

Original Paper

Simulation study of supercritical carbon dioxide jet fracturing for carbonate geothermal reservoir based on fluid-thermo-mechanical coupling model



Jian-Xiang Chen^a, Rui-Yue Yang^{a,*}, Zhong-Wei Huang^a, Xiao-Guang Wu^a,
Shi-Kun Zhang^b, Hai-Zhu Wang^a, Feng Ma^{c,d}

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

^b Sinopec Research Institute of Petroleum Engineering, Beijing, 102206, China

^c The Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, Shijiazhuang, 050061, Hebei, China

^d Technology Innovation Center of Geothermal & Hot Dry Rock Exploration and Development, Ministry of Natural Resources, Shijiazhuang, 050061, Hebei, China

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ABSTRACT

Geothermal energy is a kind of renewable, sustainable and clean energy resource. Geothermal energy is abundant in carbonate reservoirs. However, low matrix permeability limits its exploitation. The supercritical carbon dioxide (SC-CO₂) jet fracturing is expected to efficiently stimulate the carbonate geothermal reservoirs and achieve the storage of CO₂ simultaneously. In this paper, we established a transient seepage and fluid-thermo-mechanical coupled model to analyze the impact performance of SC-CO₂ jet fracturing. The mesh-based parallel code coupling interface was employed to couple the fluid and solid domains by exchanging the data through the mesh interface. The physical properties change of SC-CO₂ with temperature were considered in the numerical model. Results showed that SC-CO₂ jet fracturing is superior to water-jet fracturing with respect to jetting velocity, particle trajectory and penetrability. Besides, stress distribution on the carbonate rock showed that the tensile and shear failure would more easily occur by SC-CO₂ jet than that by water jet. Moreover, pressure and temperature control the jet field and seepage field of SC-CO₂ simultaneously. Increasing the jet temperature can effectively enhance the impingement effect and seepage process by decreasing the viscosity and density of SC-CO₂. The key findings are expected to provide a theoretical basis and design reference for applying SC-CO₂ jet fracturing in carbonate geothermal reservoirs.

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1. Introduction

With traditional fossil energy exhausted and climate change catastrophic effects, the need for renewable energy is more and more urgent. The carbonate geothermal reservoir is an excellent alternative energy source due to its high thermal conductivity and wide distribution (Wang et al., 2021). However, the hydraulic conductivity of the carbonate formations is mainly controlled by tectonic structures and karstification (Homuth et al., 2015). That means the permeability of the carbonate reservoir is highly related to the primary fracture networks. The field tests showed the matrix

permeability was very low (10^{-16} – 10^{-15} m²), even for the core samples with the highest porosity (Niederer et al., 2015). The low matrix permeability limits the exploitation of carbonate geothermal reservoirs. Therefore, stimulation treatments are necessary for the target strata with poorly developed fracture networks to efficiently develop geothermal resources. Hydraulic jet fracturing is a method that integrates the operations of jetting perforation, hydraulic fracturing and hydraulic isolation. This technology is widely used in the oil and gas industry to create fracture networks and increase reservoir permeability (Li et al., 2010; Sheng et al., 2013).

SC-CO₂ fluid is a special supercritical fluid with a density similar to an ordinary liquid and a viscosity similar to gas. It is generated when the temperature and pressure are above its critical values

* Corresponding author.

E-mail address: yangruiyue@cup.edu.cn (R.-Y. Yang).

($T_c = 31.1\text{ }^\circ\text{C}$ and $P_c = 7.38\text{ MPa}$) (Sodeifian et al., 2019a, 2021). Benefit by the advantages of no residue, non-toxicity, recyclability, environmentally friendly, and availability at low cost, supercritical carbon dioxide (SC-CO₂) is widely used in industrial field, such as oil extraction, solubility of the drug, separation of nanoparticles and chemical reaction (Sodeifian et al., 2016a, 2016b, 2017, 2019b, 2020a). In petroleum engineering, supercritical CO₂ (SC-CO₂) has been introduced into fracturing due to its high diffusion coefficient and low surface tension. What's more, the SC-CO₂ could help extract oil and dissolved organic in the porosity (Ameri et al., 2020; Ardestani et al., 2020; Razmimanesh et al., 2021; Sodeifian et al., 2020b).

In carbonate geothermal reservoir conditions, CO₂ can reach its supercritical state easily. Furthermore, the interactions of CO₂-water-rock can induce dolomite dissolution in carbonate geothermal reservoirs. This could help to further increase the porosity and permeability. In the geothermal production stage, the dissolution reaction of dolomite and clay minerals can overshadow the precipitation effect of calcite and increase the heat mining rate (Cui et al., 2017). Due to the dissolution mechanism, a large quantity of CO₂ will be permanently sequestered in the formation after the geothermal exploitation (Cui et al., 2016). Attributed to the excellent properties mentioned before, CO₂ is selected as the fracturing fluid of jet fracturing to stimulate the geothermal reservoirs in this paper (Fig. 1). The SC-CO₂ jet fracturing generally contains two steps, jetting perforation and jet pressurization. First, the abrasive SC-CO₂ jet creates the jet hole and then the fracturing procedure is accomplished under the jet pressurization effect. In this paper, we mainly focused on the first step to analyze the flow field and impact stress of the SC-CO₂ jet. Applying SC-CO₂ jet fracturing in carbonate geothermal reservoirs is a complex process. It contains compressible fluid flow, particle migration, and fluid-thermo-mechanical coupling impingement. Therefore, a comprehensive study is needed to clarify the flow field, erosion pattern of particles, and the failure scheme of rock under SC-CO₂ jet impingement.

In previous studies, Wang et al. (2015) investigated the properties of the SC-CO₂ jet through the computational fluid dynamics method. They found that the compressibility of the SC-CO₂ jet could cause an extra intense impinging load for the perforation. Besides, results also demonstrated that the flow field of the SC-CO₂ jet is similar to that of the water jet. However, others found that temperature and heat transfer distributions in the jet-hole differ from the water jet, which has a noticeable effect on fracture initiation and propagation (Cai et al., 2017). Cai et al. (2020) investigated the

SC-CO₂ jet flow field and induced strain response in the rock via high-speed photography. In addition, Cai et al. (2018) also deeply analyzed the influence of pressure drop, standoff distance, and nozzle diameter on the SC-CO₂ jet fracturing. In the jet hole, the jet pressurization effect needs to be considered. The pressurization of the SC-CO₂ jet in the jet hole leads to fracture initiation and propagation (Cai et al., 2018, 2022).

Furthermore, Hu et al. (2017) conducted experiments to explore the influence of pressurization on fracture initiation and propagation. He et al. (2015) studied the pressurization mechanism of SC-CO₂ jet in perforation and investigated the influences of pressure difference, ambient pressure, nozzle diameter, and fluid temperature by experiments. Other research also shows that the SC-CO₂ jet fracturing performs better on pressurization than water jet, generating fractures and propagating cracks at a lower pressure (Cai et al., 2018). And the lower initiation and propagation pressure are mainly attributed to the different temperatures and heat transfer of SC-CO₂ in the jet-hole (Hu et al., 2016). Besides, the thermo-elastic stresses induced by CO₂ phase change within cracks can create branching and crossing fractures around the main crack, forming the fracture networks (Huang et al., 2018).

Previous studies have analyzed the flow field of the SC-CO₂ jet and the pressurization mechanism in the jet hole based on numerical simulations and experiments. However, during perforation, the influence of jet temperature, pressure drop and phase change of SC-CO₂ on the evolution of transient impacted stress were still unclear. In addition, the seepage characteristic of SC-CO₂ in high-temperature carbonate rock pores is rarely studied during the jet fracturing process.

In this paper, a transient SC-CO₂ jet fracturing model was established to analyze the impact performance of jet fracturing. We adopted the RNG $k-\epsilon$ model to simulate the flow field of the SC-CO₂ jet. And the model was validated with the previously published experimental data. The cause of the difference in fracture propagation between SC-CO₂ and water jet was determined by analyzing the erosion rate of abrasive particles. Then, we employed the fluid-thermo-mechanical coupling model based on MpCCI to investigate the impact stress and thermal stress distribution. Finally, the seepage flow field of jet fracturing was studied. This work provided a better understanding of the application of the SC-CO₂ jet fracturing in carbonate geothermal reservoirs.

2. Mathematical model

2.1. The state equations of SC-CO₂

As a compressible fluid, the density, viscosity, and thermal coefficient of SC-CO₂ vary significantly with temperature and pressure (Wu et al., 2022). In our jet fracturing model, the SC-CO₂ forms into a high-speed jet under high pressure and high temperature, which will significantly change the physical properties of SC-CO₂. The state equations of CO₂ modified by the Span and Wagner (1996) via several experiments are commonly used by scholars. Their equations introduce dimensionless Helmholtz free energy to calculate the state parameters (Span, 2013). That makes the equations suitable for calculating the density and thermal conductivity under a wide range of pressure and temperature, from the triple-point temperature to 1100 K and pressure up to 800 MPa, respectively. The dimensionless expression is (Span and Wagner, 1996):

$$\Phi(\delta, \tau) = \Phi_0(\delta, \tau) + \Phi_r(\delta, \tau) \quad (1)$$

Based on the Span-Wagner equations, the parameters of compressibility factor Z , the specific heat capacity at constant pressure C_p , and the Joule-Thomson coefficient C_j are calculated as

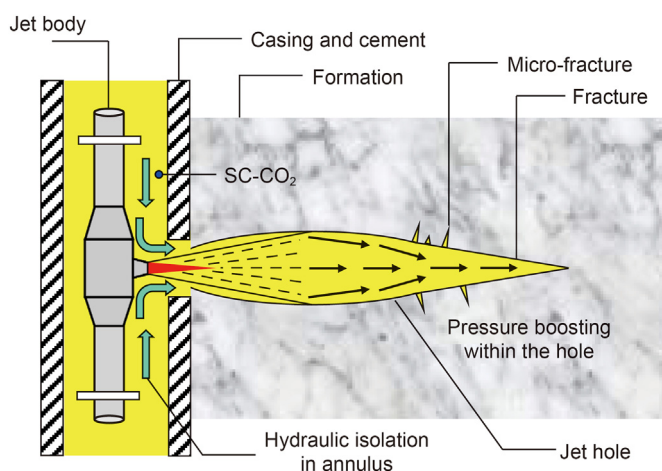


Fig. 1. The schematic diagram of SC-CO₂ jet fracturing.

below (Span and Wagner, 1996):

$$Z = \frac{\rho(\delta, \tau)}{\rho_c RT} = 1 + \delta \frac{\partial \Phi_r(\delta, \tau)}{\partial \delta} \quad (2)$$

$$C_p(\delta, \tau) = R \left[-\tau^2 \left(\frac{\partial^2 \Phi_o}{\partial \tau^2} + \frac{\partial^2 \Phi_r}{\partial \tau^2} \right) + \frac{\left(1 + \delta \frac{\partial \Phi_r(\delta, \tau)}{\partial \delta} - \delta \tau \frac{\partial^2 \Phi_r(\delta, \tau)}{\partial \delta \partial \tau} \right)^2}{1 + 2\delta \frac{\partial \Phi_r(\delta, \tau)}{\partial \delta} + \delta^2 \frac{\partial^2 \Phi_r(\delta, \tau)}{\partial \delta^2}} \right] \quad (3)$$

where Φ is the dimensionless Helmholtz energy; Φ_o is the Helm-

$$\mu(\rho, T) = \mu_o(T) + \Delta\mu(\rho, T) + \Delta\mu_c(\rho, T) \quad (5)$$

$$\lambda(\rho, T) = \lambda_o(T) + \Delta\lambda(\rho, T) + \Delta\lambda_c(\rho, T) \quad (6)$$

where μ is the viscosity of CO₂, N·s/m²; λ is the thermal conductivity of CO₂, W/(m·K); μ_o and λ_o are the viscosity and thermal conductivity in the zero-density limit; $\Delta\mu$ and $\Delta\lambda$ represent the increase in the viscosity and thermal conductivity at elevated density over the dilute gas value; $\Delta\mu_c$ and $\Delta\lambda_c$ are the increments of viscosity and thermal conductivity as the CO₂ fluid is near the critical point.

2.2. The computational fluid dynamic equations

$$C_J(\delta, \tau) = R \rho \frac{-\left(\delta \frac{\partial \Phi_r(\delta, \tau)}{\partial \delta} + \delta^2 \frac{\partial^2 \Phi_r(\delta, \tau)}{\partial \delta^2} + \delta \tau \frac{\partial^2 \Phi_r(\delta, \tau)}{\partial \delta \partial \tau} \right)}{\left(1 + \delta \frac{\partial \Phi_r(\delta, \tau)}{\partial \delta} - \delta \tau \frac{\partial^2 \Phi_r(\delta, \tau)}{\partial \delta \partial \tau} \right)^2 - \tau^2 \left(\frac{\partial^2 \Phi_o}{\partial \tau^2} + \frac{\partial^2 \Phi_r(\delta, \tau)}{\partial \tau^2} \right) \left(1 + 2\delta \frac{\partial \Phi_r(\delta, \tau)}{\partial \delta} + \delta^2 \frac{\partial^2 \Phi_r(\delta, \tau)}{\partial \delta^2} \right)} \quad (4)$$

holtz energy for ideal gas; Φ_r is the Helmholtz energy for the residual fluid part; δ is ratio of the fluid densities under standard conditions and at the critical point, $\delta = \rho/\rho_c$; ρ_c is the gas density at the critical point, kg/m³; τ is ratio of the temperature under standard conditions and at the critical point, $\tau = T_c/T$; T_c is the temperature at the critical point, K; R is gas constant, J/(kg·K).

The viscosity and thermal conductivity of the CO₂ fluid are usually calculated by the model of Fenghour (Fenghour et al., 1998):

Considering the compressible property of SC-CO₂, we adopted the three-dimensional compressible fluid equations to calculate the mass, momentum, and energy conservation equations (Versteeg and Malalasekera, 2007).

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (7)$$

$$\begin{aligned} & \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho u v)}{\partial y} + \frac{\partial(\rho u w)}{\partial z} \\ &= \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} \right) - \frac{\partial p}{\partial x} + S_i \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v u)}{\partial x} + \frac{\partial(\rho v v)}{\partial y} + \frac{\partial(\rho v w)}{\partial z} \\ &= \frac{\partial}{\partial x} \left(\mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial v}{\partial z} \right) - \frac{\partial p}{\partial y} + S_i \frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho w u)}{\partial x} + \frac{\partial(\rho w v)}{\partial y} + \frac{\partial(\rho w w)}{\partial z} \\ &= \frac{\partial}{\partial x} \left(\mu \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial w}{\partial z} \right) - \frac{\partial p}{\partial z} + S_i \end{aligned} \quad (8)$$

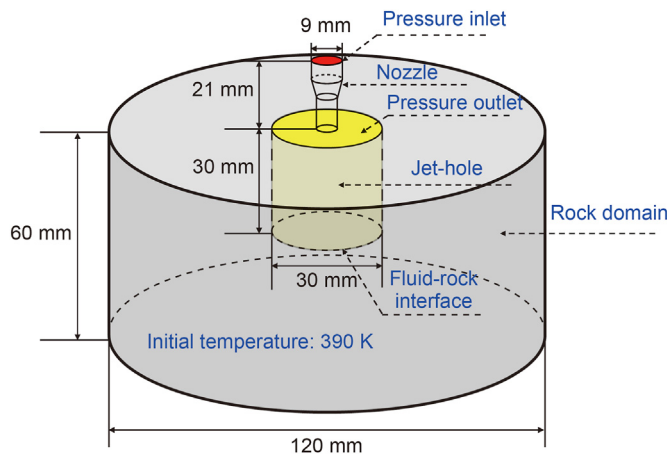


Fig. 2. The geometric model of computation zones.

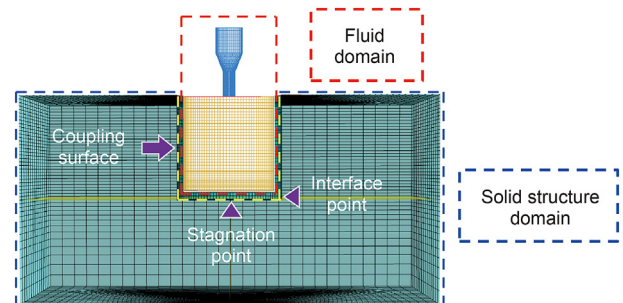


Fig. 3. Schematic diagram of fluid-solid coupling.

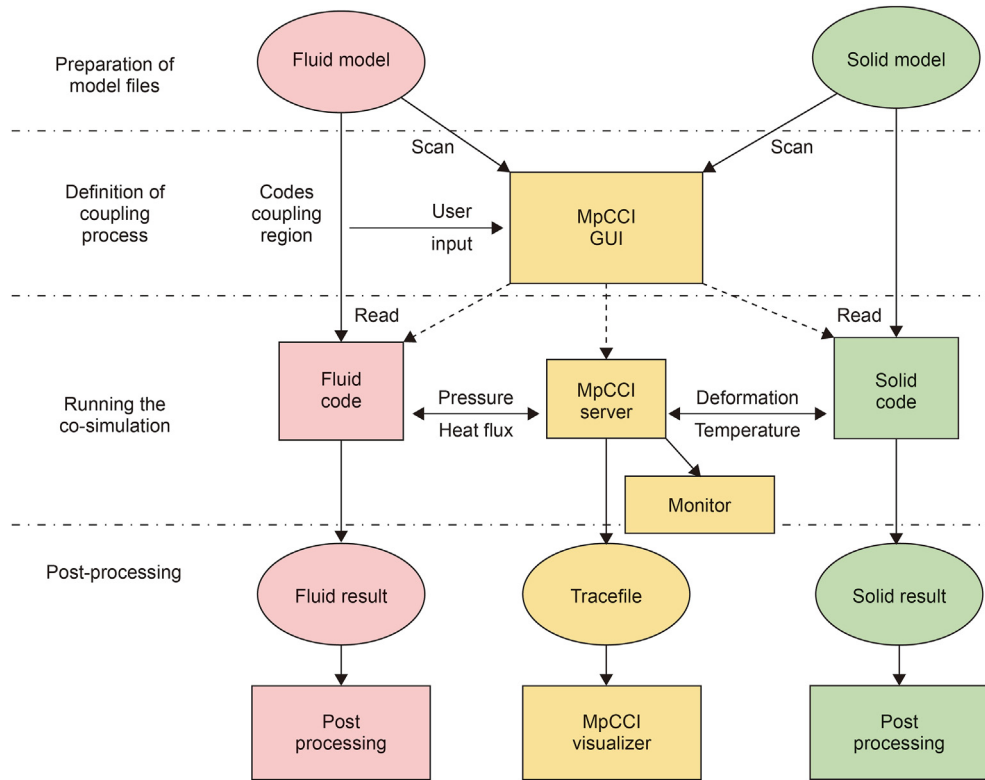


Fig. 4. Co-simulation with MpCCI: Overview of the simulation process.

Table 1
Parameters of SC-CO₂ and water in the modeling.

Modeling parameters		SC-CO ₂	Water
Inlet pressure, MPa		40	40
Outlet pressure, MPa		30	30
Fluid temperature, K		320	320
Physical properties	Viscosity, Pa·s	Determined by the real-gas-model	
	Density, kg/m ³		
	Thermal conductivity, W/(m·K)		
	Heat capacity, kJ/(kg·K)		
			1.003E-5
			998.2
			0.6
			4.182

$$\frac{\partial(\rho T)}{\partial t} + \frac{\partial(\rho u T)}{\partial x} + \frac{\partial(\rho v T)}{\partial y} + \frac{\partial(\rho w T)}{\partial z} = S_T + \frac{\partial}{\partial x} \left(\frac{k_h}{C_p} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{k_h}{C_p} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{k_h}{C_p} \frac{\partial T}{\partial z} \right) \quad (9)$$

where u, v, w are the fluid velocities at the coordinate axis direction of x, y, z , m/s; μ is the dynamic viscosity, Pa·s; p is the fluid pressure, Pa; T is the temperature, K; k_h is the thermal conductivity; S_i and S_T are the source terms of the momentum and energy conservation equations.

3. Geometric and numerical model

3.1. Model assumption

In this simulation, we assumed that the vicinity of the wellbore had been filled with CO₂ during jet fracturing (Shi et al., 2019). Under geothermal reservoir conditions, the temperature and pressure are commonly high above the critical point at 31.1 °C and

7.38 MPa. Therefore, CO₂ was assumed under a single phase in the supercritical state. According to previous studies (Chen et al., 2019), the seeping flow pattern of SC-CO₂ in geothermal reservoir pores can be simplified to Darcy's model. During the abrasive jet perforation process, rock and particles' impact was considered within the elastic collision. Furthermore, the rock was regarded as homogeneous and isotropic. And there was no large rock deformation during jet impingement.

Table 2
Carbonate rock model basic parameters (Xu et al., 2020).

Modeling parameter	Value
Density, kg/m ³	2600
Temperature, K	390
Elastic modulus, GPa	50
Poisson	0.30
Porosity	0.05
Permeability, mD	2.96
Coefficient of thermal expansion, K ⁻¹	2E-6
Specific heat capacity, J/(kg·K)	880
Heat transfer rate, W/(m·K)	1.57

3.2. Geometric model and boundary conditions

As shown in Fig. 2, a three-dimensional geometry model was built to simulate the SC-CO₂ jet fracturing process. The model can be divided into the rock domain and the jet-hole domain. The rock domain is confined in a cylinder with 120 mm diameter and 60 mm length. At the rock center, the jet hole is simplified as a cylinder with 30 mm diameter and 30 mm height. The SC-CO₂ and abrasive particles are pumped into the nozzle, flowing through the perforation cavity, impacting the bottom surface, a small portion of SC-CO₂ seeping into the rock pores and most of them flowing out to the annulus. The specific information of the geometric model is shown in Fig. 2.

Following the field applications, the boundaries of the jet hole were set as pressure inlet and pressure outlet. The interface of fluid and rock was set as a coupled wall to transform the heat flux and pressure between the two parts. The bottom and side surface of the rock domain were set as constant pressure boundary conditions. The value was equal to the formation pressure (20 MPa). Other boundaries were set as the adiabatic wall during calculation.

3.3. Coupling method

According to Fig. 3, the SC-CO₂ jet fracturing impingement simulation is a complex process that contains two parts. The fluid jet impingement effect in the fluid domain and the stress response of carbonate rock in the solid structure domain. Meanwhile, the thermal effect also needs to be considered in the geothermal reservoir. A loose coupling method was adopted to calculate the interaction between two parts, which is achieved by exchanging the coupling data across the fluid-solid interfaces (Wu et al., 2019). In this simulation, we adopted the MpCCI (mesh-based parallel code coupling interface) as the coupling connector to link the fluid domain (Fluent) and solid structure domain (Abaqus) together. MpCCI is a multi-physics professional mesh coupling interface software developed by the Fraunhofer Institute for Algorithms and Scientific Computing (Zhai et al., 2021). It creates a channel to exchange the data of different simulation codes between meshes. MpCCI has been widely used to calculate the multi-physics coupling simulation in many industry fields (Li et al., 2020). For the application in jet impingement, Wu et al. (2019) conducted the

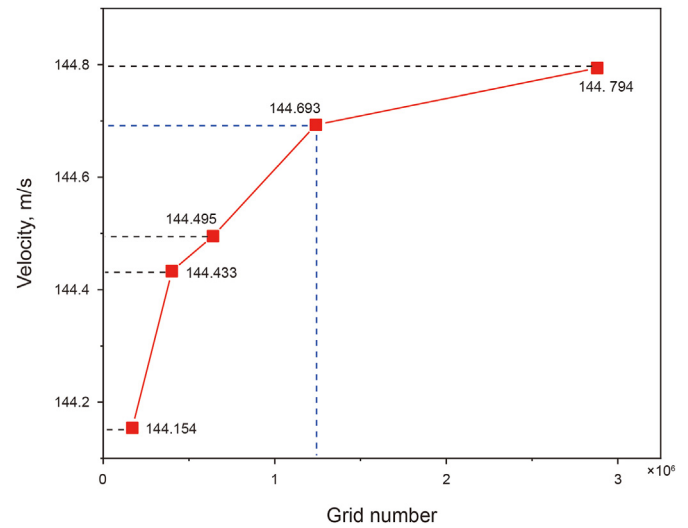


Fig. 6. Sensitivity of mesh number.

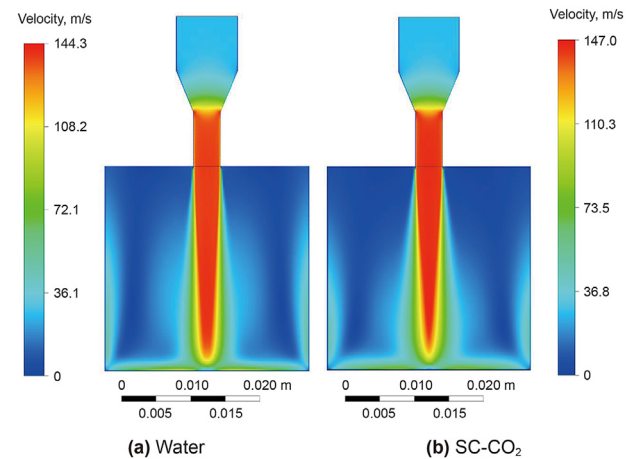


Fig. 7. Velocity contours of (a) water jet and (b) SC-CO₂ jet.

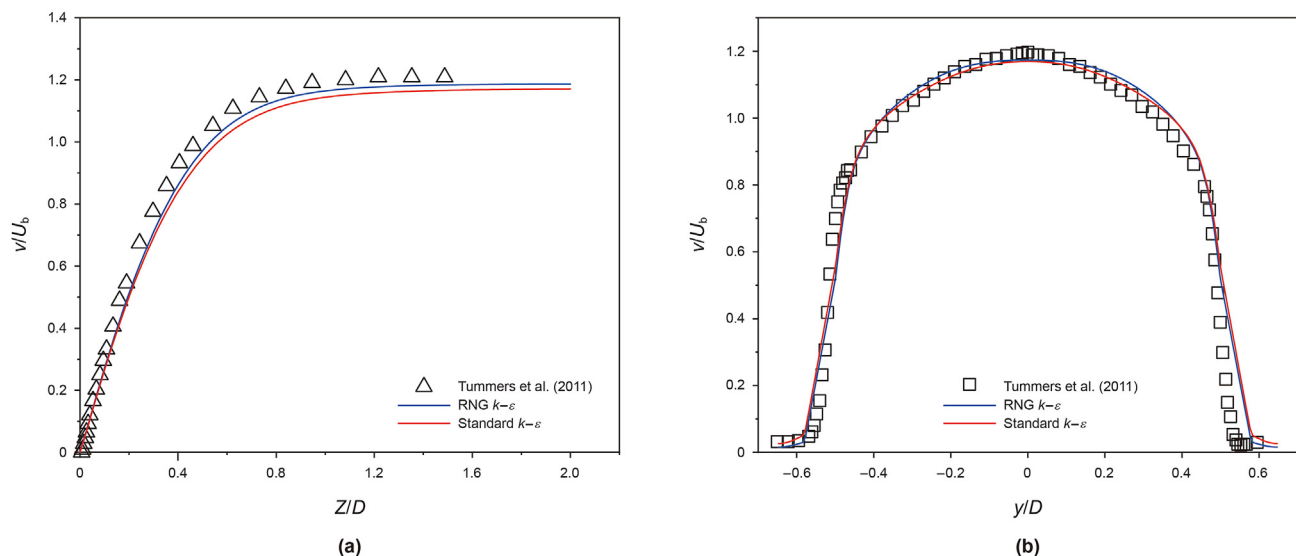


Fig. 5. Comparison between simulation results and experimental data.

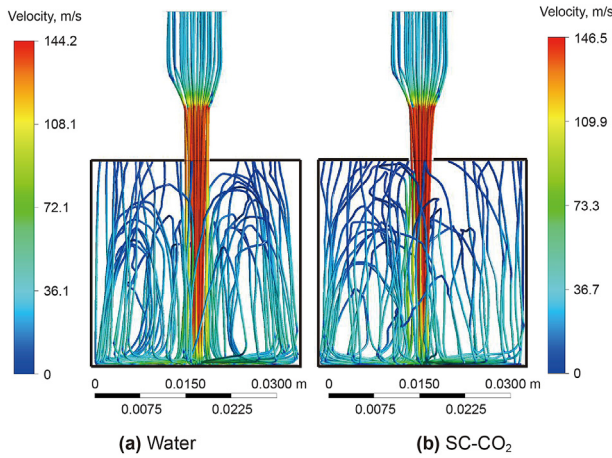


Fig. 8. Particle trajectories of (a) water jet and (b) SC-CO₂ jet.

fluid-thermo-mechanical coupling model of liquid nitrogen (LN₂) jet impingement based on MpCCI.

The detailed coupling process of MpCCI for fluid-structure interaction (FSI) is illustrated in Fig. 4. Furthermore, the coupling data should satisfy Eq. (10):

$$\begin{aligned} P_f(x, y, z, t) \cdot n_f &= P_s(x, y, z, t) \cdot n_s \\ d_f(x, y, z, t) &= d_s(x, y, z, t) \\ T_f(x, y, z, t) &= T_s(x, y, z, t) \\ h_f \frac{\partial T_f}{\partial n_f}(x, y, z, t) &= q_f = q_s = h_s \frac{\partial T_s}{\partial n_s}(x, y, z, t) \end{aligned} \quad (10)$$

where P , d , T , h , q represent the pressure, deformation, temperature, heat conduction coefficient, and heat flux, respectively; n is the normal vector of the coupling surface; subscripts f and s indicate the fluid domain and solid domain.

The pressure and heat flux data on the coupling surface are transferred from the fluid domain to the solid structure domain every iteration. After the solid domain calculates, the deformation and temperature data are transmitted back to the fluid domain with new boundary conditions. The process mentioned above is

constantly repeated and recycled before reaching the predefined time in the calculation. The mesh near the coupled surface was refined on both sides for high accuracy. The dynamic mesh method in Fluent was adopted, as the impacted surface would deform slightly after each iteration.

3.4. Fluid and solid domain modeling

3.4.1. Perforation fluid flow model

In calculating impinging jet flow, the flow field in the perforation cavity is a high Reynolds number region with drastic vortex motion. This study adopted the RNG $k - \epsilon$ model to calculate the RANS equations, which are widely used by scholars (Zhang et al., 2018a) to solve turbulence with significant vortex motion. As the physical property of SC-CO₂ is susceptible to pressure and temperature, we employed the NIST real-gas model and the coupled algorithm to address the issue of thermophysical property variations. The timestep is fixed as 0.1 ms. Detailed fluid parameters are illustrated in Table 1.

For calculating the abrasive jet flow field, two methods are commonly employed. One is to treat the solid phase as a continuous medium or pseudo-fluid, and the other method is to treat the solid phase as a discrete phase medium (Chang et al., 2019). In this model, due to the low particle density in jet flow, the discrete phase model (DPM) was introduced into the fluid domain. The model solves the Navier-Stokes equations in the Euler framework for the continuous phase (fluid) and calculates the orbital particle equation in the Lagrange framework for abrasive particles. Besides, to demonstrate the destruction effect of particles, the erosion model was activated to analyze the degree of particle erosion qualitatively. In the Cartesian coordinate system, the force balance equation for a single abrasive particle can be expressed as (Bennon and Incropera, 1987):

$$\frac{du_p}{dt} = F_D(u_f - u_p) + \frac{g(\rho_p - \rho_f)}{\rho_p} + F_X \quad (11)$$

where $F_D(u_f - u_p)$ is the drag force of the particle; $\frac{g(\rho_p - \rho_f)}{\rho_p}$ is the gravity item; F_X is the additional force item; u_p , u_f are the velocities of particle and fluid, m/s; ρ_p , ρ_f are the densities of particle and fluid,

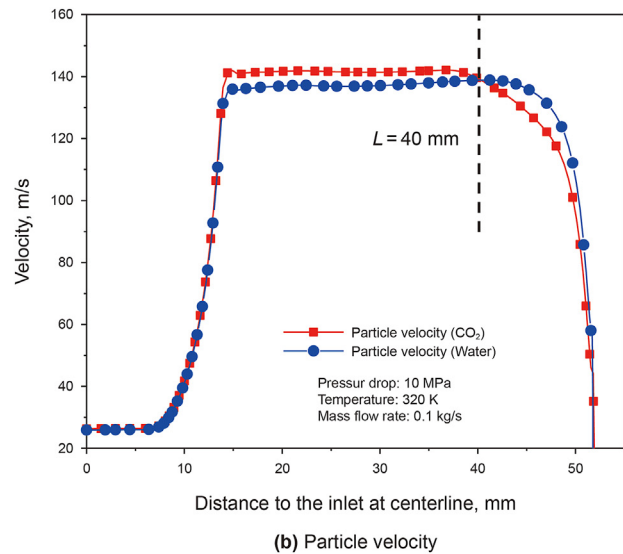
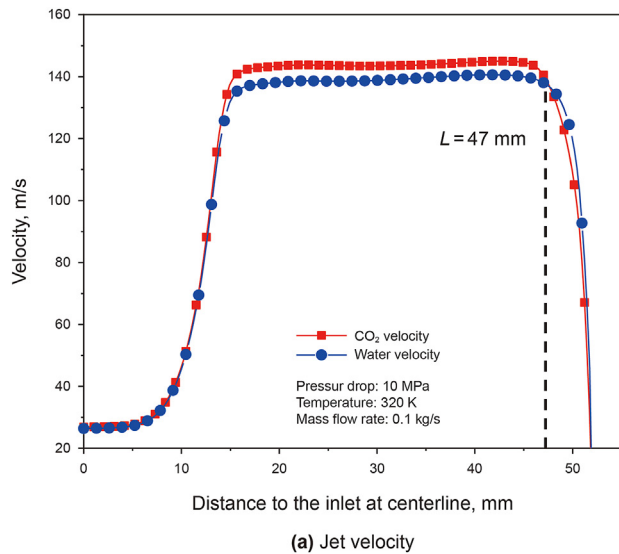


Fig. 9. Velocity distribution at the centerline.

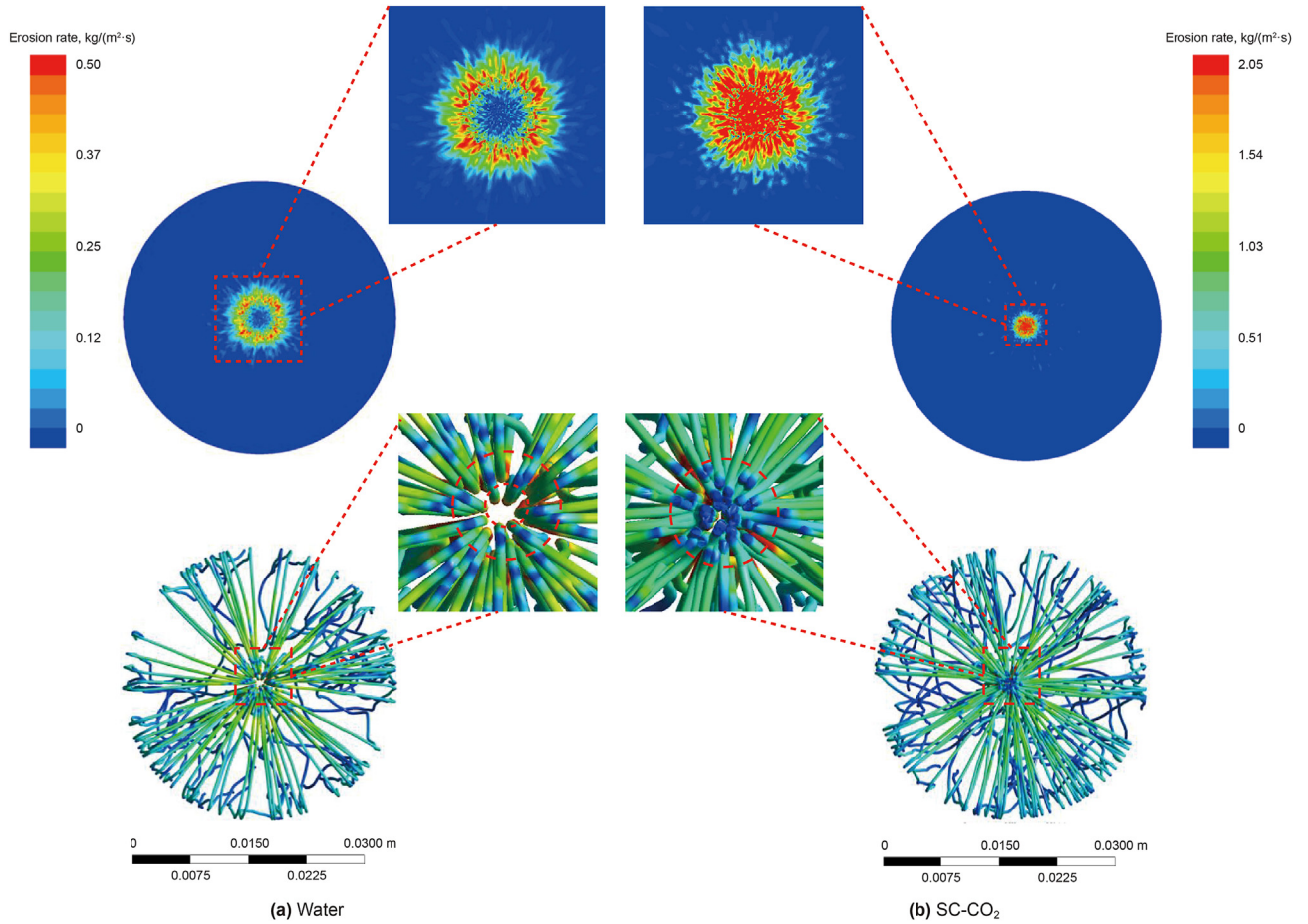


Fig. 10. Erosion rate contours and particles trajectory of (a) water and (b) SC-CO₂ at the bottom surface.

kg/m³.

The erosion model can be calculated by the equation as below (Edwards et al., 2000):

$$R_{\text{erosion}} = \sum_{p=1}^{N_p} \frac{m_p C(d_p) f(\alpha) v_p^{b(v)}}{A_{\text{face}}} \quad (12)$$

where N_p is the number of particles; m_p is the mass flux; $C(d_p)$ is the

particle size function; α is the Impact angle; $f(\alpha)$ is the impact angle function; v_p is the particle velocity; $b(v)$ is the velocity function; A_{face} is the wall area.

3.4.2. Porous flow model

The bottom carbonate rock is set as homogeneous porous media with relatively low permeability. We adopted the Darcy-Brinkman-Forchheimer model (Vafai and Tien, 1981) to calculate the flow transport in porous media. The continuity and momentum governing equations can be expressed in Eqs. (13) and (14). S_i in Eq. (15) represents the flow resistance source term. As the flow velocity u_i is small enough in the rock media, the model can be simplified to the Darcy model (Zhang et al., 2018b).

$$\frac{\partial(\phi \rho_f)}{\partial t} + \nabla(\rho_f u_i) = 0 \quad (13)$$

$$\frac{\partial(\rho_f \frac{u_i}{\phi})}{\partial t} + \nabla \left(\rho_f \frac{u_i}{\phi} \cdot \frac{u_i}{\phi} \right) = -\nabla P + \nabla \mu_f \nabla \frac{u_i}{\phi} + S_i \quad (14)$$

$$S_i = -\frac{\mu_f}{K} u_i + C \frac{1}{2} \rho_f |u_i| u_i \quad (15)$$

where ϕ is the rock porosity; ρ_f is the fluid density, kg/m³; u_i is the fluid velocity in the i direction, m/s; μ_f is the viscosity of fluid, Pa·s; P is the pressure, Pa; K is rock permeability, m².

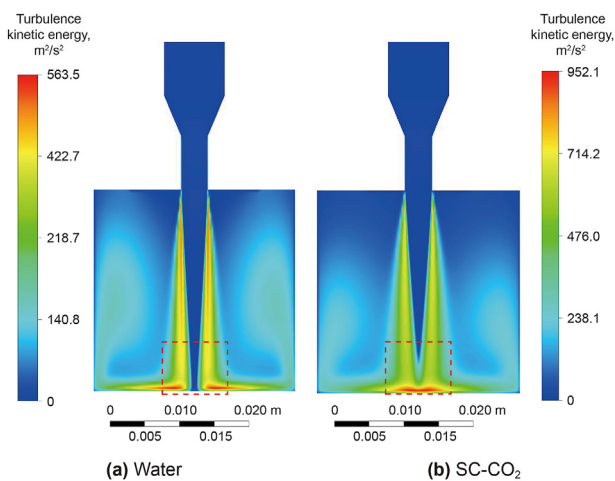


Fig. 11. Turbulence kinetic energy contours of (a) water and (b) SC-CO₂.

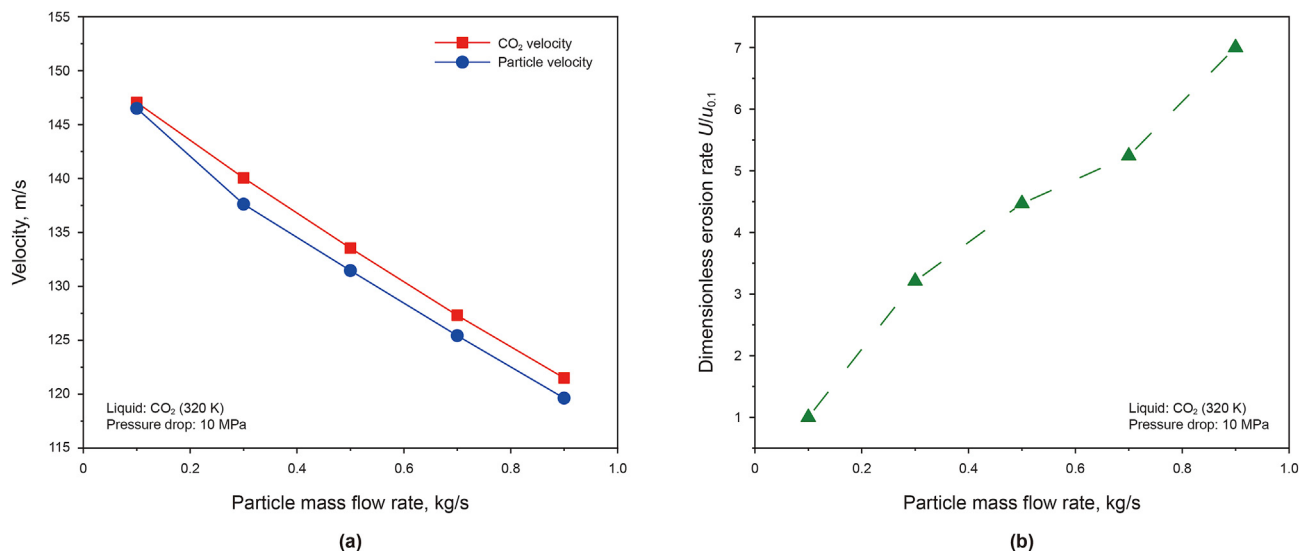


Fig. 12. The maximum jet velocity and dimensionless erosion rate distribution with different mass flow rates.

3.4.3. Solid domain model

The rock domain was set as homogenous carbonate rock in the solid domain. The effect of temperature and dilatation of rock were taken into account. The physical properties of carbonate rock were taken from the previous study, as shown in Table 2. The jet impact stress and thermal stress need to be calculated simultaneously in the calculation process. Therefore, we adopted the coupled temperature-displacement solution step to calculate this fully coupled process. NLgeom (Nonlinear geometry) was turned on to take the geometric deformation into account. The timestep is fixed as 0.1 ms to match with the fluent domain.

3.5. Model validation

Validation was conducted by comparing the results with the previous experimental data to confirm the model's accuracy. The experimental data of Tummers (Tummers et al., 2011) is widely adopted for validating the turbulent flow. Their experiments

investigated the turbulent impinging jet in a long straight pipe at a Reynolds number of 23000. We employed the RNG $k-\epsilon$ model and Standard $k-\epsilon$ model to simulate the velocity field under the experimental conditions. First, a pipe flow model was built to develop the turbulent flow adequately for better revivification with the experiment. And then, the fully developed pipe flow was imported into the nozzle as the inlet boundary condition using the "profile file". Fig. 5a and b shows the velocity comparison between simulation results and experimental data in the centerline and the velocity of the cross section which is 7 mm away from the outlet, respectively. The measured velocity is expressed in the dimensionless term v/U_b , where v is the vertical velocity along the centerline and U_b is the bulk velocity at the nozzle's exit. It can be observed that the numerical results agree well with the experimental data.

To guarantee the mesh independence of results, we calculated the velocity at the distance of 20 mm from the nozzle as the indicator (Fig. 6). It can be seen that when the grid number exceeds

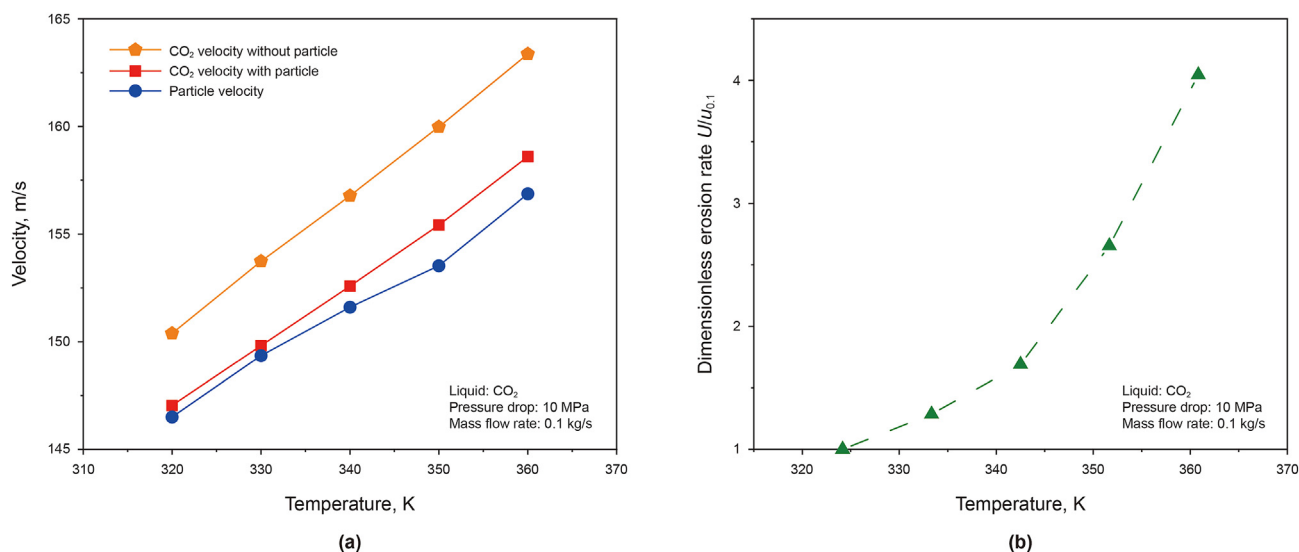


Fig. 13. The maximum velocity and dimensionless erosion rate at different temperatures.

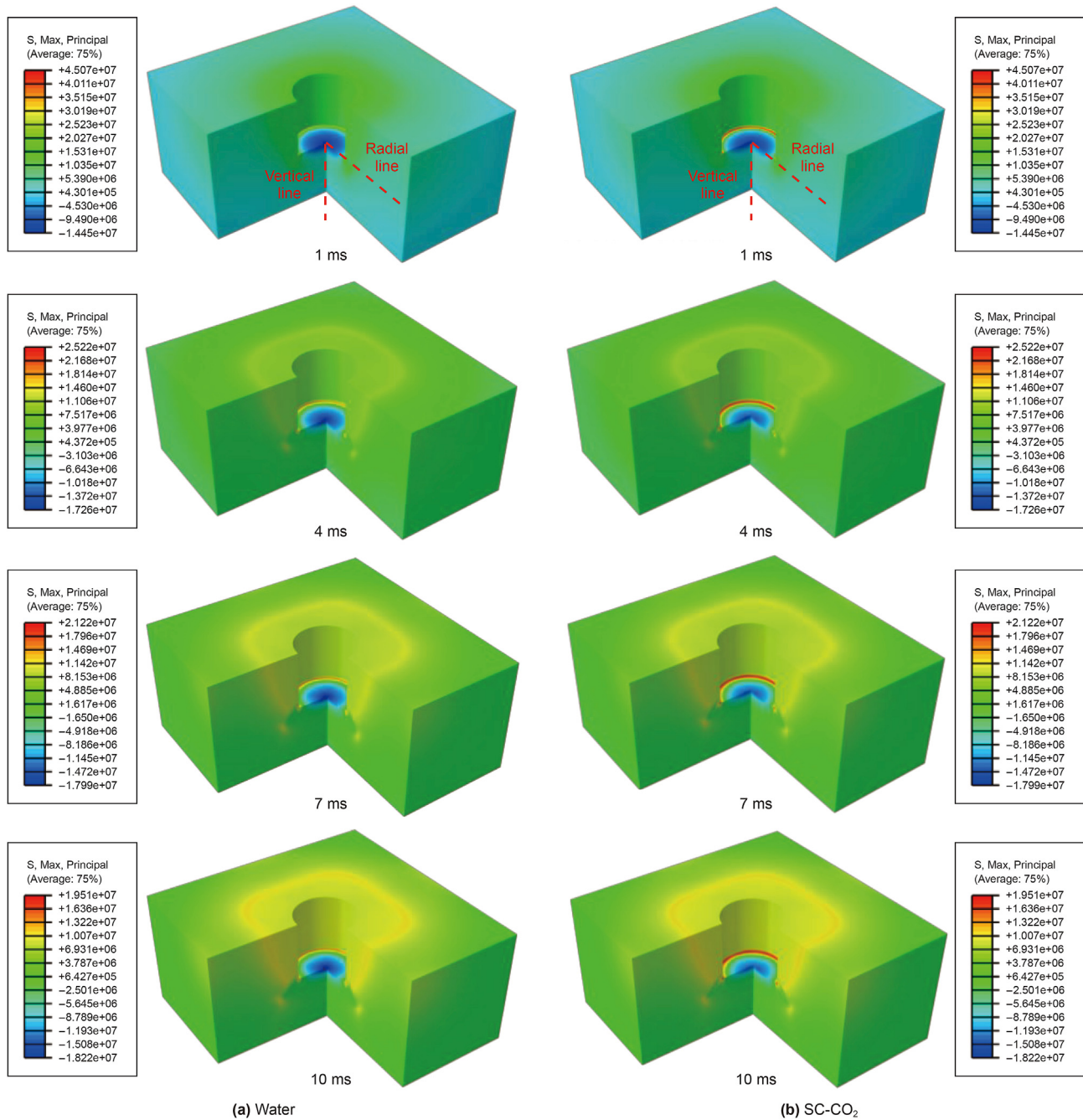


Fig. 14. Contours of maximum principle stress subjected to (a) water and (b) SC-CO₂ jet impingement.

1,240,000, the velocity has only a slight increase. Given the simulation accuracy and computation efficiency, a mesh scheme consisting of 1,313,856 cells was employed for the jet fracturing flow model.

4. Results and discussion

4.1. SC-CO₂ jet fracturing flow field

4.1.1. Jet flow field and particle trajectory

Figs. 7 and 9a show the velocity contours and distribution of the water jet and SC-CO₂ jet, respectively. We found that the SC-CO₂ had a higher maximum jet velocity (147.4 m/s) than the water jet

(144.3 m/s) at the same pressure drop. It is mainly attributed to the rheologic properties of SC-CO₂. Based on Bernoulli's principle, pressure potential energy converts to kinetic energy ($\rho v^2/2$) in jet impingement. Due to lower density and viscosity, the velocity of SC-CO₂ showed a higher value than that of the water jet.

The fluid provides and accelerates the velocity of particles. Therefore, the high jet velocity commonly leads to a high particle velocity. As shown in Figs. 8 and 9b, the maximum particle velocity of SC-CO₂ (146.5 m/s) was 1.6% higher than that of the water jet (144.2 m/s), but it also dissipates more quickly. At about 40 mm from the inlet, the particle velocity of SC-CO₂ began to lower than that of water. This phenomenon is also mainly attributed to the rheologic properties of SC-CO₂. From Eq. (11), we found that the

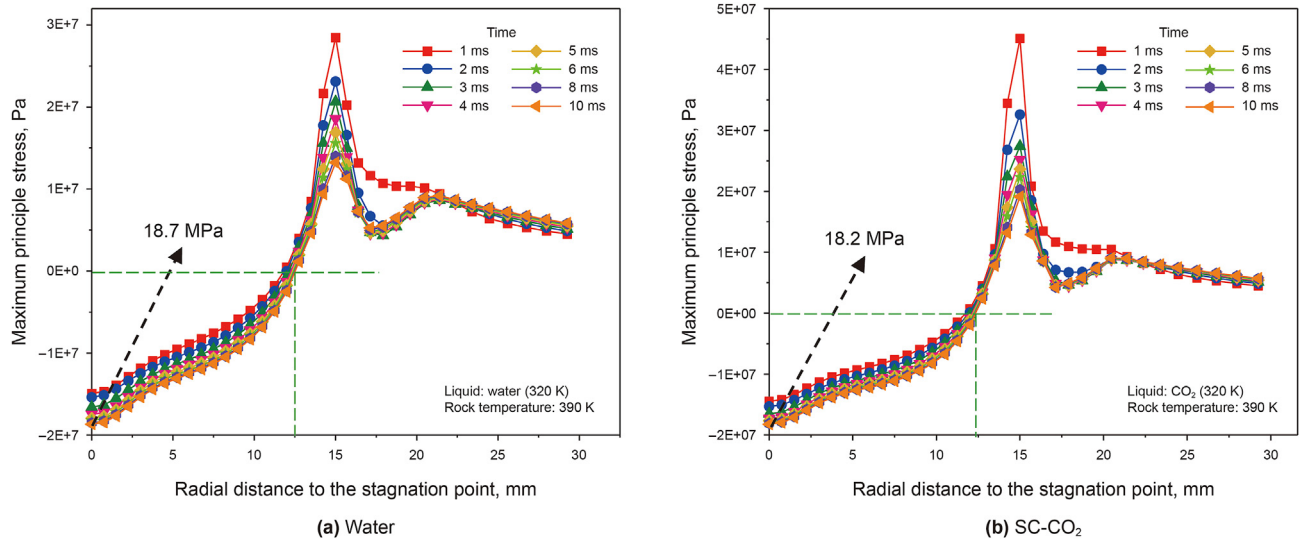


Fig. 15. Maximum principal stress distribution along the radial direction.

drag force F_D is highly related to the fluid viscosity and density. As mentioned before, the SC- CO_2 has a similar viscosity to the gas, which means a smaller drag force is carried on the particles. Hence, at the jet hole, the particle velocity of SC- CO_2 decreased more quickly.

4.1.2. Particle erosion rate

We introduced erosion analysis into the model, which is commonly employed in predicting pipe wear during fluid transport (Wang et al., 2019). We chose the widely used Generic erosion model (Edwards et al., 2000) as the governing equation (Eq. (12)) to calculate the erosion rate. It could help us to analyze the impact effect of particles qualitatively. Fig. 10 illustrates the particle erosion rate contours on the bottom surface of the water jet and SC- CO_2 jet, respectively. It can be observed that the two jets showed different erosion patterns and different degrees of damage. The water jet's erosion contour presented a ring shape, while SC- CO_2 presented a more centralized circle. The particles' trajectory also showed the same results. As shown in Fig. 10, there was no particle trajectory in

the center point on the bottom surface of the water jet compared with the SC- CO_2 jet.

This phenomenon is mainly attributed to the different fluid characteristics of the two jets. Fig. 11 illustrates the turbulence kinetic energy of the water jet and SC- CO_2 jet, respectively. The turbulence kinetic energy is an indicator to present the turbulence intensity of the fluid. It can be seen that the turbulence intensity of the SC- CO_2 jet was much greater than the water jet at the nearby bottom surface. That meant the high SC- CO_2 jet velocity dissipated more significantly when the jet reached the bottom rock surface. In contrast, the water jet could accumulate at the stagnation point, preventing the later particles from impacting this area. That led to the different erosion patterns of the two jets. The centralized erosion pattern means a higher frequency of particle impact at the stagnation point, causing a high degree of damage. Thus, in applications, decreasing the particle density during the SC- CO_2 perforation could achieve the same perforation effect as the water jet and simultaneously reduce the risk of sand plugging.

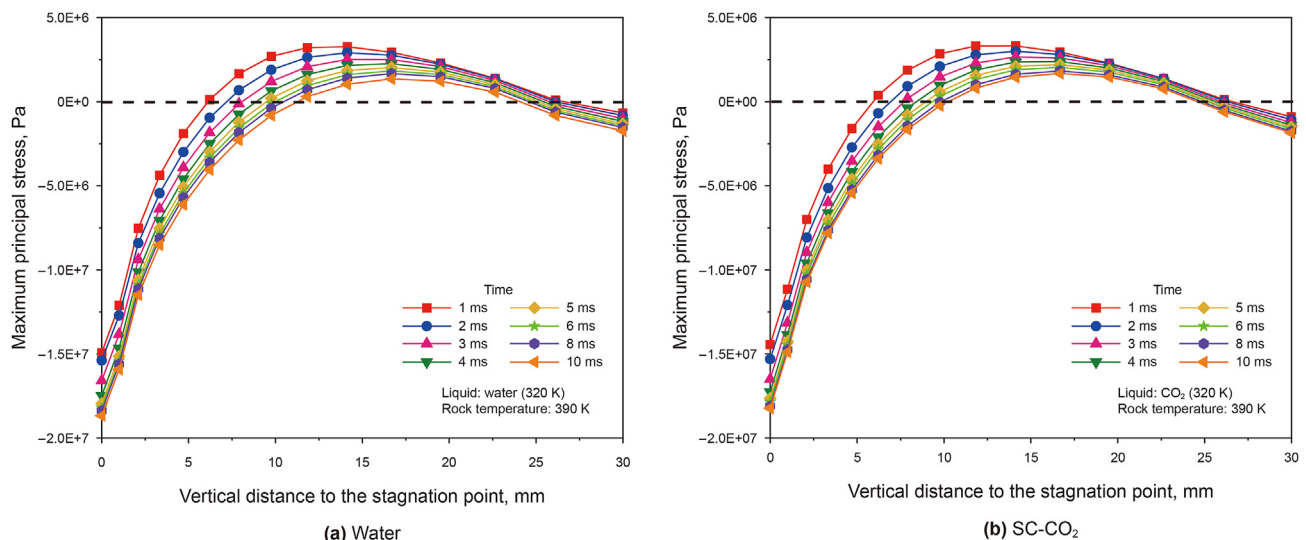


Fig. 16. Maximum principal stress distribution along the vertical direction.

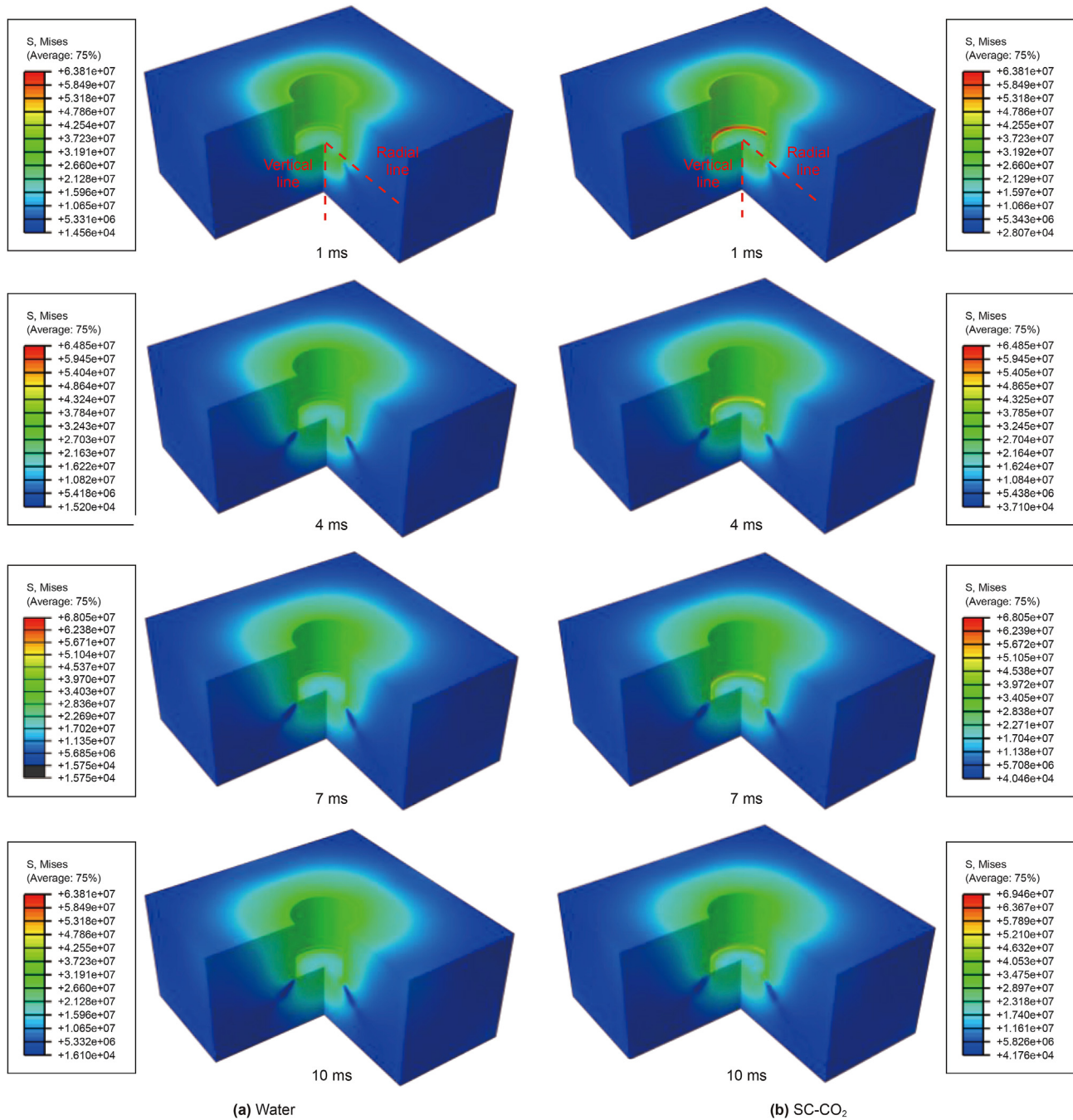


Fig. 17. Contours of Mises stress subjected to (a) water and (b) SC-CO₂ jet impingement.

4.1.3. Effect of mass flow rate and jet temperature

Fig. 12a and b illustrate the jet velocity and erosion rate change with different mass flow rates. The dimensionless term $U/u_{0.1}$ was employed to indicate the erosion degree. U is the maximum erosion rate; $u_{0.1}$ is the maximum erosion rate at particle mass flow rate equal to 0.1 kg/s. With the increase in particle mass flow rate, the maximum velocity of SC-CO₂ jet and particles decreased linearly from about 147 to 120 m/s. Moreover, the erosion rate increased about 7 times. The reason is that the high particle density needs a higher drag force to maintain the velocity. However, under the constant pressure drop conditions, the energy provided by the fluid was limited. The low velocity decreased the erosion rate. The high particle density increased the impacting frequency, and the higher

impacting frequency improved the erosion rate. In our model, the combination of two factors led to the increase in erosion rate.

Although the high erosion rate led to high perforation performance, the jet velocity could not maintain a high value. One of the critical factors for SC-CO₂ jet fracturing is the pressurization within the tunnel (Sheng et al., 2013). And the high-velocity jet flow provided the pressurization effect. Therefore, we needed to control the mass flow rate at a suitable value, performing well in perforation and maintaining high pressurization within the cavity.

Fig. 13 presents the maximum jet velocity and particle velocity distribution at different jet temperatures. It can be seen that with the increase in jet temperature, the jet velocity and particle velocity increased by about 12 m/s, and the particle erosion rate increased

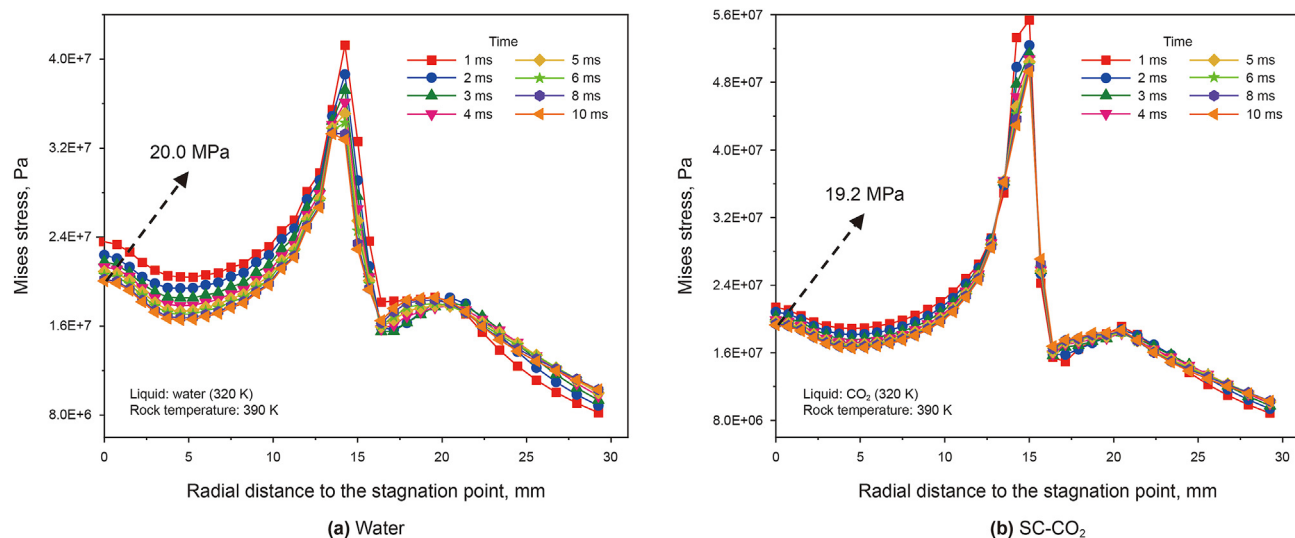


Fig. 18. Mises stress distribution along the radial direction: (a) water; (b) SC-CO₂.

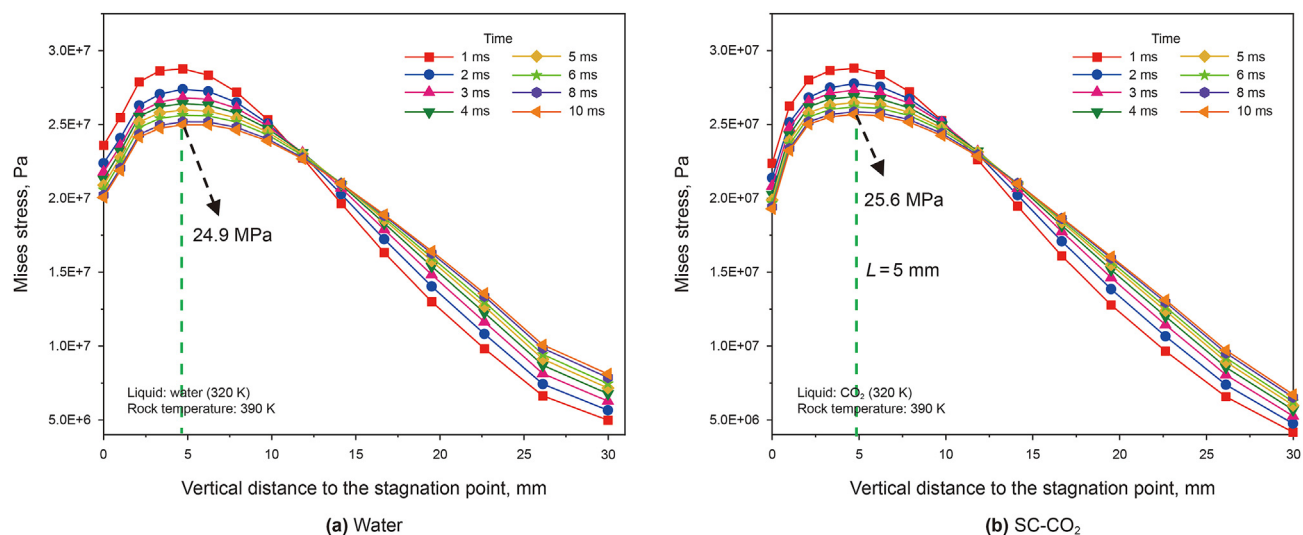


Fig. 19. Maximum principal stress distribution along the vertical direction: (a) water; (b) SC-CO₂.

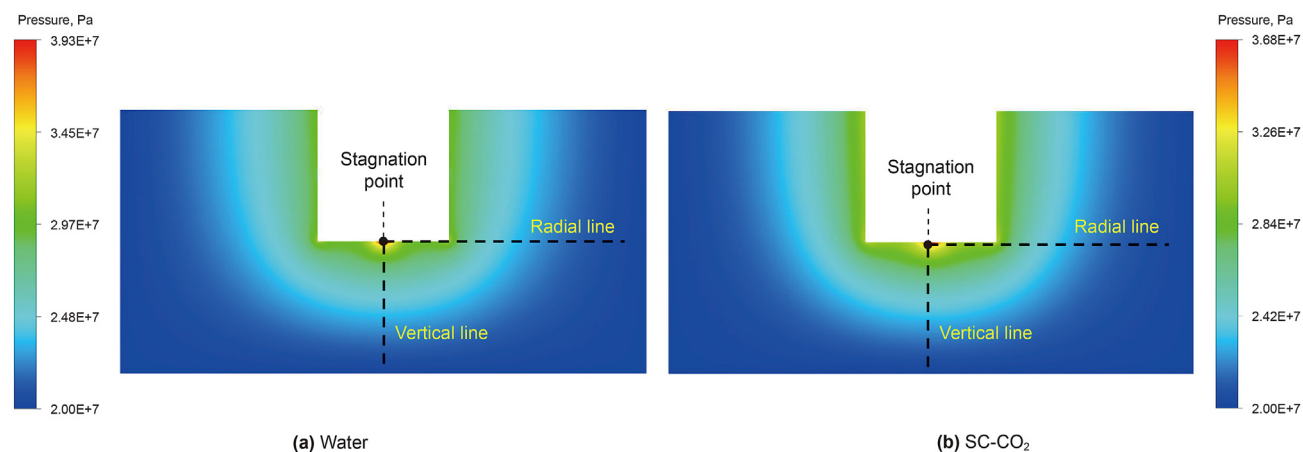


Fig. 20. The pore pressure contours of (a) water and (b) SC-CO₂.

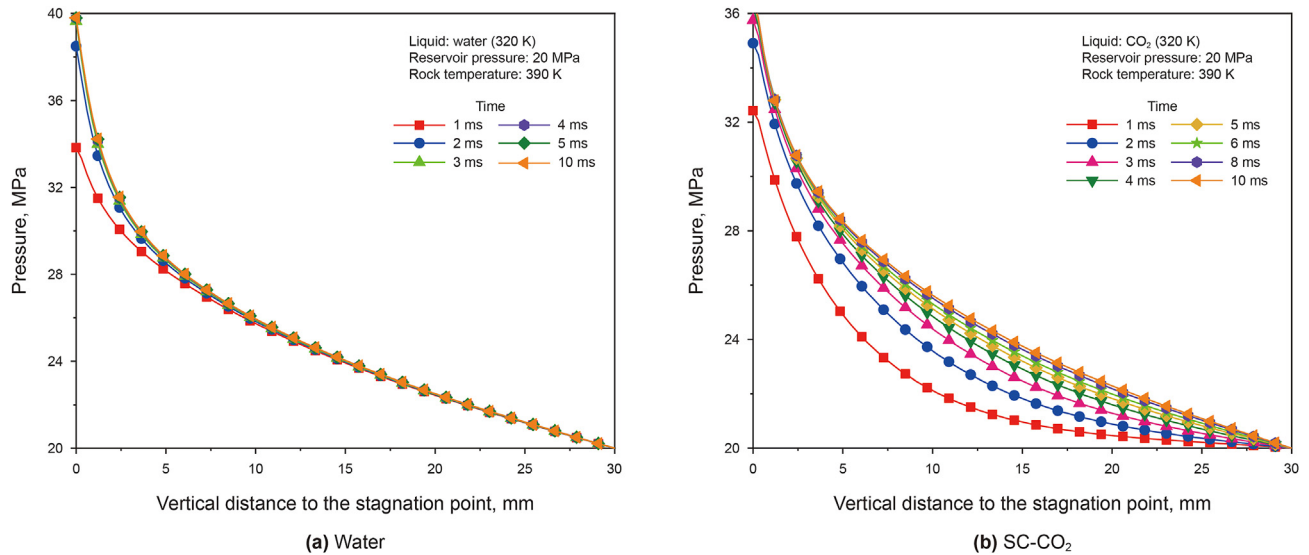


Fig. 21. The pore pressure distribution of the rock domain along the vertical direction: (a) water; (b) SC-CO₂.

about four times simultaneously. The reason is that as the temperature increases, the density and viscosity of SC-CO₂ will decrease simultaneously. That leads to the high jet velocity and high particle velocity. However, low viscosity means a low drag force. Therefore, it can be seen that the gap between the jet velocity and particle velocity gradually becomes larger. A suitable temperature increase on the ground could improve the SC-CO₂ jet perforation effect in field applications.

4.2. Carbonate rock stress field

4.2.1. Maximum principle stress

Based on the first strength theory, brittleness material fails when the max principal stresses exceed its tensile strength. Therefore, by studying the max principal stress distribution, we could figure out the tensile failure pattern of carbonate rock under jet impingement. Generally, the tensile stress is set as positive, while the compressive stress is set as negative. Fig. 14 shows the

contours of maximum principle stress subjected to water and SC-CO₂ jet impingement. Carbonate rock showed a similar failure pattern under different jet mediums. The compressive stress was mainly distributed at the center of the surface. In comparison, the tensile stress was distributed with a ring pattern and gradually enhanced along the radial direction.

We extracted the stress distribution along radial and vertical directions to better represent the failure pattern. In Fig. 15, the change of the maximum principle stress of two jets showed a similar evolution process. The compressive stresses at the stagnation point increased slightly in the initial few milliseconds on both conditions. With the increase in the radial distance, the stress value switched from negative to positive at about 12.5 mm. The tensile stress increased significantly at the boundary of the jet hole. It is mainly attributed to the stress concentration at the edge of the jet hole. The differences between the two jets were the stress value at the stagnation point and the edge of the jet hole. The carbonate rock suffered higher compressive stress under the water jet and a

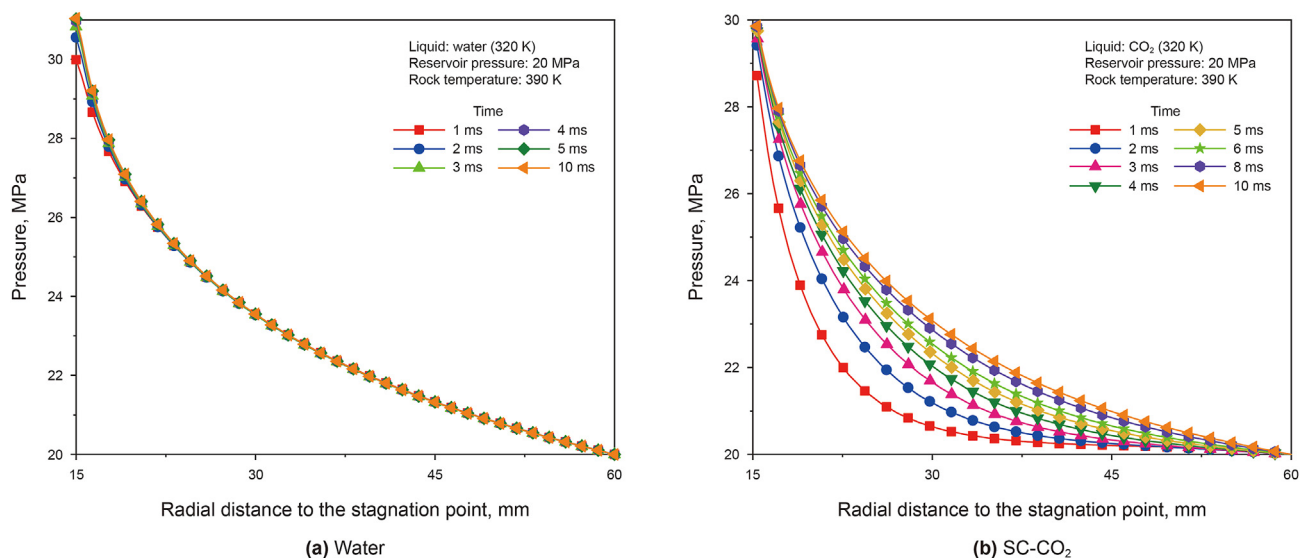


Fig. 22. The pore pressure distribution of the rock domain along the radial direction: (a) water; (b) SC-CO₂.

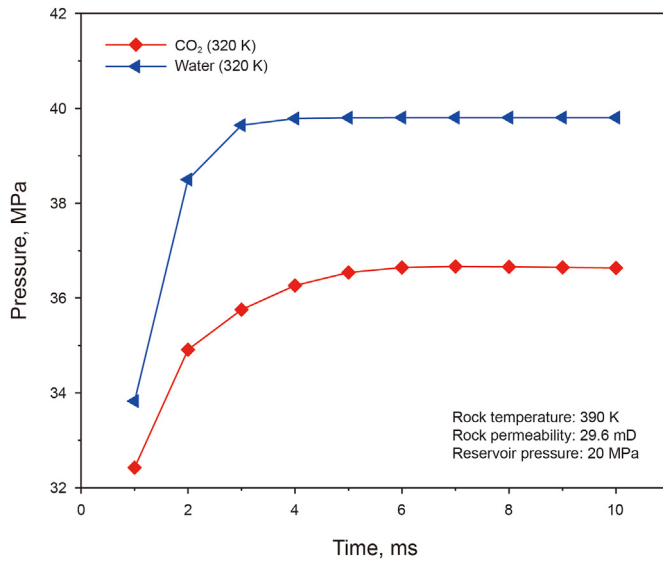


Fig. 23. The pressure distribution at the stagnation point of water and SC-CO₂.

much higher tensile stress under the SC-CO₂ jet. It is consistent with the previous discussion (Fig. 11) that SC-CO₂ jet velocity dissipated more significantly when the jet reached the bottom rock surface. This process also involved the phase change and the volume expansion of CO₂. Therefore, it led to lower impingement stress at the stagnation point and higher tensile stress at the jet-hole surface. Fig. 16 presents the maximum principle stress distribution along the vertical line of the water jet and SC-CO₂ jet, respectively. It can be seen that both stress curves went through the same changing process. In the initial few milliseconds, the compressive stress at the stagnation point increased with time. At about 6 ms, the stress reached stable. The compressive stress switched to tensile stress at about 10 mm below the stagnation point.

4.2.2. Mises stress

Von Mises stress is a yield criterion that follows the fourth strength theory. It is defined by the equation as follows:

$$\sigma_e = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad (16)$$

where σ_e is the equivalent stress; σ_1 , σ_2 and σ_3 are the first, second, and third principal stress, respectively.

According to the distribution of Mises stress, we can figure out the area likely to fail during the jet fracturing process. Fig. 17 shows the Mises stress contours of carbonate rock under water jet and SC-CO₂ jet impingement. It can be seen that the distribution of both mises stress contours originated from the jet-hole and extended to the rock boundary. We extracted the Mises stress distribution along the radial and vertical directions. As shown in Fig. 18, the value of Mises stress decreased first with the increase in the radial distance. It then increased, forming the circular ring pattern. This changing pattern of Mises stress on the impact surface was helpful for rock failure. The obstruction of the perforation edge changed the trend of Mises stress. The changing Mises stress showed the same distribution features as the maximum principle stress. The carbonate rock takes a higher Mises stress at the stagnation point under the water jet. While in the SC-CO₂ jet, the Mises stress at the jet-hole surface was much higher. Fig. 19 shows the Mises stress along the vertical direction. It can be seen that the maximum Mises stress in rock was located below the stagnation point at about 5 mm. And the stress value under the SC-CO₂ jet was higher than the water jet at this point. The shear failure was more likely to occur in this area

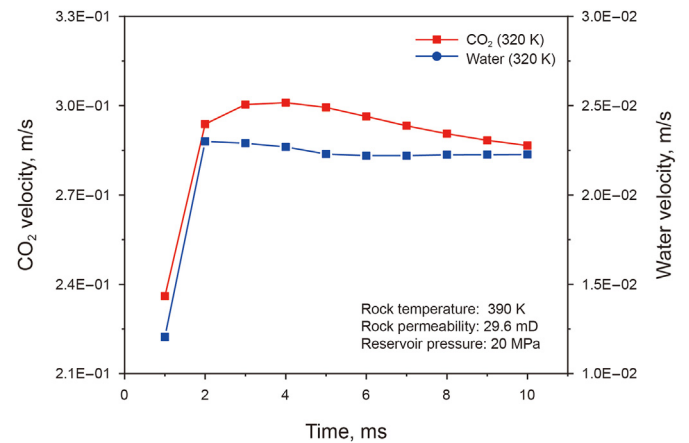


Fig. 25. The seepage velocity distribution of water and SC-CO₂ at the stagnation point.

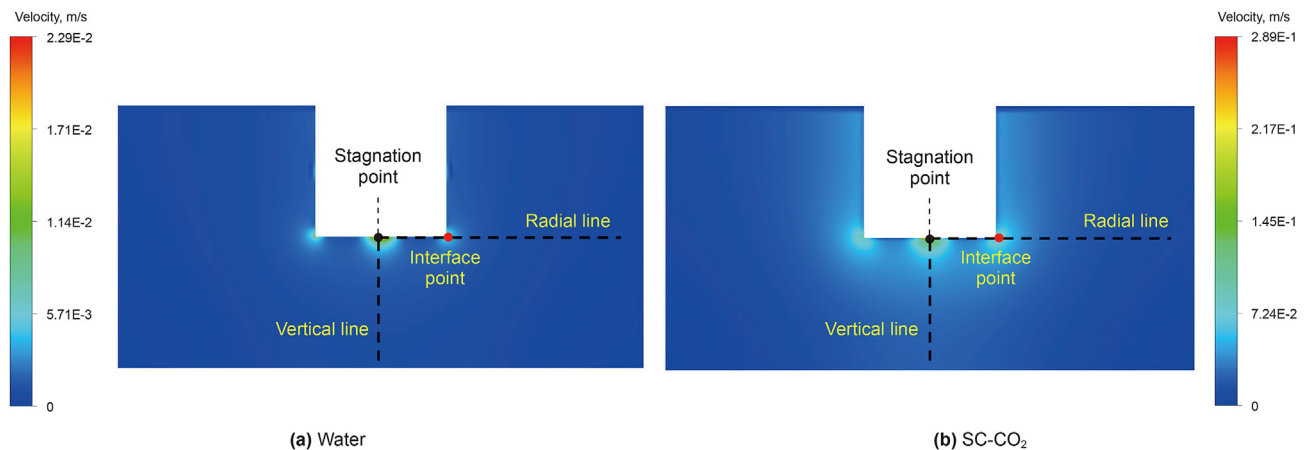


Fig. 24. The seepage velocity contours of (a) water and (b) SC-CO₂.

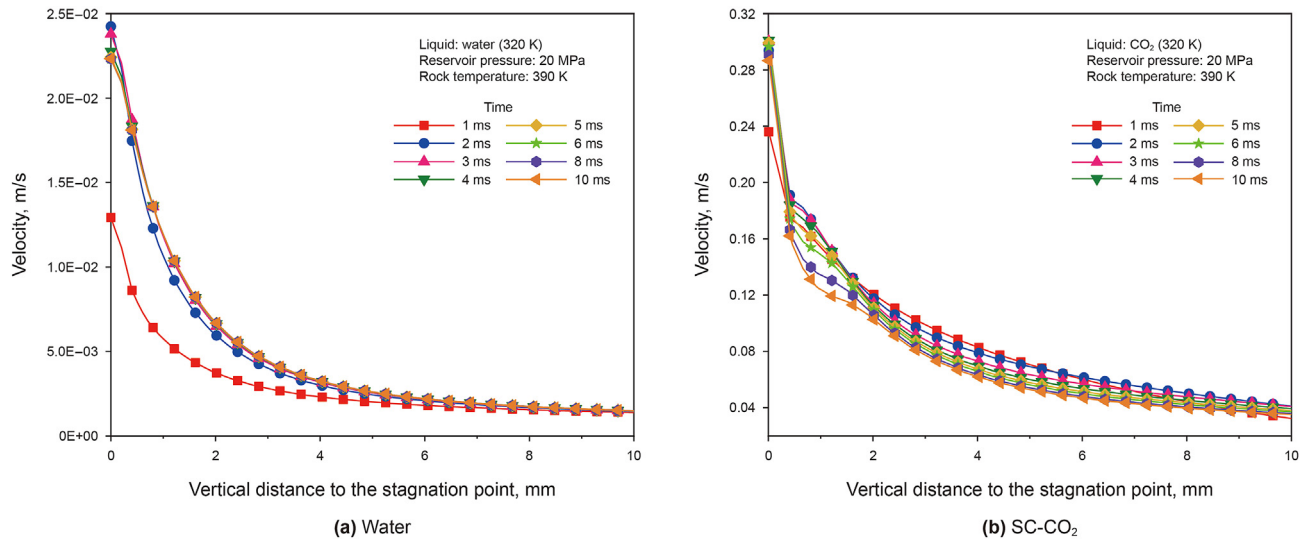


Fig. 26. The seeping velocity distribution of rock domain along the vertical direction: (a) water; (b) SC-CO₂.

during high SC-CO₂ jets. The fracture initiation and propagation would start from this failure point to the weak point on the impact surface.

4.3. Porous flow field

4.3.1. Pressure distribution of porous flow field

Fig. 20 illustrates the pressure distribution of rock under jet impingement. It can be seen that from the jet-hole to the rock boundary, the pressure dropped gradually. Moreover, according to Figs. 21 and 22, water pressure reached stabilization faster than SC-CO₂ in both directions (vertical and radial). It is mainly related to the low viscosity and the compressibility of SC-CO₂. The low viscosity and near-zero surface tension made transporting into the porous domain easier. This seeping mechanism could increase the pore pressure around the wellbore and reduce the strength of the rock. However, the compressible characteristic slowed down the speed of pressure propagation. The previous experiments also presented the phenomenon that the wellbore bottom pressure of

SC-CO₂ increases more slowly than water during the fracturing (Jian et al., 2021).

Moreover, this unique property also lowered the stagnation point pressure (Fig. 23). At the stagnation point, the pressure of the water jet is 4 MPa higher than the SC-CO₂ jet. The SC-CO₂ might need a higher pump pressure for the same crack extension effect. However, the carbonate geothermal reservoir could avoid this problem due to the chemical reaction between CO₂ and water formation. After CO₂ was injected into the pore structure, it could combine with water and produce carbonic acid. The release of H⁺ leads to mineral dissolution (Cui et al., 2017). Mineral and clay dissolution helps create microfractures, improving the fracturing effect. And the high reservoir temperature could accelerate this process. Therefore, the carbonate geothermal reservoir is one of the best formations for SC-CO₂ jet fracturing.

4.3.2. Velocity distribution of porous flow field

Fig. 24 shows the seepage velocity contours in the rock domain of water and SC-CO₂, respectively. To describe the velocity

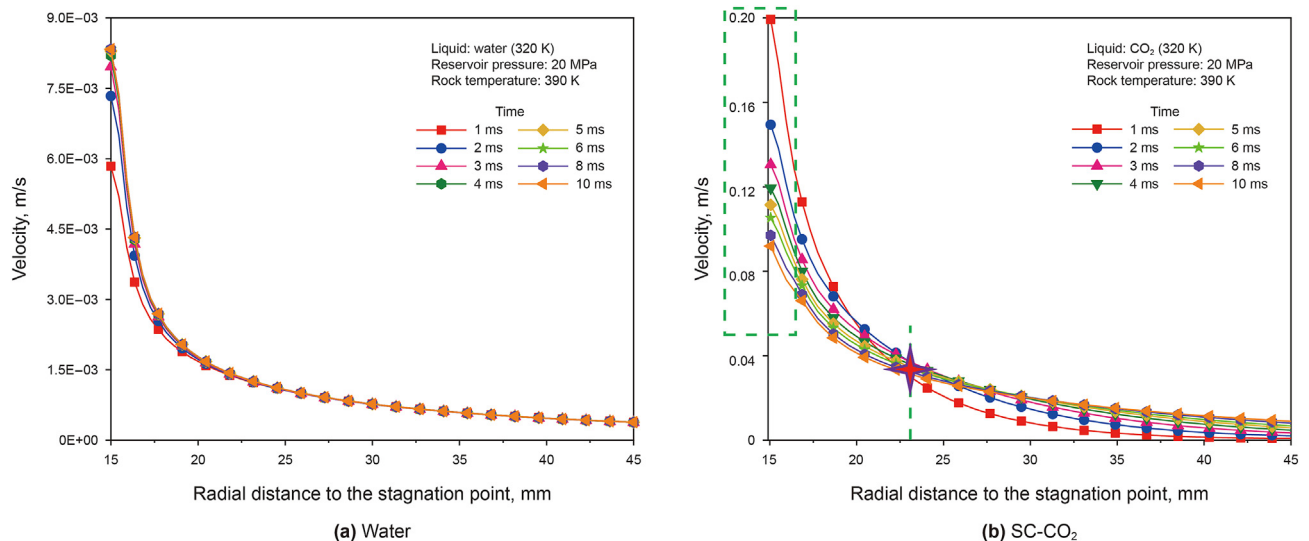


Fig. 27. The seeping velocity distribution of rock domain along the radial direction: (a) water; (b) SC-CO₂.

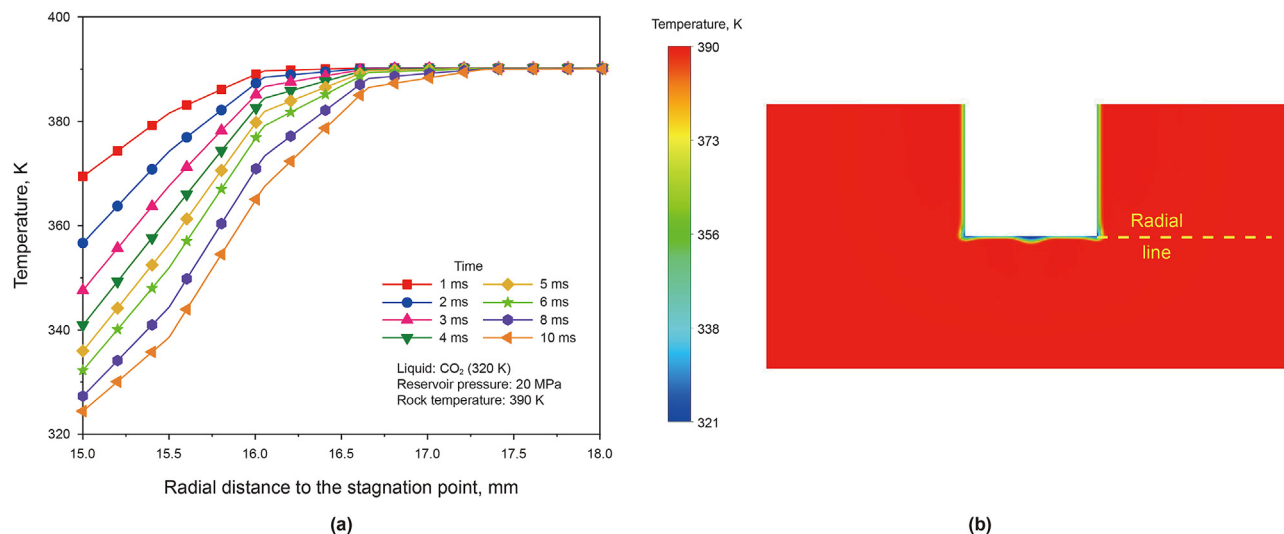


Fig. 28. The temperature distribution of the rock domain along the radial direction.

distribution clearly, we marked two points and two direction lines in Fig. 24 (stagnation point, interface point, vertical line and radial line). It can be seen that the high seeping velocity area was located at the nearby stagnation point and interface point. As illustrated in Fig. 25, the seeping velocity of SC-CO₂ was about 13 times that of water. The distribution on vertical and radial lines showed similar results with the stagnation point. The velocity of SC-CO₂ was much higher than water in both directions. And then, they all gradually decreased to stabilization from a high value (Fig. 26). The distribution character of higher seeping velocity had the same mechanism as the pore pressure mentioned above. It is attributed to the low viscosity and near-zero surface tension of SC-CO₂. The SC-CO₂ can easily seep into the pore structure and help create microfractures.

However, the seeping velocity of SC-CO₂ in the radial direction presented a different changing process. At the vicinity interface point (Fig. 27), the seeping velocity gradually decreased from 0.199 to 0.091 m/s with time. However, when the distance exceeded 23 mm, the seeping velocity gradually increased with time.

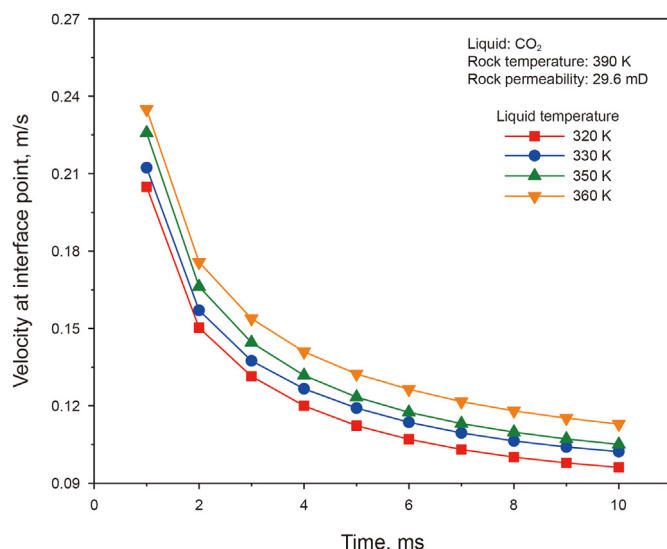


Fig. 29. The velocity at interface point with different temperatures.

This unique phenomenon is attributed to the seeping process of SC-CO₂ being controlled by pressure and temperature simultaneously. Fig. 28a shows the temperature distribution curve along the radial direction. We found that the temperature decreased (from 369 to 324 K) at the nearby interface point as time passed. This change occurs because, under the continual jet impingement, the rock (390 K) was gradually cooled down by the fluid (320 K). As illustrated in the previous section, the rheological of SC-CO₂ was affected by the temperature significantly. The high temperature could decrease the density and viscosity of SC-CO₂, which led to the high seeping velocity. Therefore, the change in seeping velocity of SC-CO₂ along the radial direction shows the different patterns in Fig. 27.

The increase of seeping velocity in the later stage can be attributed to the limited speed of heat conduction. Fig. 28a shows that the temperature remains unchanged when the distance exceeds 17 mm. The main controlling factor of seeping velocity began to switch from temperature to pressure in this region. The pore pressure increased gradually with time passing by in this region (Fig. 22). The high pressure provided high kinetic energy. It explained the change of the seeping velocity curve when the distance was above 23 mm. This phenomenon also can be verified in Fig. 29. When we increased the jet flow temperature, the seeping velocity at the interface point also augmented simultaneously. Therefore, increasing fluid temperature in the ground could promote the seepage process and help create microfractures in applications.

5. Conclusions

This study explored the feasibility of using SC-CO₂ jet fracturing, an environmentally benign fluid, to stimulate the carbonate geotherm reservoirs. The purpose of this technology was to improve the connectivity of fracture networks and realize the storage of CO₂ simultaneously. To evaluate the performance of this method, we built a transient fluid-thermo-mechanical coupled model to analyze the flow field of SC-CO₂ jet fracturing. Moreover, we considered the physical properties change of SC-CO₂ with temperature simultaneously in the model. Through analysis of this simulation, the main conclusions were drawn as follows:

- (1) Due to the low viscosity and density of SC-CO₂, the maximum jet velocity and particle velocity of the SC-CO₂ jet are 2.08% and 1.59% higher than that of the water jet, respectively. Therefore, SC-CO₂ will perform better in jet perforation under the same boundary conditions. In addition, increasing jet temperature could improve the jet and particle velocity effectively.
- (2) The maximum particle erosion rate of the SC-CO₂ jet is about four times that of the water jet. The erosion contour under water jet presented a ring shape, while that of the SC-CO₂ presented a more centralized circle. The centralized erosion pattern is in favor of increasing the perforation efficiency. Therefore, SC-CO₂ jet perforation could achieve the same perforation effect as the water jet in a lower particle density. Simultaneously, this could reduce the risk of sand plugging.
- (3) Carbonate rock stress distribution showed that the tensile and shear failure would more easily occur under the SC-CO₂ jet than the water jet. And the max principal stress and the Mises stress reached the peak value at the edge of the jet hole.
- (4) Compared with the water jet, SC-CO₂ can seep into the pore structure more easily. Both pressure and temperature control the seepage of SC-CO₂ in the geothermal reservoir. Furthermore, the temperature was the main controlling factor near the jet-hole wall. The higher fluid temperature could promote seepage by changing the rheological properties of the SC-CO₂.

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