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Numerical simulation of the abrasive supercritical carbon dioxide jet: The flow field and the influencing factors*

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Abstract: The supercritical carbon dioxide (SC-CO_2) jet can break rocks at higher penetration rates and lower threshold pressures than the water jet. The abrasive SC-CO_2 jet, formed by adding solid particles into the SC-CO_2 jet, is expected to achieve higher operation efficiency in eroding hard rocks and cutting metals. With the computational fluid dynamics numerical simulation method, the characteristics of the flow field of the abrasive SC-CO_2 jet are analyzed, as well as the main influencing factors. Results show that the two-phase axial velocities of the abrasive SC-CO_2 jet is much higher than those of the abrasive water jet, when the pressure difference across the jet nozzle is held constant at 20 MPa, the optimal standoff distance for the largest particle impact velocity is approximately 5 times of the jet nozzle diameter; the fluid temperature and the volume concentration of the abrasive particles have modest influences on the two-phase velocities, the ambient pressure has a negligible influence when the pressure difference is held constant. Therefore the abrasive SC-CO_2 jet is expected to assure more effective erosion and cutting performance. This work can provide guidance for subsequent lab experiments and promote practical applications.

Key words: abrasive supercritical carbon dioxide jet, numerical simulation, velocity distribution, impact factor

Introduction

Nowadays, the shale gas development is in full swing in China with a considerable output. However, the lavish cost of the well drilling and the simulations in the shale gas fields still constrains the economic benefit and further development of the shale gas industry in China. Therefore, new techniques instead of the use of water-based fluids are in great demands to achieve a higher yield with a lower cost. Since 2000, a great deal of theoretical and experimental studies concerning the rock-breaking process and the feasibility of well drilling using the supercritical carbon dioxide (SC-CO_2) jet have been conducted in the USA[1], as well as in China in recent years[2,3]. The SC-CO_2 fluid has unique properties such as no permeability damage caused from the water lock, rapid clean up and reduced proppant flowback during the hydraulic fracturing. Similar to the abrasive water jet, the abrasive SC-CO_2 jet is formed by adding solid particles into the SC-CO_2 jet. It might achieve a better jet perforation, by combining the technical advantages of the SC-CO_2 jet like the high velocity and the high hydrostatic pressure transmission capacity, and of the abrasive jet like the fine cutting performance on metal and hard materials.

The abrasive water jet technique is now in a matured stage and is applied into many fields like the well drilling, the hydraulic fracturing, the mining, the metallurgy, and the military industry[4,5]. Meanwhile, the micro abrasive air jet (MAAJ) machining techniques have been studied in China and utilized in the rust removal, the polishing, the micro powder manufacturing and other fields[6,7]. Successful applications of the MAAJ indicate the promising prospects of the abrasive SC-CO_2 jet due to the low viscosity and the

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satisfactory particle-carrying capacity.

The SC-CO_2 fluid has a similar density as an ordinary liquid and a similar viscosity as the gas. Its surface tension is zero and the mass transfer capacity is excellent, very good for rock-breaking[8,9]. The impact of the solid particles in the abrasive jet plays a much more important role in cutting than that of the fluid, therefore, there is a need to study and verify whether the particles in the abrasive SC-CO_2 jet can acquire a similarly high impact velocity to that of the particles in the abrasive water jet, combined with the good flow characteristics of the jet. To deal with this problem, based on the computational fluid dynamics, the flow field of the abrasive SC-CO_2 jet and the distributions of the two-phase velocities and pressure are obtained and compared with those of the abrasive water jet. The effects of several operating factors are revealed and the advantages of the abrasive SC-CO_2 jet over the abrasive water jet are preliminarily evaluated with respect to the cutting performance and the future applications in the shale gas development.

1. Modeling

1.1 *Fundamental assumptions*

This work is based mainly on the following fundamental assumptions: (1) the physical model will not be distorted in the simulations, (2) the solid particles are spheres of equal diameter, (3) no mass loss from the particles or the exchange between the particles and the fluid, (4) taking account of the forces which have a significant influence on the particle motion like the inertia force, the drag force and other forces in the direction of the particle motion, while ignoring the forces that have little influences like the Magnus force and the Saffman force, (5) at the initial stage, the SC-CO_2 fluid and the solid particles are the only two types of matter that are filled in the simulated computational domain.

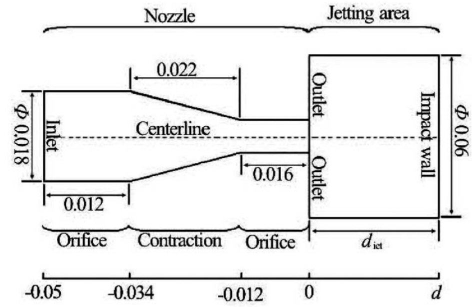

Fig.1 Plane sketch of the geometrical model (m)

1.2 *Geometrical model*

The computational domain consists of the flow fields in and out of the jet nozzle, with two straight orifices on both sides and one contraction section in the middle. According to related lab experiments on the SC-CO_2 and field applications on the abrasive water jet, the nozzle structure and the solid particles are selected[10], as shown in Fig.1. The diameter of the nozzle outlet Φ_n is 0.006 m, the ratio of the length to the diameter of the front straight pipe is 2:1, the angle of the contraction is 30.5°. The standoff distance from the jet nozzle to the impact wall d_{jet} and the distance from the investigated transverse section to the impact wall L will be given different values for different investigation aims.

Due to the severe changes of the fluid velocity and properties, the mesh is refined in the nozzle and in the cone-shaped jet flow area with the boundary surface of Face 3 in Fig.2, to improve the calculation accuracy. The mesh volume of the whole computational domain is 484 956, 76.6% of which are in the mesh refinement area.

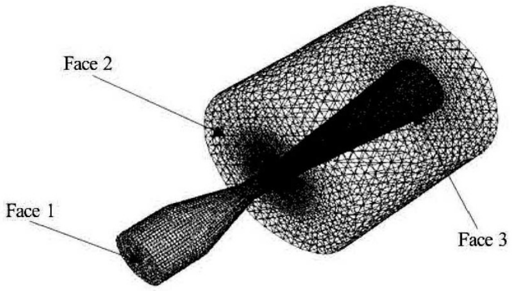

Fig.2 Physical model of the computational domain (mesh refinement included)

Mesh convergence study shows that with the mesh model used in this research, stable simulation results are obtained[11].

1.3 *Governing equations*

Unlike the water, the SC-CO_2 fluid is compressible and sensitive to temperature and pressure[8]. Span and Wagner[12] modified the calculation model for the CO_2 fluid via experiments and made it suitable for a large range of pressure and temperature. The Span-Wagner equation has significantly improved the calculation accuracy and is widely used in the research of CO_2[13]. In the Span-Wagner equation, the Helmholtz free energy is used to calculate the state parameters, and its dimensionless form is

$$\Phi(\delta,\tau)=\Phi_o(\delta,\tau)+\Phi_r(\delta,\tau) \tag{1}$$

Then the compressibility factor, the specific heat capacity at a constant pressure and the coefficient of the Joule-Thomson effect are obtained as follows:

$$Z=\frac{\rho_f(\delta,\tau)}{\rho_f RT}=1+\delta\frac{\partial\Phi_r(\delta,\tau)}{\partial\delta} \tag{2}$$