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Influences of ambient pressure and nozzle-to-target distance on SC-CO_2 jet impingement and perforation

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A B S T R A C T

It is reported that supercritical carbon dioxide (SC-CO_2) jet can efficiently erode rocks at a comparably low threshold pressure with high penetration rate. However, the influences of bottom-hole pressure and borehole irregularities on SC-CO_2 jet cutting efficiency have not been studied. Therefore, in this research, comprehensive methods of numerical simulations and lab experiments were carried out to investigate the influences of the ambient pressure and the nozzle-to-target distance on the jet impinging pressure and perforation performance. Results show that, both the effective jet impinging pressure and the eroded depth of perforation hole notably decrease with the increase of the ambient pressure, when jet inlet pressure is constant. When the pressure difference between inlet pressure and ambient pressure is kept constant, the effective impinging pressure hardly changes with ambient pressure, but eroded depth increases at first and then decreases, bounded by the critical pressure of CO_2. As the nozzle-to-target distance extends, both the depth and volume of the perforation hole decrease, and diameter of the perforation hole increases at first and then decreases. Under the research condition of certain pressure and temperature, a distance of 8 times the nozzle diameter is the critical distance that clarifies the different effect of nozzle-to-target distance on the hole diameter. Different features between using SC-CO_2 jet and water jet, including the optimal distance for rock-erosion efficiency, are attributed to the difference in fluid properties. Further simulation results show that, unlike water, SC-CO_2 fluid is compressible and it leads to specific variations of jet structure, namely the increase of length of SC-CO_2 jet potential core, and flow type from non-submerged jet to submerged jet. As a consequence, under the simulated bottom-hole conditions, SC-CO_2 jet is proven to be able to acquire high rock-erosion efficiency and the jet-assisted drilling rate at a larger application ranges. This research can promote the future application of SC-CO_2 jets.

1. Introduction

Natural gas, as a clean energy resource, has been an emphasis of research and development in the fields of petroleum and energy. Due to the gradual depletion of oil and gas in low and intermediate-level layers, it is inevitable to develop the deep and ultra-deep reservoirs. These reservoirs are always characterized by high temperature, hard rocks and ultra-low permeability. Water-based drilling fluids lead to a hold-down effect on cuttings and repeated crushing at the bottom hole, and also a water-lock effect and other permeability formation damage. These negative effects lead to low rates of penetration (ROP) and production. Underbalanced drilling (UBD) improves ROP to a certain degree, but still has shortcomings. Air drilling fluids like nitrogen and foam can achieve satisfactory under-balanced condition in annulus of low hydrostatic pressure, but can hardly provide sufficient torque for bottom-hole motors. There is an urgent need for research on new fluids for drilling and completion in deep wells that do not cause damage to the formation. Among them, supercritical carbon dioxide (SC-CO2) fluid has many unique physical properties potential advantages. Wang et al. (2012) regarded it as a good choice for development of unconventional reservoirs.

SC-CO_2 fluid has been widely used in many fields because it can be obtained relatively easily (critical pressure $P_c = 7.38$ MPa, critical temperature $T_c = 304.1$ K). Han (2005) reported that SC-CO_2 is

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similar to both liquid and gas due to high density and diffusivity and low viscosity. High diffusivity enables SC-CO_2 to enter deep fractures and pores to transmit the fluid static pressure, which is helpful to improve the rock-erosion efficiency. Moreover, Hyatt (1984) found that CO_2 has a high solubility for hydrocarbons of different carbon chain lengths, owing to the non-polar molecular structure. Besides, it has been verified through lab experiments and field cases that CO_2 has higher absorptive capacity by rock substances than hydrocarbons based on a competitive absorption mechanism (Reznik et al., 1984; Tang et al., 2006; Dong et al., 2013). These lead to more extraction of hydrocarbons. Hence, it is hopeful to improve the ROP and the output without reducing the permeability by using pure CO_2 fluid.

On the basis of these advantages, it is believed that SC-CO_2 could be used in oil and gas well drilling. In the late 1990s, Kollé (2000) first proposed this idea and conducted initiative research on jet perforation and coiled-tubing drilling using an SC-CO_2 jet via theoretical and experimental methods. He found that the ROP using a CO_2 jet was 3.3 times that using a water jet. The specific energy for eroding rock using SC-CO_2 jet is only approximately 20% that observed using water jet. SC-CO_2 fluid can provide bottom-hole motor with enough energy in drilling strings. Meanwhile, it sustains UBD condition in annulus because fluid density gradually decreases as it flows back to ground. Moreover, bottom-hole pressure can be adjusted by controlling back pressure at wellhead. So SC-CO_2 fluid is the ideal choice for UBD operations (Gupta et al., 2005; Al-Adwani, 2007). Therefore, SC-CO_2 drilling combines the advantages of conventional water-based drilling fluid and UBD fluids like nitrogen. SC-CO_2 fluid is more suitable for drilling small holes and slim holes due to the unique physical properties. Microborehole drilling brings the potential for a reduction both cost and environmental impact and an increase of production, with relatively modest modification of existing drilling equipment or CT techniques (Albright et al., 2005). So, applying SC-CO_2 jet technology in slim-hole drilling has broad prospect for development. It is demonstrated that coiled-tubing (CT) drilling using a SC-CO_2 jet is technically feasible and has many advantages in improving ROP and single-well recovery (Kollé, 2000; Shen et al., 2010; Al-Adwani, 2007).

A new technology will be eventually accepted by contractors only if it is economical feasible. Compared to air drilling, SC-CO_2 jet-assisted drilling will cost more in the extra facilities such as liquid CO_2 tanks, refrigerating units, liquid CO_2 pumps, and the transport fees of liquid CO_2. Whether is economical feasible primarily depends on its influence on increasing production effectiveness (Middleton et al., 2015). Thankfully, applying CO_2 in development has advantages in protecting drilling strings and lowering formation damage. Besides, CO_2 is abundant, and liquid CO_2 is cheapest among the common fluids except water, especially when there is a CO_2 field nearby. What's more, using CO_2 will make a contribution to reduce greenhouse gas emissions and environmental protection, as well as possess the potential socio-economic value. Therefore, it is assumed that CT drilling and completion using a SC-CO_2 jet is economically feasible with pad drilling and slim-hole drilling techniques.

However, in the field operations, complex bottom-hole pressure and borehole size or the distance between jet nozzle and target can distinctly affect fluid physical properties and jet performances (Kalumuck et al., 1993; Roisman et al., 2007; Liao et al., 2012). Therefore, in this research, the influences of the ambient pressure and nozzle-to-target distance on the SC-CO_2 jet impinging pressure and perforation performance are investigated via numerical simulations and lab experiments. These results will promote the further application of SC-CO_2 jets in oil and gas well drilling operations.

2. Test on SC-CO_2 jet impinging pressure

Lab tests and numerical simulations on SC-CO_2 jet structure and impinging pressure were carried out, to further analyze the effect of ambient pressure and nozzle-to-target distance on jet cutting efficiencies.

2.1. Test apparatus

The test apparatus for measuring the SC-CO_2 jet impinging pressure is shown in Fig. 1. There are 7 points distributed at different radii from 0 to 54 mm on the round impinging surface, and marked from P1 to P7 in the order of increasing radius. The pressure sensor marked P1 is positioned at the center of the impinging disc. The distances between P1 and other measured point are 2 mm, 4 mm, 6 mm, 9 mm, 28 mm and 54 mm, respectively. All the points connect the pressure sensors through straight tubules. Test body and ancillary pipelines and valves are made of stainless steel. O-rings made from special rubber well seals and prevents cavitation corrosion, piercement and leakage of CO_2. Honeywell pressure sensors with a measuring capacity of 60 MPa and an accuracy of 0.5% are used to measure the pressure on each point. An NI 9203 data acquisition and monitoring system (manufactured in National Instruments Corporation from Austin TX. America) with a maximum acquisition rate of 20 kS/s is used to acquire the pressure data at different time intervals and display them in real-time.

2.2. Test results and discussion

2.2.1. Ambient pressure (constant jet inlet pressure P_{in})

Fig. 2 shows the influence of the ambient pressure (P_{am}) on the SC-CO_2 jet impingement when the jet inlet pressure stays the same, plotted by the position (l) in the radial direction on the horizontal axis. In the test, Φ_n is 1 mm, d_{jet} is approximately 3, jet inlet pressure is controlled at approximately 32 MPa, and the pressure in the ambient pressure body before the choke valve is sequentially adjusted from 5 MPa to 15 MPa.

As illustrated in the plot, the measured pressures at P1, P2 and P3 are significantly higher than those at the other points, which have approximately equivalent values to ambient pressure. Measured pressure at P4, at a distance from the center of 6 mm, is lower than the ambient pressure. It is inferred that, compared to water jet, SC-CO_2 jet less spreads in the radial direction. The radial velocity after impinging on the surface is high, so the pressure at P4 is notably lower due to the entrainment effect. As the ambient pressure increases, the increments of the measured pressure at P4 to P7 are approximately 10 MPa, which are equivalent to the increment of ambient pressure. Meanwhile, the increment of the measured pressure at P1 is only 2.4 MPa, or 24.1% of the ambient pressure increase. In other words, the effective jet impinging pressure decreases as the ambient pressure increases.

2.2.2. Ambient pressure (constant jet pressure difference ΔP)

Fig. 3 shows the influence of the ambient pressure (P_{am}) on SC-CO_2 jet impingement when ΔP is constant, plotted by the position (l) in the radial direction on the horizontal axis. In the test, ΔP and the ambient pressure body are both designed at 20 MPa, and the ambient pressure is sequentially adjusted from 5 MPa to 15 MPa. It can be seen that the configurations of the pressure change with ambient pressure are similar. Therefore, it is inferred that, when ΔP is constant, the structure of the SC-CO_2 jet flow negligibly changes with the ambient pressure. Data indicate that the increment of the impinging pressure at P1 is 10.1 MPa, approximately equal to the increment of the ambient pressure. In other words, the effective jet