Experimental Study on the Impingement Characteristics of Self-Excited Oscillation Supercritical CO$_2$ Jets Produced by Organ-Pipe Nozzles

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Abstract: Supercritical carbon dioxide (SCO$_2$) jets are a promising method to assist drilling, enhance oil–gas production, and reduce greenhouse gas emissions. To further improve the drilling efficiency of SCO$_2$ jet-assisted drilling, organ-pipe nozzles were applied to generate a self-excited oscillation SCO$_2$ jet (SEOSJ). The impact pressure oscillation and rock erosion capability of SEOSJs under both supercritical and gaseous CO$_2$ (GCO$_2$) ambient conditions were experimentally investigated. It was found that the impact pressure oscillation characteristics of SEOSJs produced by organ-pipe nozzles are dramatically affected by the oscillation chamber length. The optimum range of the dimensionless chamber length to generate the highest impact pressure peak and the strongest pressure oscillation is within 7–9. The dimensionless pressure peak and the pressure ratio decreases gradually with increasing pressure difference, whereas the pressure oscillation intensity increases with increasing pressure difference and the increasing rate decreases gradually. The dominant frequency was observed to decrease monotonically with increasing chamber length but increases with the increase of pressure difference. Moreover, the comparison of impingement characteristics of SEOSJs under different ambient conditions showed that the values of dimensionless peak impact pressure are similar under the two ambient conditions, and the SEOSJ achieves higher pressure oscillation intensity and dominant frequency in SCO$_2$ at the same pressure difference. The rock breaking ability of the SEOSJ is closely related to its axial impact pressure. The erosion depth and mass loss of sandstone caused by the organ-pipe nozzle with the best impact pressure performance is higher than those produced by other nozzles. The SEOSJ results in a deeper and narrower crater in SCO$_2$ than in GCO$_2$ under the same pressure difference. The reported results provide guidance for SEOSJ applications and the design of an organ-pipe nozzle used for jet-assisted drilling.

Keywords: unconventional energy resources; jet-assisted drilling; self-excited oscillation; supercritical carbon dioxide jet; organ-pipe nozzle; rock erosion

1. Introduction

SCO$_2$ jets have been widely applied in the fields of deep hole drilling, rock breaking, metal surface processing, and cooling of electronic equipment, owing to their superior physical properties such as low viscosity, high diffusivity, and high heat transfer capacity [1,2]. With the sharp increase in world energy consumption in recent decades, economical exploitation of unconventional energy resources, represented by shale gas and coalbed methane, is gaining increasing importance [3]. To improve drilling efficiency and enhance oil and gas production, SCO$_2$-based jet-assisted drilling technology was proposed and successfully employed in practical applications [4,5]. It is reported that SCO$_2$ jets need lower threshold pressure to break hard rocks than water jets, and using SCO$_2$ as the alternative drilling fluid can avoid water blocking and clay swelling, thus reducing reservoir...
damage [6,7]. Moreover, the utilization of SCO$_2$-based oil–gas development techniques has high potential to realize CO$_2$-geological storage [8].

Many experimental investigations have been performed to study the rock-breaking characteristics and mechanisms, impingement pressure features, and flow behaviors of SCO$_2$ jets [9,10]. Du et al. [11] experimentally determined the effects of five major factors affecting the rock-breaking performance of SCO$_2$ jets. They found that the erosion depth of rock by SCO$_2$ jets is larger than that by water jets under the same experimental conditions. There are optimal nozzle diameters and standoffs that lead to the largest rock erosion depth and volume, and the rock-breaking performance improves with increasing jet pressure or decreasing rock compressive strength. Rock erosion experiments performed by Wang et al. [12] showed that the erosion depth increases with the increase of jetting time while the erosion rate decreases with the increase of jetting time. The rock erosion depth initially increased and then decreased with the jet temperature within the range 310 to 360 K. Furthermore, through SEM observation, they suggested that cement fracture and matrix particle spalling are the main microscopic failure features of rock under SCO$_2$ jet impact [13]. Tian et al. [14] found that for the same jet pressure both the jet impinging pressure and the erosion depth notably decrease with the increase of ambient pressure. However, for the same pressure difference, the impinging pressure hardly varies with ambient pressure, whilst the erosion depth increases at first and then decreases with ambient pressure. Hu et al. [15] captured images of submerged SCO$_2$ jets by high-speed photography and reported that the SCO$_2$ jet has a structure similar to that of a water jet, and the jet kinetic energy dissipates more slowly in the external flow field due to its low viscosity.

Computational studies on the flow behaviors of SCO$_2$ jets have also been conducted by researchers to obtain more detailed flow information about SCO$_2$ jets [16,17]. Lv et al. [18] found that the axial velocity and dynamic pressure of SC-CO$_2$ jets decay more slowly than that of water jets, and the SCO$_2$ jets have longer potential core length under the same working conditions. Sun et al. [19] discussed the stagnation properties of SCO$_2$ jets using the CFD method. They found that the stagnation pressure increases with the increase of jet pressure and the ambient pressure but is weakly affected by the jet temperature. Moreover, it was found that the stagnation temperature is mainly affected by the jet temperature, while the inlet pressure and ambient pressure played a minor role. Zhang et al. [20] conducted a numerical study on the oscillation characteristics of an SCO$_2$ jet exiting from a conical nozzle and reported that the SCO$_2$ jet can produce dynamic loading on the target due to the formation of concentrated high-speed SCO$_2$ mass structures in the jet potential core. Yang et al. [21] reported that the swirling-round SCO$_2$ jet has higher axial speed and stronger rock-breaking ability than a water jet, and higher pressure difference produces greater impact pressure while the influence of ambient pressure and fluid temperature on impact pressure is negligible. Liu et al. [22] pointed out that the ratio of the jet static pressure to the ambient pressure (i.e., the expansion ratio) is a suitable index to reflect the flow field structure of an SCO$_2$ jet (i.e., expansion and compression wave structure, jet boundary layer expansion rate, and potential core length) and can be changed by altering the inlet pressure and nozzle structure. Furthermore, they demonstrated that the expansion ratio is the key parameter that affects the energy conversion rate of the Laval nozzle and the coal breakage efficiency of an SCO$_2$ jet [23]. Li et al. [24,25] found that SCO$_2$ jets have a larger effective standoff distance for rock breaking, because of the lower turbulent viscosity and turbulent dissipation rate of SCO$_2$ jets, and the tensile stress and shear stress of rock under SCO$_2$ jet impact are higher than those of water jets.

The self-excited oscillation jets (SEOJs) generated by resonating nozzles can produce pulsating impact load without an excitation device and have strong material destructive ability [26], which have been the focus of numerous scholars [27–29]. Much research on periodic fluctuation and frequency characteristics of self-excited oscillation air jets and water jets has been conducted, with some acknowledged conclusions being drawn [30–32]. Based on this knowledge, Huang et al. [33,34] combined an SEOJ with an SCO$_2$ jet and found that an SEOSJ generated by the Helmholtz nozzle obtains a higher impinging
pressure peak and rock erosion rate than a continuous SCO$_2$ jet. They suggested that SEOSJ drilling technology has great potential in enhancing oil and gas recovery.

The previous studies thus far have mainly focused on the flow behaviors and rock breaking characteristics of continuous SCO$_2$ jets produced by conventional conical nozzles and pulsed water jets using experimental and numerical methods. However, as summarized in Table 1, the impact characteristics of SEOSJs generated by organ-pipe nozzles have received limited attention. Because the physical properties of SCO$_2$ are much more complex than those of water and air, and the modulation mechanism of the organ-pipe nozzle on jet flow is different from that of the Helmholtz oscillator [35,36], a study regarding its impact pressure oscillation characteristics and rock-breaking behaviors is significant for the thorough understanding of SEOSJs and improvement of SCO$_2$ jet-assisted drilling. Therefore, the peak impact pressure, pressure oscillation intensity, dominant frequency, and rock-breaking performance of SEOSJs issuing from organ-pipe nozzles are experimentally investigated in this work, and the influences of the nozzle configuration, jet pressure, and ambient condition are analyzed and discussed.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Method</th>
<th>Nozzle</th>
<th>Main Influential Parameters</th>
<th>Research Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhou et al. [16]</td>
<td>Simulation</td>
<td>Conical nozzle</td>
<td>Jet pressure</td>
<td>Flow field structure</td>
</tr>
<tr>
<td>Li et al. [24,25]</td>
<td>Simulation</td>
<td>Conical nozzle</td>
<td>Elastic modulus, Poisson’s ratio, Thermal expansion coefficient</td>
<td>Flow field, Stress field</td>
</tr>
<tr>
<td>Zhang et al. [20]</td>
<td>Simulation and experiment</td>
<td>Conical nozzle</td>
<td>Inlet pressure, Temperature, Nozzle size, Jet pressure, Standoff distance</td>
<td>Flow field, Oscillating frequency</td>
</tr>
<tr>
<td>Huang et al. [33]</td>
<td>Experiment</td>
<td>Helmholtz nozzle</td>
<td>Jet pressure, Nozzle size, Erosion time</td>
<td>Instantaneous pressure, Oscillating frequency</td>
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<tr>
<td>Huang et al. [34]</td>
<td>Experiment</td>
<td>Helmholtz nozzle</td>
<td>Jet pressure, Nozzle configuration</td>
<td>Rock erosion performance</td>
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<td>This work</td>
<td>Experiment</td>
<td>Organ-pipe nozzle</td>
<td>Ambient pressure, Pressure difference</td>
<td>Impact pressure pulsation, Dominant frequency, Rock erosion performance</td>
</tr>
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</table>

2. Experimental Setup

2.1. Experiment Apparatus and Procedures

The schematic diagram of experimental apparatus utilized for SEOSJ-impinging pressure tests and rock erosion tests in this work is shown in Figure 1, and photos of the main components of the experimental apparatus are shown in Figure 2. The experimental facility mainly consists of carbon dioxide (CO$_2$) cylinders, a CO$_2$ cooling unit, liquid CO$_2$ storage vessels, a plunger pump, a CO$_2$ heating unit, a jet impact section, a desander, and a data collecting system. During the SCO$_2$ jet impingement experiments, the CO$_2$ gas was first liquified by the cooler and temporarily stored in the storage vessels, after which the liquid CO$_2$ was pumped through the plunger pump into the buffer tank with temperature higher than the supercritical temperature. The temperature of the buffer tank and the jet chamber was kept basically constant at 60 °C by the heater in the process of experiments. The adjustable temperature range of the heater was 10–95 °C. By opening the pneumatic valve PV$_2$, the SCO$_2$ flowed into the test chamber through the side nozzle, and the SCO$_2$ flow went through the side nozzle was radial. The chamber was pressurized to a desired ambient pressure by adjusting the counterbalance valve. When the pneumatic valve PV$_1$ was switched on, the SEOSJ was jetted into the jet chamber through an organ-pipe nozzle. The regulating valve RV$_1$ was used to control the SCO$_2$ flow. To improve carbon dioxide utilization and reduce carbon emission, CO$_2$ filtered by the desander flowed back to the CO$_2$ cylinder after the experiment. The pressure transducers and the T-type thermocouples were used to monitor the inlet pressure $P_{in}$ and temperature $T_{in}$ of the SCO$_2$ flow, together with the ambient pressure $P_a$ and temperature $T_a$ in the jet chamber. A high frequency
dynamic pressure tensor (HM91) with an accuracy of ±0.1% in full span was used to measure the dynamic impinging pressure. The impact pressure of the SEOSJ was acquired in real-time by the dynamic pressure transducer mounted at the center of the target plate. The signal delivered by the pressure sensors were recorded using a data logger (model: HBM QuantumX MX840B) and transmitted to the computer. Under each designed working condition, the instantaneous impact pressure was collected for 5 s with a sampling rate of 20 kHz. The pressure data when the SCO2 flow upstream the organ-pipe nozzle was most stable were used for the statistical analysis of the impact pressure characteristics of SEOSJs. More details of the experimental circuit are given in our prior studies [6,15].

Figure 1. Schematic diagram of experimental setup.

The schematic diagram of the organ-pipe nozzle used in the experiments is shown in Figure 3. Based on previous research on the self-excited oscillating jet produced by the organ tube nozzle [37,38], preliminary experiments were carried out to determine the optimal chamber length range suitable for the experimental conditions in this study to produce strong impact pressure oscillations. Seven nozzles were tested with different oscillation chamber lengths (i.e., \(L_c = 7.5, 9, 10.5, 12, 13.5, 15, \) and 16.5 mm), and other structure parameters are summarized in Table 2. Cylindrical red sandstone specimens with a diameter of 50 mm and a length of 100 mm were prepared for the rock erosion tests. The mechanical properties of the rock specimens were measured by uniaxial compressive strength tests and Brazil split tests, and the specific mechanical parameters are shown in Table 3. The sandstone specimen held by the specimen clamping device was placed at a spacing of 9 mm from the nozzle outlet in the rock erosion tests, and the SEOSJ exiting from the organ-pipe nozzle impinged perpendicularly on the specimen eroding surface. In order to avoid the errors caused by the heterogeneity of local physical and mechanical properties of sandstone, three groups of rock erosion tests were repeated under each working condition, and the average value of each index was taken as the final test value. Carbon dioxide with a purity of 99.99% was used in the experiments. The experimental conditions are summarized in Table 4.
Figure 2. Photos of the main components of the experimental apparatus.

Figure 3. Schematic diagram of the organ pipe nozzle.

Table 2. Main structure parameters of organ pipe nozzles (unit, mm).

<table>
<thead>
<tr>
<th>Inlet Length $L_i$</th>
<th>Inlet Diameter $D_i$</th>
<th>Oscillation Chamber Diameter $D_c$</th>
<th>Exit Length $L_e$</th>
<th>Orifice Diameter $D_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>10</td>
<td>5</td>
<td>4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 3. Mechanical properties of the rock samples.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Density (kg/m$^3$)</th>
<th>Compressive Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Brazilian Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>2304</td>
<td>24.52</td>
<td>7.16</td>
<td>2.54</td>
</tr>
</tbody>
</table>

Table 4. Experimental conditions in this study.

<table>
<thead>
<tr>
<th>Experimental Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet pressure, $P_{in}$</td>
<td>10–18.5</td>
<td>MPa</td>
</tr>
<tr>
<td>Pressure difference, $\Delta P$</td>
<td>4–10</td>
<td>MPa</td>
</tr>
<tr>
<td>Ambient pressure, $P_a$</td>
<td>6, 8.5</td>
<td>MPa</td>
</tr>
<tr>
<td>Jet temperature, $T$</td>
<td>60</td>
<td>°C</td>
</tr>
<tr>
<td>Standoff distance, $s$</td>
<td>9</td>
<td>mm</td>
</tr>
</tbody>
</table>
2.2. Evaluation Methods

Figure 4 shows the impact pressure fluctuations of the SEOSJ in time domain at an inlet pressure of 14.5 MPa and ambient pressure of 6 MPa. As can be observed, the waveform of impact pressure shows obvious pulsation, which indicates that the organ-pipe nozzle can effectively modulate the continuous SCO₂ jet into a pulsed jet. According to previous studies, this pressure fluctuation is caused by the combined action of self-resonance occurring in the oscillation chamber of organ pipe nozzle, jet shear-layer instability in the external flow field, changes in physical properties of carbon dioxide, and possible phase transition of carbon dioxide fluid.

![Typical axial impact pressure fluctuation in time domain.](image)

**Figure 4.** Typical axial impact pressure fluctuation in time domain. Experimental conditions: \(P_{\text{in}} = 14.5\) MPa, \(P_a= 6\) MPa, \(L_c/D = 8\).

The dimensionless peak impact pressure \((P_m)\), pressure ratio \((P_r)\), and pressure oscillation intensity \((P_o)\) were used as the evaluation indexes to quantitatively evaluate the impact pressure oscillation characteristics of SEOSJs. To combine the effects of pressure difference and ambient pressure, the dimensionless peak impact pressure is used to compare the pressure oscillation peaks of SEOSJs achieved under different ambient pressures and is defined as follows:

\[
P_m = \frac{\bar{P}_{\text{max}} - P_a}{P_{\text{in}} - P_a}
\]

(1)

where \(\bar{P}_{\text{max}}\) is the average value of the peak pressures, \(P_{\text{in}}\) is the inlet pressure, and \(P_a\) is the ambient pressure.

Moreover, the pressure ratio directly reflects the enhancement extent of the peak impact pressure of the SEOSJ with respect to the inlet pressure and is given as follows:

\[
P_r = \frac{\bar{P}_{\text{max}}}{P_{\text{in}}}
\]

(2)

The intensity of the pressure oscillation is described by the root mean square (RMS) value of the instantaneous impinging pressure and takes the following form:

\[
P_{\text{rms}} = \sqrt{\frac{\sum_{i=1}^{N} (P_i - \bar{P})^2}{N}}
\]

(3)

where \(P_i\) is the instantaneous pressure and \(N\) is the sample number. \(\bar{P}\) is the mean pressure and can be expressed as follows:

\[
\bar{P} = \frac{1}{N} \sum_{i=1}^{N} P_i
\]

(4)
The depth and area of the erosion crater and mass loss of the specimen were used to evaluate the erosion ability of the SEOSJ on sandstone. The erosion depth was the distance from the top plane to the deepest point of the crater, measured with a specially designed vernier caliper. The area of the irregular erosion crater was determined in AutoCAD by calculating the area enclosed by the crater envelope. The adsorbed water and CO\textsubscript{2} were eliminated by drying the specimens in an oven for 6 h at 80 °C, and then the mass difference of the specimen before and after the erosion test was recorded as the mass loss.

3. Results and Discussion

3.1. Pressure Oscillation Peak

In practical applications, higher peak impact pressure of the pulsed jet can produce greater impact force and enhance rock erosion efficiency. Therefore, the pressure oscillation peaks achieved by different nozzles are first compared. Figure 5 shows the variations of the dimensionless peak impact pressure ($P_m$) and pressure ratio ($P_r$) with the dimensionless oscillation chamber length ($L_c/D$). The inlet pressures ($P_{in}$) were tested from 10 to 18.5 MPa, and the ambient pressures ($P_a$) were kept at 8.5 MPa (above the critical pressure) and 6 MPa (below the critical pressure), respectively. For $5 \leq L_c/D \leq 11$, the peak impact pressure curves all show the same tendency to first increase and then decrease with increasing chamber length for all tested working conditions. Under each working condition, there exists an optimal chamber length to maximize the dimensionless peak impact pressure. The maximum values of $P_m$ corresponding to the pressure differences of 4, 7, and 10 MPa are 1.41, 1.28, and 1.17 in SCO\textsubscript{2} ambient fluid and 1.42, 1.27, and 1.17 in GCO\textsubscript{2} ambient fluid, respectively. It is found that the dimensionless peak impact pressure of the SEOSJ is lower at higher pressure difference in both ambient fluids. Moreover, for both ambient conditions, the corresponding optimal chamber length shows a decreasing trend as the pressure difference increases. The optimal dimensionless chamber length in SCO\textsubscript{2} is found to be slightly shorter than that in GCO\textsubscript{2} under the same pressure difference. In addition, although the organ-pipe nozzle can enhance the pulsation of jet impact pressure, the average peak pressure does not always surpass the inlet pressure. For nozzles with chamber length close to the optimal value, the pressure ratio is greater than one. However, when the chamber length is out of the proper range, the organ-pipe nozzles result in relatively low impact pressure and the peak impact pressure can hardly exceed the inlet pressure. When the high speed SCO\textsubscript{2} fluid flows through the oscillation chamber, the initial excitation formed near the nozzle exit is fed back to the chamber by the exit contraction section. If the chamber length is too short, the interference between the reflected pressure wave and the incoming flow is too intense, which may chock the oscillation chamber, thus increasing the energy dissipation inside the chamber. An excessively long oscillation chamber length can trigger self-excited oscillation at higher mode number under a particular working condition, but the intensity of the exiting SEOSJ flow is weaker. This indicates that a suitable value of $L_c$ acts as an important role in augmenting the axial impact pressure peak.

Figure 6 shows the variations of dimensionless peak impact pressure $P_m$ and pressure ratio $P_r$ with pressure difference $\Delta P$ for nozzles with optimal chamber lengths at each pressure difference. It is seen that the dimensionless peak impact pressure decreases gradually with the increase of pressure difference under both ambient conditions, and the values of $P_m$ in two ambient conditions at the same pressure difference are similar. As the pressure difference increases, the pressure ratio also tends to decrease gradually, and for a given pressure difference, the $P_m$ of the SEOSJ is always higher in GCO\textsubscript{2} ambient fluid. When $\Delta P = 4$ MPa, the average peak pressure reaches 1.17 and 1.13 times of the inlet pressure in SCO\textsubscript{2} and in GCO\textsubscript{2}, respectively; but when $\Delta P = 10$ MPa, the average peak pressure is only 1.11 and 1.09 times of the inlet pressure in SCO\textsubscript{2} and in GCO\textsubscript{2}, respectively. This demonstrates that with the increase of the pressure difference, the enhancement extent of the peak impact pressure of the SEOSJ generated by the organ-pipe nozzle relative to the inlet pressure decreases. These findings agree with those of Li et al. [39] who reported that the pressure ratio of a self-excited cavitating water jet (SECWJ) produced by organ-
pipe nozzle first increases and then decreases with the increase of chamber length, while decreasing monotonously with increasing inlet pressure. Since some mechanisms involved in the SECWJ are similar to those of the SEOSJ, the experimental results are verified to a certain extent.

Figure 5. Dimensionless peak impact pressure and pressure ratio as a function of the chamber length: (a) in GCO2 and (b) in SCO2. Experimental conditions: ΔP = 4–10 MPa, 5 ≤ Lc/D ≤ 11, and Pa = 6 or 8.5 MPa.

Figure 6. Variations of dimensionless peak impact pressure and pressure ratio with increasing pressure difference. Experimental conditions: ΔP = 4–10 MPa, 7 ≤ Lc/D ≤ 11, and Pa = 6 or 8.5 MPa.

3.2. Intensity of Pressure Oscillation

Impact pressure oscillation is an essential issue of a pulsed jet as it defines how the target material is loaded. Since pressure pulsation can mitigate the water cushion effect and produce water hammering, it can be expected that violent pressure oscillation would greatly improve the material damage ability. Figure 7 shows the pressure oscillation intensity of SEOSJs as a function of the chamber length at three pressure differences under two ambient fluid states. It is observed in the figure that the length of the oscillation chamber can dramatically affect the performance of the SEOSJ, and the difference between pressure oscillation intensity of SEOSJs exiting in different ambient fluids is obvious. As shown in Figure 7, the pressure oscillation intensity of SEOSJs under all the tested conditions displays the similar tendency to first increase to a maximum value and then decay gradually with the increase of chamber length. It is found that the organ-pipe nozzle with the chamber length that leads to the maximum peak impact pressure always produces the most violent pressure oscillation under each pressure difference. The pressure oscillation intensity of the SEOSJ is more sensitive to the chamber length in GCO2 ambient fluid. When the chamber length deviates from the optimal value, the Prms value drops more rapidly in GCO2 than in SCO2. Moreover, it can be observed in the figure that under SCO2 ambient condition, the three Prms curves are more scattered from each other and the difference between the maximum Prms values under different pressure differences is also greater.
Figure 7. RMS value of impact pressure as a function of the chamber length: (a) in GCO₂ and (b) in SCO₂. Experimental conditions: ΔP = 4–10 MPa, 5 ≤ Lc/D ≤ 11, and Pa = 6 or 8.5 MPa.

Figure 8 compares the maximum pressure oscillation intensity of the SEOSJ under different pressure differences when exiting in SCO₂ and in GCO₂. It is seen that for both ambient conditions, the value of P_{rms} increases monotonously with the increase of pressure difference while the rate of increase decreases gradually with increasing pressure difference. This behavior is attributable to the fact that the local energy loss when the SCO₂ fluid flows through the organ-pipe nozzle with abrupt cross-section change is larger at higher pressure difference, and the large-scale vortex rings with high vorticity may attenuate the pressure pulsation near the jet axis due to the enhanced entrainment ability of the jet with higher kinetic energy for the stagnant ambient fluid. Moreover, it is seen that the P_{rms} of the SEOSJ is always higher when exiting in SCO₂ than in GCO₂ under a given pressure difference, and the gap between P_{rms} values for two ambient conditions appears to widen gradually as the pressure difference increases.

Figure 8. Variations of the pressure oscillation intension with increasing pressure difference. Experimental conditions: ΔP = 4–10 MPa, 7 ≤ Lc/D ≤ 9, and Pa = 6 or 8.5 MPa.

3.3. Oscillation Frequency

The time-resolved pressure signal is transformed into the frequency-resolved one by fast Fourier transform (FFT), thus determining the frequency characteristics of SEOSJs. A typical frequency spectrum of impact pressure of the SEOSJ generated by the organ-pipe nozzle with dimensionless oscillation chamber length of 8 at inlet pressure of 15.5 MPa
is shown in Figure 9. It can be found from the figure that the frequency characteristics of the self-excited oscillation jet are complex. There are three obvious peaks in the frequency spectrum of the impact pressure, and the amplitude of the three peaks decrease with the increase of frequency. The observed frequency characteristics are mainly the consequence of jet shear layer instability, resonance effect, and pressure feedback mechanism, which in turn depend on the physical properties of SCO₂ fluid, the nozzle configuration, the generation and shedding of vortices, and the propagation of disturbance wave. In this paper, the oscillation frequency with the maximum amplitude is defined as the dominant frequency of the SCO₂ jet ejected from the organ-pipe nozzle.

![Figure 9](image)

**Figure 9.** Typical frequency spectrum distribution of the impact pressure. Experimental conditions: $P_{\text{in}} = 15.5$ MPa and $L_c/D = 8$.

Figure 10 shows the variation of dominant frequency of the SEOSJ with oscillation chamber length and pressure difference. It is observed that the dominant frequency shows the feature of decreasing monotonously with the increase of oscillation chamber length at a fixed pressure difference under both ambient conditions. This phenomenon can be explained by the fact that the pressure waves produced at the downstream contraction when the SEOSJ passing through the nozzle travels a shorter distance to interact with the incoming flow and vortexes generated at the upstream contraction. Specifically, the pressure wave takes less time to feed back the downstream disturbance to the upstream jet in a shorter oscillation chamber.

![Figure 10](image)

**Figure 10.** Variations of dominant oscillation frequency: (a) with the chamber length and (b) with the pressure difference. Experimental conditions: $\Delta P = 4$–10 MPa, $5 \leq L_c/D \leq 11$, and $P_a = 6$ or 8.5 MPa.
It is seen from Figure 10b that the dominant frequency of impact pressure increases continuously with the increase of pressure difference when the length of the oscillation chamber remains constant. This trend is mainly attributed to two factors: the speed of vortex generation and shedding is increased due to the enhanced jet kinetic energy; the pressure fluctuation intensity and the Kelvin–Helmholtz instability are also strengthened under higher pressure difference. It is also seen from Figure 10b that the dominant frequency has a higher increasing rate with pressure difference in SCO$_2$ ambient fluid. Moreover, as shown in Figure 10, the ambient fluid state has obvious effects on the dominant frequency of the SEOSJ flows. The dominant frequency of the SEOSJ in SCO$_2$ ambient fluid is always higher than that in GCO$_2$ ambient fluid for a given chamber length under the same pressure difference. Because part of the SCO$_2$ phase transition into GCO$_2$, the SEOSJ exited in GCO$_2$ is a two-phase flow, and the sound speed within the jet can be much lower than that in SCO$_2$, which greatly slows the feedback of the pressure wave. It can be concluded that the frequency of the SEOSJ can be adjusted by changing the structural parameters of the organ-pipe nozzle and the operating pressure.

3.4. Rock Erosion Performance of SEOSJs

In this section, the rock erosion performance of SEOSJs generated by organ-pipe nozzles with different oscillation chamber lengths under two ambient conditions was studied. Figure 11 shows the macroscopic appearances of rock specimens eroded by SEOSJs under a pressure difference of 10 MPa at a dimensional standoff distance of 6. The damage patterns due to SEOSJ impingement on the red sandstones appear similar. Under both ambient conditions, the specimens were eroded in a “drilling-type damage” method and regular deep erosion craters were formed in the samples with the area of jet erosion zone larger under GCO$_2$ ambient condition for a given chamber length.

Figure 12 illustrates the variation in the corresponding erosion depth, erosion area, and mass loss with the dimensionless oscillation chamber length. As shown, the effect of the chamber length and the ambient fluid state on the rock erosion performance of SEOSJs is substantial. The erosion depth increases at first and then reduces gradually with the
increase of oscillation chamber length. When the pressure difference across the jet nozzle is held constant at 10 MPa, the maximal erosion depths of the erosion craters in SCO$_2$ and in GCO$_2$ are found at $L_c/D = 7$ and 8, respectively. This corresponds well to the optimal nozzle configurations observed in the pressure oscillation analysis, which demonstrates that impact pressure peak and pressure oscillation intensity of SEOSJs are closely related to its the rock breaking ability. The SEOSJ is more efficient in producing a deeper erosion hole for all chamber lengths when operated in SCO$_2$ ambient fluid. It is observed that the maximum erosion depth caused by the SEOSJ in SCO$_2$ is 1.17 times that by the SEOSJ in GCO$_2$. When the rock samples are eroded in SCO$_2$, higher ambient pressure increases the rock strength, but the increase in the density of SCO$_2$ fluid due to higher inlet pressure leads to greater mass flow rate and dynamic pressure of the jet, which improves the jet impact force. For the experiments where the SEOSJ exits from GCO$_2$, although the SCO$_2$ fluid may keep supercritical state at small standoff distance, as erosion crater deepens the SCO$_2$ will phase transition into the gaseous state in the external flow field. It can be expected that the erosion capability of the jet far from the nozzle exit would be greatly undermined.

![Figure 12](image)

Figure 12. (a) the variation in erosion depth and erosion area with the oscillation chamber length, and (b) the variation in mass loss with the oscillation chamber length. Experimental conditions: $\Delta P = 10$ MPa, $5 \leq L_c/D \leq 11$, and $P_a = 6$ or 8.5 MPa. It can be observed that under a particular ambient condition the variation of erosion area with the chamber length is relatively small. This indicates that the effective jet diameters exiting from the tested nozzles with the same nozzle exit structure are similar. Moreover, at a given chamber length, the open area of the erosion crater eroded in GCO$_2$ is larger than that in SCO$_2$. This phenomenon could seek explanations from flow characteristics of SEOSJs in different ambient fluids. With the ambient pressure below the critical point, the jet is more divergent in GCO$_2$ than that in SCO$_2$, consequently increasing the impact area of the jet on the rock sample. Moreover, the more intense radial expansion of the SEOSJ under subcritical pressure can exert additional normal stress on the sidewall of the erosion crater, which leads to tensile and shear failure of the specimen, thereby promoting a larger diameter of the erosion crater.

The behavior of the mass loss as a function of the dimensionless chamber length shows a similar trend to that of the erosion depth. The SEOSJ produced by the same nozzle results in higher mass loss in SCO$_2$ ambient fluid, except for erosion test with $L_c/D = 11$. Combined with the results obtained in Sections 3.1 and 3.2, the optimal chamber length that produces the highest impact pressure peak and the strongest pressure oscillation always causes the largest erosion depth and mass loss, but the maximum erosion area does not correspond to it. This demonstrates that the axial impact pressure characteristics play a decisive role in the depth of the erosion crater, while the erosion area also depends on factors such as jet expansion and radial velocity distribution.
4. Conclusions

To further improve the drilling efficiency of SCO\textsubscript{2} jet-assisted drilling, organ-pipe nozzles were applied to generate SEOSJs. Impact load measurements and rock erosion tests were conducted to investigate the impact pressure fluctuation characteristics and rock erosion ability of the SEOSJ. The effects of nozzle structure size and pressure difference on the impingement characteristics of SEOSJs under supercritical and subcritical ambient pressures were researched. The performances of SEOSJs generated by organ-pipe nozzles with different chamber lengths were evaluated using statistical data of impact pressure oscillations and erosion crater size. The following conclusions were drawn.

1. The impact performance of the SEOSJ is conditioned by the oscillation chamber length of organ-pipe nozzle. Under a particular working condition, there exists an optimal chamber length leading to the highest peak impact pressure and the most violent pressure oscillation. The optimal chamber length in SCO\textsubscript{2} is slightly shorter than that in GCO\textsubscript{2} under the same pressure difference. The most efficient SEOSJ is found to occur when \( L_c/D = 7–9 \) under the tested experimental conditions.

2. When the oscillation chamber length remains constant, the dimensionless peak impact pressure \( P_m \) and the pressure ratio \( P_r \) decrease, but the pressure oscillation intensity \( P_{rms} \) increases with increasing pressure difference. Under the same pressure difference, the SEOSJ exited in SCO\textsubscript{2} has higher \( P_m \) and \( P_{rms} \) as compared to that in GCO\textsubscript{2}.

3. The dominant frequency of the SEOSJ decreases with the increase of oscillation chamber length but increases with the increase of pressure difference. When other conditions remain unchanged, the dominant frequency of the SEOSJ exited in SCO\textsubscript{2} is higher than in GCO\textsubscript{2}.

4. The SEOSJ leads to a deeper and narrower erosion crater in SCO\textsubscript{2} for a given working condition. There is a strong correlation between the rock breaking ability of the SEOSJ and its impact pressure characteristics. The nozzle that produces the highest impact pressure peak and pressure oscillation intensity always causes the largest rock erosion depth and mass loss.

The results obtained enable optimize the organ-pipe nozzle configurations according to practical operating pressures and ambient condition, and improve the rock-breaking ability and the industrial utilization performance of the SEOSJ.

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