INTRODUCTION

Supercritical carbon dioxide (SC-CO₂) fracturing is regarded as a promising means in the development of the unconventional oil and natural gas on account of its great advantages of environmental protection and resource conservation.¹-⁴ CO₂ (usually reach a supercritical state when the temperature is higher than 304.1 K and pressure is higher than 7.38 MPa in the fracturing crack in deep wells) is injected into the wells as a fracturing fluid to make cracks in the formation in order to form a flow channel for oil and natural gas from the reservoir to the well in supercritical carbon dioxide fracturing.⁵-⁷ Although the conventional hydraulic fracturing has huge contributions, the great water consumption (about 2.3 ~ 5.5
million gallons per well)\(^8\) and serious formation pollution (lots of chemical additives which will be harmful to formation) bring great challenges to environmental protection and economic cost. Compared to the conventional hydraulic fracturing, SC-CO\(_2\) fracturing has great advantages in the environment protection as it can reduce the emissions of greenhouse gases, the squander of water resource, and the damage of the formation at the meantime.\(^9,10\) Besides, SC-CO\(_2\) has the advantages of better properties of diffusivity, solubility, flowability, and permeability and having less chemical additives, which make this technology a promising method to develop unconventional resources.\(^11-13\) In recent years, SC-CO\(_2\) fracturing has been tested on-site in North America and China and achieved good performance in the development of unconventional resources.

Although SC-CO\(_2\) is of obvious advantages as fracturing fluid, there are some key issues which restrict the development of this technology. One of the most important issues is the temperature field in fracture for supercritical carbon dioxide fracturing which will affect the flow behavior of SC-CO\(_2\) fracturing fluid, proppant-carrying capacity of CO\(_2\), the expansion of the fracturing cracks, and many other questions related to the fracturing fluid.\(^14,15\) Therefore, study on temperature field in fracture for supercritical carbon dioxide fracturing is of great importance to the fracturing design.\(^6,16,17\) Physical properties of CO\(_2\) (like density, viscosity heat capacity and so on) change with temperature and pressure in a nonlinear manner.\(^2,13\) As a result, physical properties of CO\(_2\) will change with the effect of flow in crack, heat, and mass transfer with the formation rock in the crack. Correspondingly, the changing property of CO\(_2\) will affect the progress of flow, heat, and mass transfer in the crack.\(^18\) Therefore, the temperature field of SC-CO\(_2\) fracturing in the crack needs to be calculated coupled with the physical properties of CO\(_2\).

With the development of hydraulic fracturing, the temperature field in crack of fracturing fluid has been studied by many scholars. Ramey\(^19\) raised an equation which could calculate the transient temperature field. Hasan\(^20\) put forward a transient equation to calculate the temperature field of gas flowing which considered the heat transfer in the wellbore. Song\(^21\) calculated the temperature and pressure field in the wellbore in SC-CO\(_2\) drilling. Kamphuis\(^22\) proposed a numerical model which can well describe the temperature distribution with the effect of leak-off in fracturing. However, by comparison with hydraulic fracturing, the effect of changes in physical property and strong permeation of CO\(_2\) in the formation rock should be considered in the temperature field model. For CO\(_2\) fracturing, relevant issues of flow in wellbore and crack have been studied. Settari\(^23\) studied the possibility for application of CO\(_2\) as a fracturing liquid in the 1980s, mainly focusing on the carrying capacity for liquid CO\(_2\). Wang\(^6\) studied the temperature field for CO\(_2\) fracturing from wellbore to crack with a 2D model.

However, effect of changing property and leak-off in the crack have hardly been considered in the temperature field for the current studies of SC-CO\(_2\) fracturing. Meanwhile, the model established in existing research on temperature field is mainly 2D model which would not be accurate on account of the leak-off effect in surrounding rocks. The purpose of this paper is to establish a method to calculate the temperature field in the crack coupled with the physical property model and heat and mass transfer model. A 3D model is used to describe the crack, and the porous medium model is used to describe the formation rock. The temperature field and changes in the density and viscosity have been analyzed in this paper. In addition, influencing parameters of temperature field in the crack have also been discussed in the passage. Results obtained in this paper could provide fundamental data for the design of SC-CO\(_2\) fracturing. In the long run, it could be helpful to the promotion of SC-CO\(_2\) fracturing and the protection of water resources and the formation.

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**FIGURE 1** Geometry model of crack in SC-CO\(_2\) fracturing
2 | MATHEMATICAL MODELS

A three-dimensional model (shown in Figure 1) of fracture for SC-CO₂ fracturing was established in this paper. The model was built as a shape of cuboid with the fracture in the middle and the stratigraphic rocks around. When it enters the fractures as a fracturing fluid, CO₂ will be heated by the rocks around the fracture. At the same time, the temperature and pressure field in fracture are also affected by the process of CO₂ flows and leak-off.

What’s more, physical properties of CO₂ change with temperature and pressure during the process of carbon dioxide flowing in the fracture. Therefore, physical properties of CO₂ need to be coupled in the calculation.

2.1 | Physical properties of CO₂

Carbon dioxide is in a supercritical state when the temperature is higher than 304.2 K and the pressure is greater than 7.38 MPa. Temperature field in the crack would change with the properties of CO₂ controlled by temperature and pressure.

Liang-Biao Ouyang²⁴ method is used to calculate the carbon dioxide density:

\[
\rho = A_0 + A_1p + A_2p^2 + A_3p^3 + A_4p^4
\]  

(1)

\[
A = b_{10} + b_{11}T + b_{12}T^2 + b_{13}T^3 + b_{14}T^4 (i = 0, 1, 2, 3, 4)
\]  

(2)

In the formula, \( A \) and \( b \) are coefficient constants. In 1997, Fenghour²⁵ added a new CO₂ viscosity experiment. According to the summary and analysis of the experimental data, the model of Vesovic²⁶ was modified, the temperature was added to the calculation of residual viscosity, and the modified model is also cited by NIST.²⁷ The viscosity can be based on

\[
\mu(T, \rho) = \mu_0 + \Delta \mu(T, \rho) + \Delta \mu_e(T, \rho)
\]  

(3)

The zero-density viscosity calculated by Fenghour²⁵ is as follows:

\[
\mu_0(T) = \frac{1.00697 T^{1/2}}{G'(T^*)}
\]  

(4)

In the formula:

\[
\ln G'(T^*) = \sum_{i=0}^{4} a_i (\ln T^*)^i
\]  

(5)

\[
T^* = kT / \varepsilon \cdot \varepsilon / k = 251.196K
\]  

(6)

According to the fitting, the formula for the residual viscosity is

\[
\Delta \mu(\rho, T) = d_{11}\rho + d_{21}\rho^2 + d_{64}\rho^6 + d_{81}\rho^8 + d_{82}\rho^8
\]  

(7)

Similar to the viscosity, the thermal conductivity of CO₂ is given by:

\[
\lambda(T, \rho) = \lambda_0 + \Delta \lambda(T, \rho) + \Delta \lambda_e(T, \rho)
\]  

(8)

The isobaric heat capacity²⁸ of CO₂ can be written as.

\[
\frac{M \cdot c_p}{R} = -\varepsilon^2 (\phi'_{\tau \tau} - \phi'_{\eta \eta}) + \frac{(1 + \delta \phi'_{\eta} - \delta \tau \phi'_{\tau \tau})^2}{1 + 2\delta \phi'_{\eta} + \delta^2 \phi'_{\eta \tau}}
\]  

(9)

2.2 | Mathematical model of heat transfer in the fracture

To explore the flow rules of SC-CO₂ in this model, the following assumptions were proposed.

1. The cracks are uniform cuboids.
2. The formation is regarded as homogeneous and isotropic.
3. The geological parameter of the formation is considered to be constant in the process of heat transfer and mass transfer.
4. The influence of proppants is ignored.
5. Porous medium model is used to describe the formation in this paper, while effects of acceleration and diffusion of fluid crossing the porous areas are ignored.

The temperature field equations of CO₂ fluid in the fractures could be established when the specific enthalpy is taken as the primary unknown.

\[
\frac{\partial}{\partial t} \left[ (W + H_i) \rho_i \cdot \left( C_p f \cdot T_i + \frac{1}{2} \rho_i u_i^2 \right) \right] + \frac{\partial}{\partial x} \left[ (W + H_i) u_i \left( \rho_i H + \frac{1}{2} \rho_i u_i^2 \right) \right] = -4\rho_i v_f C_p f T_i + 2h_{wall} \cdot (T_{rw} - T_i)
\]  

(10)

where \( W \) is the crack width, \( m; H_i \) is the height of the crack, \( m; \rho_i \) is the density of CO₂, \( \text{kg/m}^3; C_p f \) is the heat capacity of CO₂ at constant pressure, \( J/(\text{kg·K}) \); \( T_i \) is the temperature of CO₂ in the crack, \( K; u \) is the velocity of CO₂ in the crack, \( m/s; H \) is the specific enthalpy of CO₂, \( J/\text{kg}; v_f \) is the leak-off velocity of CO₂ on the contact surface between crack and rock, \( m/s; h_{wall} \) is the heat transfer coefficient of the crack wall, \( W/(\text{m}^2·\text{K}) \); and \( T_{rw} \) is the temperature of matrix-leak-off zone in the fracture, \( K \).

The expression for the specific enthalpy of the CO₂ fluid can be written as

\[
H(P, T) = \int_{T_0}^{T} C_p f dT_i + \int_{P_0}^{P} V(1-T\beta) dP
\]  

(11)
where $T_0$ and $P_0$ are the temperature and pressure of the triple point, respectively; $V$ is the specific volume, m$^3$/kg; $\beta$ is the thermal-expansion coefficient of CO$_2$, $1/K$.

The expression for the leak-off rate of the CO$_2$ $v_F$ can be written as

$$v_F(x,t) = \frac{C_a C_b}{C_a + C_b} \frac{1}{\sqrt{1 - \tau}}$$  \hspace{1cm} (12)

The leak-off coefficient $C_a$ and $C_b$ can be calculated by

$$C_a = 7.07 \times 10^{-7} \left( \frac{K \phi (P-P_{ei})}{\mu} \right)^{0.5}$$  \hspace{1cm} (13)

$$C_b = 5.64 \times 10^{-7} (P-P_{ei}) \left( \frac{K \beta' \phi}{\mu} \right)^{0.5}$$  \hspace{1cm} (14)

where $C_a$ is the leak-off coefficient controlled by the fracturing fluid viscosity, m$^3$/s; $C_b$ is leak-off coefficient controlled by the compressibility of the formation porous medium, m$^3$/s; $C_{\phi}$ is the formation permeability, D; $\phi$ is the formation porosity; $P$ is the pressure in the crack, Pa; $P_{ei}$ is the formation pore pressure approximate to the fracturing layer, Pa; $\mu$ is the viscosity of CO$_2$, Pa·s; $s$ is the distance from the crack inlet, m; $\tau$ is the time when the fracture extended to $x$, $s$; and $\beta'$ is the total compressibility coefficient of the fractured formation, $1$/Pa.

### 2.3 Equations for heat and mass transfer in porous rock

The process of heat conduction from rock to fluid was directly coupled with the energy transfer processes within the rock itself. Porous medium model was used to describe the rocks around the fracture. The heat and mass transfer in porous rocks can be written as

$$\frac{\partial}{\partial t} \left( \phi \rho_f Q_f + (1-\phi) \rho_s Q_s \right) + \nabla \cdot (\nabla H) = H + \nabla \cdot \lambda_{eff} \nabla T - \left( \sum_i \frac{h_i}{1 + (\nabla \cdot \vec{v})} \right)$$  \hspace{1cm} (15)

where $\phi$ is the porosity of the rock,%; $\rho_f$ and $\rho_s$ are the density of CO$_2$ and rock matrix, kg/m$^3$; $Q_f$ and $Q_s$ are the total fluid energy and total solid medium energy, J; $p_i$ is the pressure in porous medium, MPa; $\lambda_{eff}$ is the effective thermal conductivity of the porous medium which can be calculated through the volume average of the fluid conductivity and the rock-solid conductivity:

$$\lambda_{eff} = \phi \lambda_f + (1-\phi) \lambda_s$$  \hspace{1cm} (16)

where $\lambda_f$ is the thermal conductivity of CO$_2$; $\lambda_s$ is the thermal conductivity of the rock, which can be obtained through heat transfer correlation.

$$Nu = 0.0023 Re^{1.1} Pr^{0.87} \left( \frac{\rho_f}{\rho_s} \right)^{0.69} \left( \frac{C_p}{C_v} \right)^{0.8}$$  \hspace{1cm} (17)

where $Nu$ is Nusselt number; $Re$ is Reynolds number; $Pr$ is Prandtl number; $\rho_f$ is the density of CO$_2$; $\rho_s$ is the density of rock; $Gr$ is Grashof number; $d_m$ is the equivalent diameter of the fracture; and $L$ is the length of the fracture.

Ignoring convective acceleration and diffusion, the pressure drop of the porous medium model can be obtained according to Darcy’s law:

$$\nabla p = -\frac{\mu}{K} v_F$$  \hspace{1cm} (18)

where $\mu$ is the viscosity of CO$_2$, Pa·s; $\alpha$ is the permeability of the porous medium.

### 2.4 Boundary and initial conditions

Mass flow inlet and pressure outlet were used in the calculation. The mass flow rate of the fracture inlet was regarded as the same with that in the wellhead. The temperature and pressure of the fracture inlet were assumed as the same with those in the wellbore at the same depth during fracturing. It means that the changes in pressure and temperature when CO$_2$ flow across the fracture inlet are ignored. And the initial conditions are

$$\begin{align*}
&T_{in} = T_{mf}(t), \quad (x = 0, y = 0, z = 0, t \geq 0) \\
&T_{in} = T_{mf}, \quad (x \geq 0, y \geq 0, z \geq 0, t = 0) \\
&T = T_{mf}, \quad (x \geq 0, y \to \infty, z \to \infty, t > 0)
\end{align*}$$  \hspace{1cm} (19)

Some other values of parameters used in the calculation are listed in Table 1.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Influence distance in the formation rock

The formation is cooled by low-temperature SC-CO$_2$ injected into the crack. The influence distance of the formation rock is defined as the maximum distance that temperature is affected by the SC-CO$_2$. Influence distance of the formation rock in Y
direction and Z direction under three kinds of displacement is shown in Figure 2.

The left diagram in Figure 2 is the influence distance of the formation rock in Y direction, and the right one is in Z direction. The influence distance in Y direction is much larger than that in Z direction on account of the wider leak-off areas. It can be seen that the influence distance in both Y direction and Z direction increases with time and displacement, while the increasing rate is decreasing. The influence distance is related to rock parameters like density and porosity and injection parameters like temperature and pressure except time and displacement. From Figure 2, we can see that the maximum influence distance is 0.23 m in Y direction and 0.0123 m in Z direction at 6 minutes. The influence distance is far less than the rock thickness (both 4 m in Y and Z direction) set in this paper which would make the calculation more accurate.

### 3.2 Analysis of temperature field

#### 3.2.1 Temperature field

It contains both heat transfer and mass transfer during the flow of CO₂ in the crack. According to the mathematical model established in the previous section, the temperature field can be calculated. The temperature field of XY plane and XZ plane in the fracture is shown in Figures 3, 4.

From Figure 3, it can be seen that CO₂ is gradually heated by the rock and the temperature of areas near the crack decrease as the effect of heat and mass transfer between matrix rock and CO₂. At mean time, the temperature of CO₂ in the crack increases with crack length as CO₂ is injected into the crack continuously. On the contrary, the temperature at the same X position decreases on account of that the continuous

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**TABLE 1** Initial values for the parameters in the calculation

| Item                      | Values          | Item                      | Values          |
|---------------------------|-----------------|---------------------------|-----------------|
| Length of fracture        | 60 m            | Temperature gradient      | 0.03 k/m        |
| Width of fracture         | 0.02 m          | Density of rock           | 2600 kg/m³      |
| Height of fracture        | 8 m             | Specific heat capacity of rock | 900 J/(kg·K) |
| Thickness of rock in Y direction | 4 m          | Thermal conductivity of rock | 6 W/(m·K)     |
| Thickness of rock in Z direction | 4 m          | Porosity of rock          | 0.15            |
| Injection pressure        | 20 MPa          | Temperature of rock in fracture layer | 373 K     |
| Injection temperature     | 310 K           | Displacement              | 12 m³/min       |

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**FIGURE 2** Influence distance of the formation rock in Y direction and Z direction

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injection of cold CO\textsubscript{2} will displace hot CO\textsubscript{2} at the same X position and the heat flow rate will decrease as the increase in temperature near the contact wall concurrently. Compared to the XZ plane (shown in Figure 4), the temperature distribution in XY plane is nonuniform. The temperature on the bottom wall of the crack is much lower than that on the top face caused by the effect of buoyancy lift.

Temperature of SC-CO\textsubscript{2} on top wall of the crack increases with crack length and get a constant value 373 K terminally which equals to the temperature of the formation rock (shown in Figure 5). At 3 minutes, the temperature on top wall reaches the constant value in the position of 14 m. As time goes on, the position at which the temperature achieves constant moves to the further place of the fracture, reaching 25 m at 6 minutes. On the bottom wall, temperature of SC-CO\textsubscript{2} increases firstly and decreases later with the crack length. The temperature at stability is 341 K at 3 minutes and 333 K at 6 minutes. At last, temperature on bottom wall gradually increases when SC-CO\textsubscript{2} arrived a certain position. Temperature at the same position decreases with time as the injection of continuous cold CO\textsubscript{2}.

### 3.2.2 Density and viscosity field

Compared to conventional fracturing fluids, the equilibrium height of SC-CO\textsubscript{2} is higher and the proppants bed length is shorter (length of proppant bed is about 1.2 times shorter and 2 times higher than slick water under a case of Song\textsuperscript{27}) with the same fracturing time according to the relevant studies\textsuperscript{29,30}. With the density and viscosity field in the fracture, relevant injection factors could be controlled to improve the proppant transportation in SC-CO\textsubscript{2} fracturing.

The density change in SC-CO\textsubscript{2} in the crack was shown in Figure 6. The density and viscosity of SC-CO\textsubscript{2} increase with pressure and decrease with temperature. In the crack, the pressure gradually decreases as the leak-off and hydraulic loss. The density and viscosity controlled by temperature and pressure decrease with length on the top wall.

On the bottom wall, there is a process of decrease-increase-decrease which is contrary to the rules of temperature
in last section. The density and viscosity at the same position increase with time. The density at stability on top wall reaches 475 kg/m³ at 3 minutes and raises to 498 kg/m³ at 6 minutes. The maximum density on bottom wall could reach 796 kg/m³ at 6 minutes. The rules of viscosity change in SC-CO₂ which has not been drawn is the same with that of density.

3.3 Influence factors

Injection temperature and displacement, the two main parameters which can be controlled on the ground, were analyzed in this paper in order to find out the influencing rules of temperature and density in the crack. Another parameter of the formation rock, the rock porosity, was also studied which could provide reference for the application of SC-CO₂ fracturing in different kinds of formations.

3.3.1 Effect of injection temperature

Displacement 12 m³/min, rock porosity 0.15, time 6 minutes, and other parameters listed in Table. 1 were kept constant.

On the top wall, the temperature at the same position increases with the injection temperature and will finally get the balance with the formation rock. However, the lower the injection temperature, the farther the distance to reach a stable temperature will be. The distance to reach stable temperature on the top wall is 25, 29, and 34 m when the injection temperature is 310, 300, and 290 K. On the bottom wall, the temperature increases initially and then decreases to a constant value. According to the critical line in Figure 7, it can be seen that CO₂ will turn to supercritical state quickly after being injected into the crack. The lower the injection temperature, the longer it will take to turn into the supercritical state. CO₂ near the bottom wall will turn to supercritical state earlier than the top wall. For example, CO₂ turns to supercritical state at 3.5 m on bottom wall and at 13 m on top wall when the injection temperature is 290 K.

The density of SC-CO₂ at the same position decreases with injection temperature (shown in Figure 8). The change rule of viscosity is the same with density. The carrying capacity of SC-CO₂ to transport proppants is proportional to its density and viscosity. Therefore, low injection temperature will make SC-CO₂ carry more proppants which can make the “proppant bed” longer. Besides, tackifier of SC-CO₂ is suggested to be added in SC-CO₂ fracturing as the viscosity decreases with fracture length.
3.3.2 | Effect of injection displacement

Injection temperature 310 K, rock porosity 0.15, time 6 minutes, and other parameters listed in Table 1 were kept constant.

The temperature of SC-CO₂ at the same position decreases with the injection displacement (shown in Figure 9). On the top wall, the larger the displacement, the longer the distance to reach the maximum temperature it will be. The distance to reach stable temperature on the top wall is 18, 22, and 26 m when the injection displacement is 8 m³/min, 10 m³/min, and 12 m³/min. Velocity of the fluid increases with displacement, which means that more “cold” CO₂ is injected into the crack at one time. On the bottom wall, temperature at the same position is also lower than that of higher displacement. The stable temperature on the bottom wall of the crack is 332, 328, and 323 K when the injection displacement is 8, 10, and 12 m³/min.

To the changing of density, higher displacement will make SC-CO₂ higher density as the lower temperature at the same position of the crack (shown in Figure 10). Stable density of CO₂ increases from 433 to 496 kg/m³ on the top wall and increases from 777 to 800 kg/m³ on the bottom wall as the displacement changes from 8 to 12 m³/min. As a result, high density will reduce the sedimentation of particles in the crack which is beneficial to the extension of the “proppant bed.” On the other hand, high velocity caused by the increase in displacement will also be helpful to the movement of proppants to the further position.

3.3.3 | Effect of rock porosity

Compared to the conventional fracturing fluid, the temperature field of SC-CO₂ is quite different as the effect of leak-off. The property of the formation rock will have certain impact on the temperature field of SC-CO₂ fracturing. Therefore, effect of rock porosity was conducted in this section in order to explore the applicability of SC-CO₂ in different formations.

Displacement 12 m³/min, injection temperature 310 K, time 6 minutes, and other parameters listed in Table 1 were kept constant.

Temperature at the rock porosity of 0.15 is higher than that of 0.2 both on the top and bottom wall (Figure 11). Stable temperature of CO₂ increases from 323 to 328 K on the bottom wall as the porosity changes from 0.15 to 0.2. The effect of mass and heat transfer in the crack will be enhanced with the increase in rock porosity. Pressure in the crack will decrease with rock porosity as more CO₂ leak-off into the formation rock. As a result, the CO₂ density in the crack under the condition of high porosity formation is relatively low on account of the increase in temperature and decrease in pressure at
the same position caused by the stronger effect of leak-off (shown in Figure 12). Stable density of CO$_2$ decreases from 499 to 328 kg/m$^3$ on the top wall and from 770 to 750 kg/m$^3$ on the bottom wall as the porosity changes from 0.15 to 0.2. Therefore, the high density and viscosity of CO$_2$ under the condition of low porosity formation are more beneficial to carry proppants in the application of SC-CO$_2$ fracturing.

4 | CONCLUSIONS

A calculation model for temperature field in the SC-CO$_2$ fracturing coupled with the physical property of CO$_2$ was established in this paper. A 3D crack model surrounding by the formation rock described by porous medium model was built which is similar to the actual crack in the fracturing. According to the results and discussions, this study can achieve the following conclusions:

The influence distance in Y direction is much larger than that of Z direction on account of the wider leak-off areas. Meanwhile, influence distance both in Y direction and in Z direction increases with time and displacement, while the increasing rate is decreasing.

Temperature field in XY plane is symmetric distribution and is nonuniform in XZ plane where temperature of the top wall is much larger than that of the bottom wall. Changing rules of the density and viscosity are contrary to the temperature rules.

Temperature of SC-CO$_2$ is directly proportional to injection temperature and rock porosity and is inversely proportional to injection displacement. According to the changes in the density and viscosity, low injection temperature, and high injection displacement are suggested to be conducted in SC-CO$_2$ fracturing in order to improve the proppant-carrying capacity.

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NOMENCLATURE

- $A$: Coefficient constant for density calculation
- $b$: Coefficient constant for density calculation
- $W$: Crack width, m
- $H_f$: Crack height, m
- $\rho_f$: Density of CO$_2$, kg/m$^3$
- $C_{pf}$: Heat capacity of CO$_2$ at constant pressure, J/(kg·K)
- $T_f$: Temperature of CO$_2$ in the crack, K
- $u$: Velocity of CO$_2$ in the crack, m/s
- $h_{wall}$: Heat-transfer coefficient of the crack wall, W/(m$^2$·K)
- $T_{rw}$: Temperature of matrix-leak-off zone in the fracture, K
- $T_0$: Temperature of the triple point, respectively
- $P_0$: Pressure of the triple point, respectively
- $V$: Specific volume, m$^3$/kg
- $\beta$: Thermal-expansion coefficient of CO$_2$, 1/K
- $C_a$: Leak-off coefficient controlled by the fracturing fluid viscosity, m/√s
- $C_b$: Leak-off coefficient controlled by the compressibility of the formation porous medium, m/√s
- $K$: Formation permeability, μm$^2$
- $\phi$: Formation porosity
- $P$: Pressure in the crack, Pa
- $P_{ei}$: Formation pore pressure approximate to the fracturing layer, Pa
- $x$: Distance from the crack inlet, m
- $\tau$: The time when the fracture extended to $x$, s
- $\beta'$: The total compressibility coefficient of the fractured formation, 1/Pa
- $\rho_s$: Density of rock matrix, kg/m$^3$
- $Q_t$: The total fluid energy, J
- $Q_s$: The total solid medium energy, J
- $p_r$: The pressure in porous medium, Pa
- $\lambda_{eff}$: The effective thermal conductivity of the porous medium, W/(m·K)
- $Nu$: Nusselt number
- $Re$: Reynolds number
- $Pr$: Prandtl number
- $Gr$: Grashof number
- $d_m$: Equivalent diameter of the fracture, m
- $L$: Length of the fracture, m

FIGURE 12  Density change in the crack with porosity of rock
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