Wellbore flow field of coiled tubing drilling with supercritical carbon dioxide

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Abstract: To achieve better well control for supercritical carbon dioxide drilling, a mathematical model was presented to investigate the pressure and temperature profile in both the tubing and the annulus. The closed model fully couples the hydraulics, heat transfer, and compressibility of carbon dioxide, and then the wellbore flow field is presented and analyzed based on field application. The results show that the pressure change of carbon dioxide is 36.7% smaller than that of water along the annulus in the study case. Carbon dioxide changes into supercritical state when the depth equals 700 m \(\leq 223^\circ C \leq 830 \) m in the tubing, and it could maintain in supercritical state in the whole annulus. Both the pressure profile and the temperature profile are highly coupled with the physical properties of carbon dioxide. The density of carbon dioxide is large enough to drive downhole motors and its capacity is much larger than that of air in the wellbore. The pressure increases lightly with increasing mass flow rate in the annulus; however, it is significantly and positively impacted by the outlet pressure. The influence of outlet pressure on temperature profile is negligible in the tubing. The inlet temperature could not impact the pressure profile in the annulus, and its influence on temperature profile mainly lies in the shallow section of the tubing. It is newly validated that supercritical carbon dioxide drilling is more suitable for the exploitation of unconventional reservoirs with narrow pressure windows. The results could lay a theoretical foundation for practical application. © 2017 Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: supercritical carbon dioxide; coiled tubing drilling; heat transfer; hydraulics calculation; pressure profile

Introduction

Aiming to get increased rate of penetration (ROP) and minimize formation damages, researchers have tested the feasibility of underbalanced-drilling with carbon dioxide (CO\(_2\)) since 2000s, which is generally conducted with coiled tubing.\(^1,2\) Under normal circumstances, CO\(_2\) would change into supercritical state at the bottom hole (when the temperature is 304.2 K or higher and the
pressure is above 7.38 MPa), where its density equals that of water approximately to provide enough torque for downhole motors. Supercritical CO₂ could also effectively dissolve heavy oil components in pay zone, helping to achieve enhanced oil recovery (EOR). Recent studies demonstrate its advantages or feasibility in rock-breaking, cutting-transportation, mitigating formation damages, and geological storage. Thus, supercritical CO₂ has a promising future, especially suitable for depleted and unconventional reservoirs.

In the exploitation of depleted and unconventional reservoirs, it is quite challenging to prevent lost circulation or gas kicks while drilling through narrow pressure (or collapse pressure) and fracture pressure windows, therefore, it is of fundamental importance to investigate the wellbore flow field and its influencing factors. In field application, hypothermic liquid CO₂ would be pumped into the tubing and then get heated by formation rocks. It is nearly impossible to test and record the temperature and pressure along the whole wellbore during drilling, and the difficulties in mathematical calculation mainly lie in the compressibility of CO₂. The physical properties of CO₂ (e.g. density, viscosity, and heat capacity) all change much with temperature and pressure, and then they would furthermore lay significant impact on pressure and temperature when circulating in the tubing and the annulus. Phase state change is also inevitable during circulation. Wang and Ni have modeled the heat transfer in CO₂ coiled tubing drilling. Wang et al. have tested the flow friction coefficient of CO₂ in pipes at different Reynolds numbers through experiments. Wang et al. have discussed the phase state variations by calculation samples. Ni et al. proposed a coupling model to calculate the wellbore flow field and heat transfer. The preliminary results lay the foundation for this study to some extent.

This paper proposes a fully closed model to investigate the influence of mass flow rate, inlet temperature, and outlet pressure on the wellbore flow field. The mathematical model couples the temperature, hydrostatic pressure, flow friction, and properties of CO₂, and it also considers the temperature change of sidewall surrounding rock to ensure accuracy. In the results, the pressure profile and temperature profile of CO₂ are presented compared with that of water, and then they are analyzed, coupled with the density profile, viscosity profile, thermal conductivity profile, and heat capacity profile. Finally, the sensitivity analysis on wellbore flow field is conducted. By this study, we aim to lay a theoretical foundation for better well control of supercritical CO₂ drilling.

**Mathematical models**

In actual drilling processes, hypothermic liquid CO₂ is pumped from the wellhead to the bottom hole through coiled tubing. CO₂ would inevitably endotherm from formation rock because of the temperature difference and finally it would change into supercritical state at certain depth. During circulation, sidewall surrounding rock would get cooled and then absorb heat from formation rock far away from the annulus. The temperature change of sidewall surrounding rock has been neglected in former research and it would result in relatively higher temperature profile. Figure 1 is presented to illustrate the flow field. Heated CO₂ would flow out the annulus. Meanwhile, thermal energy transfers from far-field formation rocks into this system and finally reaches heat balance. Wellhead back pressure (outlet pressure) is applied by choke to compensate the annulus pressure for this underbalance drilling technique.

Zhang et al. have reported that the geothermal reaction between CO₂ and formation rock does not
have a significant impact on temperature; therefore, the
g eo thermal reaction is beyond consideration when
calculating downhole temperature profile in this study.
Other assumptions include (i) the influence of cuttings
(in the annulus) on pressure profile and temperature
profile is negligible, due to its low volume fraction; (ii)
the geothermal gradient is constant with increasing
well depth; (iii) time effect is beyond the consideration
because this study aims to reveal the steady state (when
the heat balance is reached).

**Governing equations**

The temperature and pressure in the flow field is also
coupled by influencing the properties of CO₂. Eulerian
method is one of finite volume methods, and it
assumes that the pressure and temperature is constant
in every flow field element. The flow field characters in
neighboring elements could be obtained by solving
governing equations. The Eulerian method is most
commonly used for illustrating compressible flow
model. The governing equations of the Eulerian
method are composed of continuity equation,
momentum equation, and energy equation. The
modified governing equations for this steady
compressible flow can be expressed as

\[
\begin{align*}
\text{div}(\rho \vec{v}) &= 0 \\
\text{div}(\rho v_i \vec{v}^i) &= -\rho \vec{v} \cdot \text{grad}(v_i) \\
\sum_{i=1}^{3} \frac{\partial (\rho v_i h)}{\partial x_i} &= -\text{div}(k \text{grad}T) - S_h = 0
\end{align*}
\]

where density \( \rho \) is in kg/m³; \( \vec{v} \) stands for flow velocity
vector, m/s; \( v_i \) represents the component of \( \vec{v} \) on \( i \)
axis, m/s; the specific enthalpy \( h \) can be achieved by
\( h = c_p T \); \( c_p \) is isobaric heat capacity, J/(kg·K); \( T \)
represents temperature, K; \( k \) stands for thermal
conductivity, W/(m·K); \( S_h \) is the heat generating rate in
every flow unit.

As the density, viscosity, and thermophysical
properties are all involved in the governing equations
and they all change much with changing temperature
and pressure, the equations of state of CO₂ are
introduced to close the governing equations. The phase
change of CO₂ could also be reflected by changes in
physical properties.

Compared with the data of American National
Institute of Standards and Technology (NIST), the
Span and Wagner model\(^{14}\) is the most accurate for
calculating the density and isobaric heat capacity of
CO₂. The implicit equations are given by

\[
P(\delta, \tau) = \rho R T \left( 1 + \delta \Phi_\delta^\tau \right)
\]

where the dimensionless reduced density is given as
\( \delta = \rho / \rho_c \) and \( \tau = T_c / T \) is the inverse reduced
temperature. Dimensionless \( \Phi_\delta^\tau \) is the partial derivative
of the Helmholtz energy \( \Phi(\delta, \tau) \).

The equation for isobaric heat capacity of CO₂ is
presented as

\[
\frac{M \cdot c_p}{R} = -\tau^2 (\phi_r^0 - \phi_r^\tau) + \frac{(1 + \delta \phi_r^\tau - \tau \phi_r^\tau)^2}{1 + 2 \delta \phi_r^\tau - \delta^2 \phi_r^\tau}
\]

The density \( \rho \) and heat capacity \( c_p \) could be
calculated with the Span and Wagner model\(^{14}\) after the
pressure \( P \) and temperature \( T \) are obtained in finite
elements, and the detailed procedure is presented in
Span and Wagner.\(^{14}\)

Fenghour and Wakeham\(^{21}\) modified Vesovic and
Wakeham\(^{22}\) equations for viscosity and thermal
conductivity of CO₂ to get enhanced accuracy, and the
modified model is closest to NIST data until now. The
viscosity is calculated by

\[
\eta(T, \rho) = \eta_0 + \Delta \eta(T, \rho) + \Delta \eta_v(T, \rho)
\]

where

\[
\eta_0(T) = \frac{1.00697 T^{1/2}}{G_\eta^*(T^*)}
\]

\[
\ln G_\eta^*(T^*) = \sum_{i=0}^{4} \left( a_i \ln \frac{T}{251.196} \right)^i
\]

\[
\Delta \eta(T, \rho) = d_{11} \rho + d_{21} \rho^2 + \frac{d_{64} \rho^6}{T_s^3} + d_{83} \rho^8 + \frac{d_{82} \rho^8}{T_s^8}
\]

The equations for thermal conductivity is in similar
form with that of viscosity

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

The governing equations should also include
turbulence equations to make them closed and
solvable. The Standard \( k-c \) model is suitable for
compressible flow and is then introduced to illustrate turbulence:

\[
\begin{align*}
\frac{\partial}{\partial x_j} \left( \rho u_j \frac{\partial k}{\partial x_j} - (\mu + \mu_\varepsilon) \frac{\partial k}{\partial x_j} \right) \\
= \tau_{ij} S_{ij} - \rho \varepsilon + Q_k \\
\frac{\partial}{\partial x_j} \left( \rho u_j \varepsilon - \left( \mu + \frac{\mu_\varepsilon}{1.3} \right) \frac{\partial \varepsilon}{\partial x_j} \right) \\
= 1.45 \frac{\varepsilon}{k} \tau_{ij} S_{ij} - 1.92 f_\tau \frac{\varepsilon^2}{k} + \varepsilon
\end{align*}
\]

where \( \tau_{ij} = 2\mu_\tau \left( S_{ij} - S_{ij} \delta_{ij}/3 \right) - 2\rho k \delta_{ij}/3 \), and \( \mu_\varepsilon \) stands for eddy viscosity and is expressed as \( \mu_\varepsilon = 0.09 f_\tau \rho k^2/\varepsilon \). The near wall attenuation functions are calculated by \( f_u = e^{-3.4/(1+0.02Re_\tau)} \) and \( f_\tau = \frac{\varepsilon k}{\mu} \). The wall terms are given as \( Q_k = 2\mu \left( 2\varepsilon \right)/\partial y^2 \) and \( Q_\varepsilon = 2\mu_\varepsilon \rho \left( \frac{2\varepsilon}{\mu_\varepsilon} \right)^2 \). \( S_{ij} \) is the mean-velocity strain-rate tensor, and \( \delta_{ij} \) represents the Kronecker delta.

**Solution procedure**

According to field application, the boundary conditions should include mass flow rate, inlet temperature, and outlet pressure; thus, they are assigned values at first. The temperature of every flow field unit is initialized as the same with inlet temperature, and then the iteration begins with assuming inlet pressure a value. In the solution of Eulerian model, temperature and pressure are regarded as constant in every divided unit, so that the properties of CO\(_2\) at inlet can be calculated according to Eqns (2)–(8), and then the heat transfer and flow friction is obtained based on Eqns (9)–(15). The iteration carries on from inlet to the bottom hole along the tubing, and then returns to outlet along the annulus. By modifying inlet pressure based on the difference between assigned outlet pressure and calculated outlet pressure, the iteration would finally reach convergence and the flow field in both the tubing and the annulus are obtained.

The heat transfer process involves both sidewall surrounding rocks and coiled tubing, thus they are treated as thermal boundaries for flowing CO\(_2\) in Eqn (1). To make the governing equations solvable and understandable, the heat transfer can be divided into three parts (Fig. 1), that is \( Q_{ap}, Q_{sa}, \) and \( Q_{cs} \) respectively, where \( Q_{ap} \) stands for the heat transferred from CO\(_2\) in the annulus to that in pipe, \( J; Q_{sa} \) is the heat transferred fromsidewall surrounding rocks to CO\(_2\) in the annulus, \( J; \) and \( Q_{cs} \) represents the heat transferred from constant-temperature layer to sidewall surrounding rocks, J. Actually, the formation rock is divided into many thin layers radially to get enhanced accuracy, and apparently heat conductivity is dominant in the heat transfer among rock layers.

\[
Q_{cs} = \frac{T_s - T_p}{2\pi \lambda_r l} \ln \frac{r_c}{r_i}
\]

where \( T_s \) represents the temperature of formation rock and it keeps constant during heat transfer, \( K. T_p \) stands for the temperature of sidewall surrounding rock, \( K. \lambda_r \) is the thermal conductivity coefficient of rock, \( W/(m\cdot K). r_c \) represents the radius of constant-temperature layer and \( r_i \) is the radius of sidewall surrounding rocks, m. \( l \) is the length of finite units, m.

The thermal convection dominates the heat transfer when CO\(_2\) flows around the sidewall surrounding rocks, thus the \( Q_{sa} \) can be calculated by

\[
Q_{sa} = \frac{T_a - T_s}{2\pi \tilde{h} r_l l}
\]

where \( T_a \) is the temperature of CO\(_2\) in the annulus, \( K. \tilde{h} \) represents the convective heat transfer coefficient between rock and CO\(_2\), \( W/(m^2\cdot K). \)

Both thermal conductivity and convection are involved in \( Q_{ap} \)

\[
Q_{ap} = \frac{T_a - T_p}{2\pi \lambda \tilde{h} l} \ln \frac{r_c}{r_i} + \frac{1}{2\pi \tilde{h}} r_i l
\]

where \( T_p \) is the temperature of CO\(_2\) in pipe, \( K. \tilde{h} \) represents the convective heat transfer coefficient between the inner wall of the pipe and CO\(_2\), and \( \tilde{h} \) is that between the outer wall and CO\(_2\), \( W/(m^2\cdot K). \lambda \) is the thermal conductivity coefficient of pipe, \( W/(m\cdot K). r_i \) stands for the inner radius of pipe, and \( r_o \) is outer radius of pipe, m.

As radiation is negligible and it does not include any heat resource in the heat transfer, \( S_h \) equals zero in Eqn

<table>
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<th>Table 1. Parameters of well structure.</th>
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<td>( L = 1500 \text{ m} )</td>
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<td>( r_t = 0.0543 \text{ m} )</td>
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After the heat transfer is modeled, the temperature change in a certain finite cell would be calculated by

$$\Delta T = \frac{Q}{c_p m}$$  \hspace{1cm} (13)

where \(m\) represents the mass in an infinitesimal unit, kg. Equation (13) is suitable for both CO\textsubscript{2} and rocks.

In hydraulics calculation, the route loss of CO\textsubscript{2} flow could be obtained according to formula of Darcy-Weisbach:

$$hf = \frac{1}{2} \frac{v^2}{d} \lambda$$  \hspace{1cm} (14)

where \(\lambda\) is the flow friction coefficient of CO\textsubscript{2} in the pipe or the annulus, dimensionless. \(d\) represents the equivalent diameter, m; and \(g\) is the gravity and it equals 9.81, m/s\textsuperscript{2}.

Wang \textit{et al.}\textsuperscript{16} have tested the flow friction coefficient of CO\textsubscript{2} in pipes through experiments based on formula of Darcy-Weisbach: \textsuperscript{16}

$$\lambda = \frac{1}{2} \frac{v^2}{d} \frac{1}{\sqrt{\frac{1}{\lambda}}} = -2.34 \times \log \left( \frac{\varepsilon}{1.72d} - \frac{9.26}{Re} \times \log \left( \frac{\varepsilon}{29.36d} \right)^{0.95} \right) + \left( \frac{18.35}{Re} \right)^{1.108}$$  \hspace{1cm} (15)

The throat effect of the bit jet is modeled and expressed as: \textsuperscript{20}

$$m = A P_2 \sqrt{\frac{2k}{R_s T_1 (k - 1)}} \left[ \left( \frac{P_2}{P_1} \right)^{\frac{1}{k-1}} - \left( \frac{P_1}{P_2} \right)^{\frac{1}{k-1}} \right]$$  \hspace{1cm} (16)

$$\Delta T_j = -\int_{P_1}^{P_2} \mu_{JT} dP$$  \hspace{1cm} (17)

where \(A\) is the section area of the jet, m\textsuperscript{2}. \(P_1\) and \(P_2\) are the pressure of the jet inlet and outlet, Pa. \(\Delta P_j\) represents the pressure drop of bit (\(\Delta P_j = P_1 - P_2\)). \(T_1\) is the temperature of the jet inlet, K. Isentropic coefficient \(k = 1.28\), specific gas constant \(R_s = 0.1889\text{kJ/(kg}\cdot\text{K})\), and throttle coefficient \(\mu_{JT} = \frac{1}{c_p} \left[ T \left( \frac{dV}{dT} \right)_p - V \right] \).

**Results and discussion**

Table 1 presents the well structure parameters for the study case, in addition, the equivalent diameter and length of the bit jet are both given as 2 cm, and the standoff distance is 2 times the equivalent diameter. The outlet pressure (or wellhead back pressure, applied by choke at the top annulus) is mainly determined by the requirement of well control and it is set as 9 \(\times\) 10\textsuperscript{6} Pa in the sample.\textsuperscript{2} The discharge capacity (given by mass flow rate) is highly relevant with wellbore cleanout and it is set as 25 kg/s for the compressible gas flow. It is assumed the atmosphere temperature is...
293.15 K at surface and the geothermal gradient is constant at 0.028 K/m. The temperature of CO$_2$ at inlet (named as inlet temperature for short) is given as 253.15 K.

Analysis of pressure profile

Researchers would pay much attention to the pressure profile to avoid downhole complications. The pressure profiles of CO$_2$ in the tubing and the annulus are presented in Fig. 2, compared with that of water. Approximately, the pressure gradient (or the increasing rate of pressure) of CO$_2$ with increasing depth equals that of water in the tubing. As in the annulus, the decreasing rate of CO$_2$ pressure is much slower than that of water as they flow upward; however, they are both in linear correlation with depth, which is in good agreement with earlier studies. Quantitatively, the pressure change of CO$_2$ ($10.9 \times 10^6$ Pa) is 36.7% smaller than that of water ($14.9 \times 10^6$ Pa) along the annulus, which validates the advantages of employing CO$_2$ as a drilling fluid in unconventional reservoirs with narrow pressure windows.

The pressure profile in the wellbore is highly relevant with density and viscosity. In the tubing, larger density would result in faster increase in pressure (or larger pressure gradient); however, larger viscosity would lead to larger friction and prohibit the pressure to increase fast. It explains why the pressure gradient does not change much with depth, although the changing trend of density profile and viscosity profile (Fig. 3) are similar but not linear. When it comes to the flow field of the bit jet, the density of CO$_2$ is 16.7%~20.1% smaller than that of water. Smaller density means larger flow rate and larger flow friction when the mass flow rate is constant, which explains why the pressure drop of CO$_2$ ($9.78 \times 10^6$ Pa) is 11.7% larger than that of water ($8.64 \times 10^6$ Pa). As CO$_2$ flows from the jet outlet toward the bottom rock, energy converts from kinetic energy to pressure energy and the pressure increases ($4.03 \times 10^6$ Pa). The distance between the center of the bottom bore and the center of the annulus is 8.575 cm, thus the pressure profile (Fig. 2), the density profile, and the viscosity profile (Fig. 3) all present a gap at the bottom hole.

The density profile and the viscosity profile could provide engineers the convenience to calculate the optimum displacement to clean out the annulus. Obviously, the density is still large enough to provide torque for downhole motors, which demonstrates the feasibility of drilling with CO$_2$ in a point. Based on the Span and Wagner model and the Fenghour and Wakeham model, increasing pressure (or depth) would result in increasing density and viscosity. Apparently, only the density profile and the viscosity profile in the annulus develops in the mentioned method, which reflects the different changing trends of temperature (Fig. 4) between the tubing and the annulus.

Analysis of temperature profile

Figure 4 presents the temperature profile of CO$_2$, and in the tubing, it increases faster at a shallower section because of its larger difference with geothermal temperature. In this sample, the temperature increases...
to 304.19 K at a depth of 780 m, and then CO₂ changes into supercritical state. The changing trend of temperature agrees well with that in an earlier result, but the critical depth is larger than the earlier value (450 m). The reason lies in that the temperature change of the sidewall surrounding rock is considered in this study. Theoretically, this model is more like the actual heat transfer process and improves calculation accuracy.

When CO₂ flows through the bit jet, the temperature drops at 11.7 K and then it increases when flowing from the jet outlet toward the bottom rock, which reflects the energy conversion from kinetic energy to internal energy. In this sample, CO₂ maintains in a supercritical state when it flows upward along the annulus, which provides advantages in rock-breaking, reservoir protection, and EOR. Both density and viscosity would decrease with increasing temperature, and the changing rate of the annulus temperature is relatively slower than that of the tubing temperature (Fig. 4). Consequently, the pressure change dominates the change of density and viscosity in the annulus, thus the mentioned profiles witness constant decrease with decreasing depth. On the contrary, the changing temperature dominates the changing density and viscosity in the tubing, and then they both decrease with increasing depth (Fig. 3).

The thermal conductivity and capacity of CO₂ could also significantly impact temperature profile, besides the mentioned temperature difference between CO₂ and formation rock. In the tubing, thermal conductivity witnesses constant decrease when flowing downward (Fig. 5) because of increasing temperature at deeper section (Fig. 4), which will slow down heat transfer and then the changing rate of conductivity furthermore. As the conductivity of CO₂ is in positive correlation with pressure, it decreases with decreasing depth in the annulus (Fig. 5) because of the larger influence of pressure change than that of temperature change.

Generally, the heat capacity of CO₂ increases with increasing temperature or decreasing pressure. As is shown in Fig. 5, the capacity change is quite insignificant overall in the tubing; however, it increases fast as CO₂ flows upward in the annulus. The changing trend of capacity reflects that it is more sensitive to pressure change than to temperature change.

As also presented in Fig. 5, the capacity in the annulus is much larger than that in the tubing, especially at the shallower section. When the temperature is 308.15 K and the pressure is 10 × 10⁶ Pa (near the annulus outlet), the capacity of CO₂ (5.63 × 10³ kJ/(kg·K)) is 4.85 times that of air (1.16 × 10³ kJ/(kg·K)) and is even 33.3% larger than that of water (4.15 × 10³ kJ/(kg·K)). The large capacity well explains why the temperature change in the annulus is smaller than that in the tubing, and why the annulus temperature is higher than geothermal temperature at shallow section (Fig. 4).

**Sensitivity analysis of the flow field**

The adjustment of discharge capacity and outlet pressure is the main method to control wellbore flow field and avoid complications. Besides, the temperature of CO₂ in the surface tank (inlet temperature) would change with atmospheric temperature, and then it might impact the wellbore pressure profile and temperature profile.

**Influence of mass flow rate**

Figures 6 and 7 present the pressure profile and temperature profile via changing mass flow rate, respectively. In the tubing, the pressure increases significantly with increasing mass flow rate at certain depth; however, the pressure increases lightly as mass flow rate increase in the annulus (Fig. 6). It could be concluded that the changing trend of pressure profile is mainly dominated by the pressure drop of the bit jet via mass flow rate. As the outlet pressure is set as constant (9 × 10⁶ Pa), the pressure difference (with changing
mass flow rate) at the bottom annulus could reflect the influence of the mass flow rate on flow friction in the annulus. As the mass flow rate mainly depends on the need of wellbore clean-out, and the pressure profile is highly relevant to well control, then we can conclude that wellbore clean-out does not contradict well control, which is another advantage of supercritical CO$_2$ drilling and is validated for the first time.

As shown in Fig. 7, the temperature decreases with increasing mass flow rate at a certain depth in both the tubing and the annulus, and then the critical depth increases consequently. A larger mass flow rate would also result in a larger temperature drop in the bit jet.

**Influence of outlet pressure**

At a certain depth, the annulus pressure is approximately in linear correlation with outlet pressure (Fig. 8), and this knowledge could provide the convenience to control the annulus pressure profile. As a larger outlet pressure would obviously result in a larger density of CO$_2$ and then a smaller pressure drop in the bit jet, the influence of outlet pressure gets lighter in the tubing than in the annulus.

As shown in Fig. 9, the outlet pressure could not impact the temperature profile in the tubing; however, the temperature drop decreases with increasing outlet pressure and then the temperature profile in the annulus is impacted.
Conclusions

A fully coupled model is proposed to investigate the flow field with CO₂ as a drilling fluid. This study presents and analyzes the pressure profile, temperature profile, and physical property profiles in both the tubing and the annulus. A sensitivity analysis on the flow field is then conducted. Based on the results and discussions, this study can conclude the following:

1. The pressure in both the tubing and the annulus is in positive correlation with well depth, and the pressure drop of the bit jet is 9.78 MPa in this sample. The pressure change of CO₂ is 36.7% smaller than that of water along the annulus. In the tubing, the temperature increases fast at the shallow well section and then the increasing rate slows down with increasing depth. CO₂ changes into supercritical state when the depth equals 700 m ~ 830 m. CO₂ could maintain a supercritical state in the annulus, and then it provides advantages for reservoir exploitation.

2. Both the pressure and temperature are highly coupled with physical properties of CO₂. The changes in physical properties are mainly dominated by temperature change in the tubing and pressure change in the annulus. The density, viscosity, and thermal conductivity all present a constant decrease along the flow route. The density is large enough to drive downhole motors. The capacity is much larger than that of air in the wellbore.

3. The pressure increases lightly as the mass flow rate increases in the annulus. The outlet pressure could significantly and positively impact the pressure profile in the annulus; however, its influence on the temperature profile is negligible in the tubing. The inlet temperature could not impact the pressure profile in the annulus, and its influence on the temperature profile mainly lies in the shallow section of the tubing.

4. The newly validated advantages include that supercritical CO₂ drilling is more suitable for the exploitation of unconventional reservoirs with narrow pressure windows. Wellbore clean-out does not contradict well control, and the temperature change of CO₂ at the inlet would not induce disadvantages for well control. The adjustment of outlet pressure is the main and convenient method to control the pressure profile in the annulus.
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References

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