \)  
**Dynamic viscosity, Pa.s**

\( \lambda \)  
**Thermal conductivity, W/(m.K)**

\( \sigma_{ij} \)  
**Stress, Pa**

\( \varepsilon_{ij} \)  
**Displacement, dimensionless**

\( E, G \)  
**Young’s and shear moduli, Pa**

\( \alpha \)  
**Thermal expansion coefficient, K^{-1}**

\( v \)  
**Poisson’s ratio, dimensionless**

\( q_v \)  
**Heat generation rate, J/(m^3.s)**

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