Numerical investigation on the expansion of supercritical carbon dioxide jet

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Abstract. Supercritical carbon dioxide (SC-CO$_2$) fluid is characterized by low rock breaking threshold pressure and high rock breaking rate. Meanwhile, SC-CO$_2$ fluid has relatively low viscosity near to gas and high density near to liquid. So, it has great advantages in drilling and rock breaking over water. In this paper, numerical study of SC-CO$_2$ flowing through a nozzle is presented. The purpose of this simulation is to ascertain why the SC-CO$_2$ jet flow has better ability in drilling and rock breaking than the water jet flow. The simulation model was controlled by the RANS equations together with the continuity equation as well as the energy equation. The realizable k-epsilon turbulence model was adopted to govern the turbulent characteristics. Pressure boundary conditions were applied to the inlet and outlet boundary. The properties of carbon dioxide and water were described by UDF. It is found that: (1) under the same boundary conditions, the decay of dimensionless central axial velocity and dynamic pressure of water is quicker than that of the SC-CO$_2$, and the core length of SC-CO$_2$ jet is about 4.5 times of the nozzle diameter, which is 1 times longer than that of the water; (2) With the increase of inlet pressure or the decrease of outlet pressure, the dimensionless central axial velocity of water keeps the same, while the decay of central axial velocity of SC-CO$_2$ turns gentle; (3) the change of central axial temperature of SC-CO$_2$ is more complex than that of the water.

1. Introduction

High-pressure water jet technology has seen successful applications in various sectors of the petroleum industry, such as the abrasive jet drilling and perforation [1], the water jet-assisted multilayer fracturing [2], and the offshore wellhead cutting with the abrasive water jet technique [3]. However, comparing with water using as the working fluid, supercritical carbon dioxide (SC-CO$_2$) is more suitable in drilling technology [4]. It is characterized by low rock breaking threshold pressure and high rock breaking rate. Meanwhile, SC-CO$_2$ fluid has a relatively high density, so it is easy to control the bottom hole pressure. Table 1 shows the density and viscosity of water and SC-CO$_2$. But there are still few relevant studies on analyzing the different ability in drilling because of the complex properties of CO$_2$. So, this paper adopts the CFD technique to try to figure out the reason why SC-CO$_2$ has better ability for drilling than that of the water.

| Water | SC-CO$_2$ |
|-------|----------|
|       |          |

Table 1. Comparison of density and viscosity about water and SC-CO$_2$ (T=320K).
2. CFD Model
The flow outside the nozzle was assumed as axisymmetric flow and the CFD model was therefore simplified as two-dimension one. Axisymmetric solver was applied to take the three-dimension (3-D) effect into account in this work. The models and structured meshes are shown in Figure 1. The dimensions of the calculation domain are shown in Table 2. The diameter of the nozzle \(D_0\) is 4mm. The diameters of the inlet \((D_s)\) and outlet \((D_1)\) pipe are 50mm and 800mm. The contract angle \((\theta)\) is 13.5°.

The jet flow was assumed to be steady, controlled by the RANS equations together with the continuity equation as well as the energy equation. The realizable k-epsilon turbulence model was adopted to govern the turbulent characteristics with the standard wall function adopted to resolve the near-wall region. CFD code Fluent was employed in all the simulation works. In the simulation, pressure boundary conditions were applied on the inlet and outlet boundary. The governing equations were discretized by the finite volume method and the 2nd order upwind scheme was adopted for spatial discretization of the convection terms. The properties of SC-CO\(_2\) and water were defined by UDF files. The grid number was initially made at about 25 thousand and later increased to about 40 thousand to confirm that the results were grid independent. The maximum wall \(y^+\) value was around 120 and for most of the wall regions, \(y^+\) was around 40.

![Figure 1. The models and structured meshes of the jet flow model.](image)

### Table 2 Pump dimensions.

| Symbol | \(D_0/\text{mm}\) | \(D_s/\text{mm}\) | \(D_1/\text{mm}\) | \(L_1/\text{mm}\) | \(\theta/°\) |
|--------|------------------|------------------|------------------|------------------|---------|
| Dimension | 4 | 50 | 800 | 1500 | 13.5 |

3. Fluid Properties

3.1. Properties of carbon dioxide
According to Bender [5], the fluid range of CO2 is divided into three regions as I, II, and III: region I is the dilute (gas) region, region II is the critical and supercritical region and region III is the dense fluid (or liquid) region. The phase diagram for CO\(_2\) is shown in Figure 2.

The critical point of CO\(_2\) is located at \(T_c=304.1282\) K and \(P_c=7.3773\) MPa, as reported by Span and Wagner [6], and the triple point is located at \(T_t=216.592\) K, \(P_t=0.51795\) MPa. When the temperature is higher than 304.25 K and the pressure is higher than 7.38MPa, the state of carbon dioxide changes into supercritical.
CO₂ is supercritical fluid gas under downhole pressure and temperature conditions. If the borehole pressure is kept high enough to balance formation pressure, the fluid pressure at depths below 750 m will be above 7.4 MPa—the critical pressure for CO₂. Temperature gradients in the Earth are typically 25°C/km or higher so the temperature in a borehole is also typically higher than the CO₂ critical temperature. Under these conditions, CO₂ jet will be a supercritical fluid—SC-CO₂ [7].

![Figure 2. Phase diagram of carbon dioxide.](image)

The Huang [8] equation is recommended to calculate the density of SC-CO₂. To cover its viscosity, the equation derived by Altunin and Sakhabetdinov [9] is recommended. And the equation developed by G. Scalabrin et al [10] is used to calculate thermal conductivity. The suitable region of temperature and pressure and the biggest average deviation about the three equations are shown in Table 3.

**Table 3.** The suitable region of temperature and pressure and the biggest average deviation.

| property              | equation                        | range of temperature(K) | range of pressure(MPa) | average deviation |
|-----------------------|---------------------------------|--------------------------|------------------------|-------------------|
| density               | Huang et al[8]                  | 216-423                  | <=310                  | <=1%              |
| viscosity             | Altunin and Sakhabetdinov[9]    | 220-1300                 | <=120                  | <=2%              |
| thermal conductivity  | G. Scalabrin[10]                | 216-1000                 | <=200                  | <=1.2%            |

### 3.2. Properties of water

The variations of pressure and temperature have little effect on the density and thermal conductivity of water. But viscosity is closely related to temperature. So its density and thermal conductivity can be seen as constant. And the viscosity is a function that depends on temperature. Joseph Kestin and Mordechai Sokolov*[11] developed an equation that is valuable for temperatures from 265 K to 423 K. The absolute derivation is no more than 0.2%.

### 4. Validation of the Flow Simulation

The jet flow has a character of self-preserving in the region of fully developed flow [12]. If the central axial velocity \( u \) is divided by \( u_m \) (the maximum central axial velocity at that section), \( b_c \) represents a typical length for that section and take it as the value of \( r \) where \( u \) is equal to half the maximum axial velocity. Then the dimensionless \( u/u_m \) against \( r/b_c \) can be plotted. The result is that the velocity distributions of different section fall on one common curve.

The validation results of self-preserving about water and SC-CO₂ were plotted in Figure 3 and Figure 4 respectively. The boundary conditions of them are the same (the inlet pressure is 50MPa, the
outlet pressure is 30MPa, the inlet temperature is 340K, the outlet temperature is 320K). The results show that the jet flow of water and SC-CO$_2$ has a good character of self-preserving. So the simulation is reliable.

5. Results and analysis

5.1. Comparison of dimensionless central axial velocity attenuation between water and SC-CO$_2$

The axial velocity of jet flow does not decay in the development region. The core of a rough turbulent jet flow is not precisely defined, because no direct and exact measurements exist. Ervine and Falvey indicated an estimate for core length of about 3~4 diameters for circular jet. As is shown in Figure 5 and Figure 6 (50/20 means the inlet pressure is 50MPa, the outlet pressure is 20MPa), the core length of SC-CO$_2$ is about 4.5 times of the nozzle diameter, and the core length of water is 3.5 times. The dimensionless central axial velocity of SC-CO$_2$ decays slower than that of the water. With the increase of inlet pressure or the decrease of outlet pressure, the dimensionless central axial velocity attenuation of water keeps the same, but the decay of dimensionless central axial velocity of SC-CO$_2$ turns gentle. The main reason for this difference is that water and SC-CO$_2$ have different magnitude of viscosity.

Table 1 shows the data of viscosity of water and SC-CO$_2$ (the temperature is 320K). It can be seen from the table that the viscosity of water is nearly 5 times higher than that of SC-CO$_2$. High viscosity leads to quicker dissipation of energy. So the core length of water is shorter than that of the SC-CO$_2$, and its central axial velocity decays quicker.
5.2. Comparison of dimensionless central axial dynamic pressure attenuation between water and SC-CO$_2$
One of the main reasons that affect the rock breaking ability of jet flow is the dynamic pressure. Figure 7 and Figure 8 give the dimensionless central axial dynamic pressure attenuation of water and SC-CO$_2$. The decay of central axial dynamic pressure of water is not affected by the change of inlet and outlet pressure. But the decay of central axial dynamic pressure of SC-CO$_2$ is closely related to the change of pressure. The higher the inlet pressure is, the more gradual the trend of the central axial dynamic pressure will be, the same as the decrease of outlet pressure. This is because the central axial velocity attenuation of SC-CO$_2$ is affected by pressure. So if the boundary conditions are the same, SC-CO$_2$ will have better rock breaking ability than water.

![Figure 7](image1.png)  
**Figure 7.** Dimensionless central axial dynamic pressure attenuation with different inlet pressure and same outlet pressure.

![Figure 8](image2.png)  
**Figure 8.** Dimensionless central axial dynamic pressure attenuation with same inlet pressure and different outlet pressure.

5.3. Temperature analysis of water and SC-CO$_2$ at central axis

Figure 9 shows simulating temperature curves in the central axis of water and SC-CO$_2$ (the boundary conditions are: the inlet pressure and temperature are 50MPa and 340K, the outlet pressure and temperature are 20MPa and 320K). The distribution of these two fluids is very different. The temperature of water decreases through the nozzle to the entrance of the outlet part. While the temperature of SC-CO$_2$ decreases in Part A, then it increases in Part B, and decreases in Part C. The main reason is that they have different magnitude of viscosity and thermal conductivity. Meanwhile, SC-CO$_2$ is compressible. The water has higher viscosity, so its energy lost quickly. And higher thermal conductivity leads to quicker heat transfer, so the temperature decreases quickly. But for SC-CO$_2$, in Part A, the expanding through the nozzle makes the density decreases, and then the velocity increases, so the temperature decreases. In Part B, the density decreases little, the velocity increases much, so the increase of internal energy leads to higher temperature. In Part C, the jet flow is fully developed. It is convenient for heat transfer, so the temperature decreases.
6. Conclusions

SC-CO\textsubscript{2} fluid is widely used in drilling technologies rather than water because of its low rock breaking threshold pressure and high rock breaking rate and special properties, such as low viscosity near to gas and high density near to liquid. Based on the simulation results, the details of the jet flow field of SC-CO\textsubscript{2} and water were analyzed and some conclusions are obtained as followed:

(1) Under the same boundary conditions, the decay of dimensionless central axial velocity and dynamic pressure of water is quicker than that of the SC-CO\textsubscript{2}. And the core length of SC-CO\textsubscript{2} is about 4.5 times of the nozzle diameter, which is 1 times longer than that of the water.

(2) With the increase of inlet pressure, or decrease of outlet pressure, the dimensionless central axial velocity and dynamic pressure attenuation of water keep the same, but the decay of central axial velocity of SC-CO\textsubscript{2} turns gentle.

(3) Central axial temperature of water decreases along the flow direction. But the temperature of SC-CO\textsubscript{2} has an increasing part.

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