INTRODUCTION

The increasing demand for petroleum and natural gas resources around the world substantially promotes the exploration and development of deep sea and deep ground resources. The drilling process accounts for up to one-third of the well-construction period and over half the development cost of conventional depth (<5000 m) wells. The strength.

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hardness, and abrasiveness of the rock increase as the well depth increases, resulting in poorer drilling ability, lower penetration rate, longer drilling cycles, and higher cost.\textsuperscript{1,2} Therefore, it is urgent to seek available cost-effective rock-breaking methods for improving the penetration rate in hard formations of deep wells.\textsuperscript{3,4}

A high-pressure waterjet is considered one of the most promising assisted rock-breaking technologies.\textsuperscript{5} To overcome the problem of tool wear caused by high pressure and take full advantage of hydraulic energy at the bottom, several types of waterjets, including pulsed,\textsuperscript{6} cavitating,\textsuperscript{7} and abrasive waterjets,\textsuperscript{8} have been proposed. Compared with different types of pure waterjets, waterjets with abrasive particles can break harder rock. The most commonly used abrasive particles include garnet and quartz with diameters ranging from 0.06 to 0.3 mm, and the abrasive particles are irregular shaped. The abrasive characteristics may lead to pipe and nozzle wear. Particularly, spherical steel balls with a greater diameter (ranging from 0.5 to 5 mm) and lower particle volume concentration (ranging from 0.5% to 5%) are used as abrasive particles added to waterjets proposed by Curlett et al.\textsuperscript{9} The experimental results indicated that the rock-breaking volume by a steel ball jet is three to four times that by a pure waterjet under identical conditions.\textsuperscript{10,11} The particle jet is essentially a particular case of the abrasive jets which grind the tools less. Most past studies have focused on the rock-breaking efficiency, the factors of the abrasive jet, and the injection manner of the abrasive.\textsuperscript{12-17} The cutting volume and depth efficiency tend to increase with increasing water pressure and traverse speed and are strongly dependent on the standoff distance.\textsuperscript{18} Compared with pure waterjets, the drilling depth of abrasive jets increases by 63% and the thrust force and torque decrease by 15% and 20%, respectively.\textsuperscript{19} The erosion volume of a particle is linearly proportional to its kinetic energy.\textsuperscript{20} As the extent of strain exceeds the elastic limit, the impacting solid particles skid over the surface. The threshold strain is a function of the impact and rotating velocity and the particle surface contact time.\textsuperscript{21} In addition, the reason for rock breaking has been studied by many scholars,\textsuperscript{22-24} and tensile fracture caused by the shock pressure wave of abrasion was the main reason for the rock breaking.\textsuperscript{25,26}

According to the high-efficiency rock-breaking characteristics of particle jets and inspired by projectile impact rock breaking, Curlett et al\textsuperscript{9} proposed particle impact drilling (PID) technology. Field tests in Utah, and Texas, USA, and in the Sichuan Basin, China, showed that the PID technology is an efficient rock-breaking technology for hard rock buried in the deep sea and ground.\textsuperscript{27-32} However, the PID technique requires complicated supporting facilities on the ground compared with conventional drilling, including a particle injection system, a specially made drill bit and a particle recycling and clarification system, which restricted the application of PID technology. In view of this limitation, Wang et al proposed a new type abrasive jet-assisted rock-breaking drilling method using the cuttings as the abrasive material and modulating the cuttings jet directly in the bottom hole.\textsuperscript{33} Figure 1 shows the structure of the cuttings jet modulation tool and its drilling procedure. The modulation tool is mounted between the drill bit and the drill collar during drilling. The drilling fluid is pumped into the drill-string, is ejected out of the nozzles on the drill bit, and circulates back to the ground in the annulus between drill string and formation or casing pipe. When the drilling fluid flows through the Helmholtz oscillating cavity\textsuperscript{34} of the tool, self-excited oscillation will be induced, and a pressure difference between the internal and external cavity will be generated. Then, part of the cuttings in the annulus will first be drawn into the cavity through the two symmetrical suction ports; the surplus cuttings continue to circulate with the drilling fluid and are discarded from the mainstream when they flow through the solid control equipment on the ground. The cuttings sucked into the self-excited oscillation cavity are accelerated and then ejected out of the drill bit nozzles impacting the bottom hole rock. Different from PID technology, ground particle processing equipment is not required and the field drilling process does not need to change. Simultaneously, a small quantity of other abrasives (such as steel balls) can also be intermittently added into the drill string from the wellhead during pipe connection, which greatly reduces the consumption of steel particles and makes large-scale industrial applications possible.

Whether the abrasives can be sucked into the Helmholtz oscillating cavity (ie, the modulation mechanism of abrasives)
and whether the waterjet with abrasives can break rocks are two key issues of this technology discussed in this paper. First, the particle jet modulation mechanism is studied by numerical simulation. The volume fraction distribution of the particle phase, the suction process, trajectory, and outlet velocity amplitude of a single particle are obtained. The influences of particle diameter, particle density, confining pressure and pump pressure on the trajectory, and outlet velocity amplitude of a particle were also studied. Second, the rock-breaking experiments with different particle types, including cuttings, steel balls, steel emery, garnet, and silicon carbide, were carried out. The influences of particle type, particle concentration, and confining pressure on rock-breaking volume and depth were researched. The influences of standoff distance, steel ball diameter, steel ball concentration, and pump pressure on rock-breaking volume were also studied as a contrast. The results show that the all particle types could be drawn into the Helmholtz oscillating cavity and accelerated to considerable velocity amplitude to impact rock. The rock-breaking efficiency of pure cuttings is lower than that of fractional cuttings (ie, 50% cuttings and 50% steel ball) and pure steel balls, but do not affect it is an effective assisted rock-breaking method.

2 | MODULATION MECHANISM SIMULATION

2.1 | Numerical model

The mixture multiphase flow model and discrete phase model in Fluent software, which follow the Euler-Lagrange approach and the Euler-Euler approach, respectively, were used to calculate the multiphase flow fields of the cuttings jet modulation tool and the particle trajectories. The mixture multiphase flow model needed to solve the continuity and momentum equations for the mixture, volume fraction equation for the secondary phase, and algebraic expressions for the relative velocities. The continuity and momentum equations for the mixture are:

\[
\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = 0
\]  

(1)

\[
\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_k}{\rho_m}
\]

(2)

\[
\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k
\]

(3)

\[
\frac{\partial}{\partial t} (\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot \left[ \mu_m \left( \nabla \vec{v}_m + \nabla \vec{v}_m^T \right) \right] + \rho_m \vec{g} + \vec{F} - \nabla \cdot \left( \sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k} \right)
\]

(4)
\[
\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k
\]

where \( \vec{v}_m \) is the mass-averaged velocity; \( \rho_m \) is the mixture density; \( \alpha_k \) is the volume fraction of phase \( k \); \( \rho_k \) is the density of phase \( k \); and \( n \) is the number of phases; \( p \) is the static pressure; \( \rho_m \vec{g} \) and \( \vec{F} \) are the gravitational body force and external body force, respectively; \( \mu_m \) is the viscosity of the mixture;

FIGURE 5  Volume fraction of a particle phase at different times: (A) 1.5 s, (B) 1.6 s, (C) 1.7 s, (D) 1.8 s, (E) 1.9 s, and (F) 2.0 s
\( \mu_m \left( \nabla \bar{v}_m + \nabla \bar{v}_m^T \right) \) is the viscous stress tensor; \( \mu_k \) is the viscosity of phase \( k \); \( \bar{v}_k \) is the velocity of phase \( k \); and \( \bar{v}_{dr,k} \) is the drift velocity for secondary phase \( k \).

The standard \( k-\varepsilon \) model was adopted to illustrate the turbulence and close the Navier-Stokes equation. The turbulence kinetic energy \( k \) and its rate of dissipation \( \varepsilon \) in the standard \( k-\varepsilon \) model are obtained from the following transport equations:

\[
\begin{align*}
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} & = \tau_{ij} S_{ij} - \rho \varepsilon + \phi_k \\
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_j \varepsilon)}{\partial x_j} & = 1.45 \frac{\varepsilon}{k} \tau_{ij} S_{ij} - 1.92 f_2 \rho \varepsilon^2 k + \phi_\varepsilon
\end{align*}
\]

where the Reynolds stress \( \tau_{ij} = 2 \mu \left( S_{ij} - \frac{S_{ij}}{3} \right) - 2 \rho k \delta_{ij} / 3, \)  

\( \mu \) is the dynamic viscosity; \( \mu_t \) is the eddy viscosity, \( \mu_t = 0.09 f_u \rho k^2 / \varepsilon \); \( \rho \) is the fluid density; and \( x \) is the axial coordinate. The near wall attenuation functions are given as \( f_u = e^{-3.4/(1+0.02 Re)} \) and \( f_2 = 1 - 0.3 e^{-Re_i} \), where \( Re_i = \frac{u_i}{\mu} \).

The wall terms are given as \( \phi_k = 2 \mu \left( \frac{\partial^2 y}{\partial y^2} \right)^2 \) and \( \phi_\varepsilon = 2 \mu \frac{\mu}{\rho} \left( \frac{\partial u_j}{\partial y} \right)^2 \); \( u_i \) is the flow velocity parallel to the wall.

\( S_{ij} \) is the mean-velocity strain-rate tensor, and \( \delta_{ij} \) is the Kronecker delta.

The drift velocity and relative velocity \( \bar{v}_{pq} \) are connected by the following expression:

\[
\bar{v}_{dr,p} = \bar{v}_{pq} - \sum_{k=1}^{n} \frac{\alpha_k \rho_k}{\rho_m} \bar{v}_{kq}
\]

\[
\bar{v}_{pq} = \frac{\tau_p}{f_{\text{drag}}} \left( \frac{\rho_p - \rho_m}{\rho_p} \right) \bar{a}
\]

\[
\tau_p = \frac{\rho_p d_p^2}{18 \mu_q}
\]

\[
f_{\text{drag}} = \begin{cases} 1 + 0.15 Re^{0.687} & (Re \leq 1000) \\ 0.0183 Re & (Re > 1000) \end{cases}
\]

where \( \bar{v}_{pq} \) is the velocity of a secondary phase \( (p) \) relative to the primary phase \( (q) \); \( \bar{v}_{kq} \) is the velocity of phase \( k \) relative
FIGURE 7 Trajectories and residence times of single particles with different diameters.
to phase \( q \); \( \tau_p \) is the particle relaxation time; \( d \) is the diameter of the bubbles (or droplets or particles) of secondary phase \( p \); and \( \ddot{a} \) is the acceleration of the secondary phase, m/s\(^2\); \( \tau_p \) is the relaxation time of a dispersed bubble, s; and \( f_{\text{drag}} \) is the drag function.

The volume fraction equation for secondary phase \( p \) can be obtained from its continuity equation:

\[
\frac{\partial}{\partial t} \left( \alpha_p \rho_p \right) + \nabla \cdot \left( \alpha_p \rho_p \vec{v}_p \right) = -\nabla \cdot \left( \alpha_p \rho_p \vec{v}_{dr,p} \right) \tag{14}
\]

where \( \alpha_p \) is the volume fraction of the dispersed phase. The drift velocity \( \vec{v}_{dr,p} \) is given by \( \vec{v}_{dr,p} = \vec{v}_p - \vec{v}_m \).

After the flow field is calculated using the “mixture model,” the “discrete phase model” is used to calculate the particle trajectory. The fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles through the calculated flow field. The dispersed phase can exchange momentum, mass, and energy with the fluid phase. The particle trajectories are computed individually at specified intervals during the fluid phase calculation. The trajectory of a discrete phase particle is predicted by integrating the force balance on the particle in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written as:

\[
\frac{d\vec{u}_p}{dt} = \frac{\ddot{\vec{a}} - \vec{u}_p}{\tau_p} + \frac{\ddot{\vec{a}}}{\rho_p} \left( \rho_p - \rho \right) + \vec{F} \tag{15}
\]

\[
\tau_p = \frac{\rho_p d_p^2}{18 \mu} \frac{24}{C_d \text{Re}} \tag{16}
\]

where \( \vec{F} \) is an additional acceleration (force/unit particle mass) term; \( \frac{\ddot{\vec{a}}}{\tau_p} \) is the drag force per unit particle mass; \( \tau_p \) is the particle relaxation time; \( \ddot{\vec{a}} \) is the fluid phase velocity, \( \vec{u}_p \) is the particle velocity, \( \mu \) is the molecular viscosity of the fluid, \( \rho \) is the fluid density, \( \rho_p \) is the density of the particle, and \( d_p \) is the particle diameter; \( \text{Re} \) is the relative Reynolds number.

Additional forces \( \vec{F} \) in the particle force balance that can be important under special circumstances. These additional forces include the virtual mass and pressure gradient forces (which are not important when the density of the fluid is much lower than the density of the particles), forces on particles that arise due to rotation of the reference frame, the Brownian and Saffman’s lift forces (for which are for sub-micron particles), and the Magnus or rotational lift force.

### 2.2 Physical model and boundary conditions

The structure parameters of a self-excited oscillation cavity are shown in Figure 2. The diameters of the inlet \( (d_1) \), upper nozzle \( (d_1') \), lower nozzle \( (d_3) \), and inlet 2 \( (d_3') \) are, respectively, 62, 5, 9, and 6 mm. The diameter \( (D) \) and length \( (L) \) of the self-excited oscillation cavity are 55 and 45 mm, respectively. The lengths of \( L_1, L_2, L_3, \) and \( L_4 \) are 128, 8, 11, and 175 mm, respectively. The position \( (H) \) of inlet 2 equals 15 mm. Considering the symmetry of the modulation tool, take one half as computing area and use a polyhedron for mesh division and add a boundary layer. The total number of grids is 710,501 (see Figure 3).

A pressure boundary that is equal to the pump pressure is adopted for inlet 1 \( (P = 15 \text{ MPa}) \). A pressure boundary that is equal to atmosphere pressure is adopted for inlet 2 and the outlet. The wall condition is determined by the wall function method, and the solid surface adopts the non-slip boundary condition. The main fluid parameters during simulation include the following: the main phase is water, whose density and dynamic viscosity are 1000 kg/m\(^3\) and 1.005 \times 10\(^{-3}\) Pa·s, respectively, and the second phase is particle flow, whose density and dynamic viscosity are 2500 kg/m\(^3\) and 10 Pa·s, respectively. The particle phase is drawn from inlet 2 with diameter and volume fraction of 0.5 mm and 20%, respectively. The confining pressure equals zero.

### 2.3 Suction and volume fraction distribution of particle phase

The pressure field of a self-excited oscillation cavity can be divided into four zones (as shown in Figure 4): (a) the upper nozzle outlet low-pressure zone, (b) the gasified low-pressure zone, (c) the boundary negative-pressure zone, and (d)
the collision high-pressure zone. As shown in Figure 4, a pair
of vortex rings forms symmetrically in Zone 2. The pressure
and size of the vortex rings change periodically, and the jet
near the axis is dampened periodically. Under the effect
of the pressure difference between the ambient pressure and the
pressure of Zone 2, the cuttings are sucked into a self-excited
oscillation cavity from the annular, and a cutting-based par-
ticle jet is formed. Because of the formation of Zone 2, the
flow rate of the fluid near the upper nozzle increases and the
upper nozzle outlet low-pressure zone (Zone 1) is formed.
The flow rate of the fluid near the lower nozzle decreases, es-
pecially when the fluid is about to flow into the lower nozzle.

As a result, the collision high-pressure zone is formed (Zone
4).

Figure 5 shows the particle suction process and volume
fraction distribution change of particle phase. From Figure
5, a particle phase (ie, cuttings) is continually sucked into
the cavity from the suction ports and is ejected through
the lower nozzle. Its volume fraction distribution changes
with time, which indicates the self-excited oscillation cav-
ity can feasibly modulate a particle pulsed jet. According
to the particle phase volume fraction, the cavity interior
can be divided into four zones (see Figure 5A), that is, 1
suction port high, 2 upper high, 3 central low, and 4 vortex

**FIGURE 9** Trajectories and residence times of single particles with different density

\[
\rho_p = 1500 \text{ kg/m}^3
\]

\[
\rho_p = 2500 \text{ kg/m}^3
\]

\[
\rho_p = 3500 \text{ kg/m}^3
\]

\[
\rho_p = 7500 \text{ kg/m}^3
\]
ring low concentration areas. The reasons for the above phenomena are as follows: The particle phase is sucked into the cavity and first enters zone 1, which makes a high particle volume fraction. As the flow velocity of zone 3 is the highest, a minute quantity of particles can be drawn into zone 3, and most are retained in zone 2, where they are filled with low-velocity fluid and move downward parallel to the center high-speed jet. Due to the blocking effect of the lower nozzle, part of the central high-speed jet moves against the inner wall of the cavity and a pair of vortex rings are gradually formed. The volume fraction of particles gradually decreases from outside to inside the vortex rings. The volume fraction of the particle phase changes between 2% and 5%, which is the optimum value for rock breaking according to references. However, the changes between 2% and 5%, which is the optimum value vortex rings. The volume fraction of the particle phase gradually decreases from outside to inside the vortex rings. The volume fraction of the particle phase changes between 2% and 5%, which is the optimum value for rock breaking according to references. However, the volume fraction of particle ejected from the lower nozzle is influenced by the cuttings concentration in the annulus, the structure of the self-excited oscillation cavity, the flow rate, and drilling fluid viscosity, which needs further research.

Figure 6 shows liquid and particle flow rate changes along the center axis and radial coordinates of the outlet. From Figure 6(A), the initial fluid flow rate in the cavity is zero (location: 0 mm); the flow rate of the inlet 1 section (location: 0 ~ −150 mm) changes slightly, as it is long and its diameter changes slowly, and the flow rate of water increases rapidly when the location is between −150 and −220 mm, corresponding to the converging portion between the upper nozzle and cavity as the open area decreases suddenly. Meanwhile, the particles are sucked into the tool chamber from the inlet due to the pressure difference between the internal and external cavity and accelerated to the maximum in a very short time, which is close to the flow rate of water; the flow rate difference between particles and water remains constant from then on. When the location is between −220 and −260 mm, the flow rate of particles decreases quickly. This effect occurs because the self-oscillation vortex rings generated in the cavity consume a large part of the energy, which makes the kinetic energy and flow rate of liquid and particles decrease based on the energy conservation principle. When the coordinate in the center axis is below −260 mm, which corresponds to the outlet section, the flow rates of the two phases stay constant. From Figure 6(B), the flow rates of liquid and particle phases are both zero when the radial coordinates are −0.0045 and +0.0045 m, which corresponds to the cavity wall, due to the assumption that the wall condition is nonslip during simulation. The flow rates of the liquid and particle phases increase exponentially when the radial coordinates are between −0.0045 and −0.003 m. The flow rates of both phases remain at approximately 50 m/s and change slightly when the radial coordinates are between −0.003 and 0.003 m.

### 2.4 Factors influencing waterjet performance

The two-phase flow field numerical simulation of the self-excited oscillation cavity found that a pair of primary vortex rings can be formed in the cavity due to the entrainment of the jet under given conditions, resulting in a pressure difference inside and outside of the suction ports. Then, a particle phase can be drawn into the cavity through the suction ports and mixed with the high-speed liquid flow, accelerated, and finally ejected with the outlet forming particle jet. However, the modulation of the particle jet is affected by many factors. Herein, based on the discrete phase model, the influences of particle diameter and density, and confining and pump pressure on the trajectory, flow rate and residence time of a single particle in the self-excited oscillation are researched to further verify the feasibility of particle attraction, acceleration, and jet modulation. Without special instructions, the default numerical parameters include the following: 15 MPa pump pressure, 2500 kg/m³ particle density, 0 MPa confining pressure, and 10 m/s particle velocity equal to the water in the suction port. The structure parameters of the self-excited oscillation cavity are the same as section 2.2.

1. Influence of particle diameter. Figure 7 shows the trajectory and residence time of single particles with different diameters (including \(d_p = 0.1, 0.5, 1.0, 1.5, 2, \) and 2.5 mm). From Figure 7, the trajectory of the particle becomes simpler, and its residence time decreases with increasing particle diameter due to the weaker turbulence effect. When the particle diameter is small, sufficient acceleration and high mixing efficiency can be achieved, while the probability that a wall surface collision increases and wall surface wear is inevitable, such that extra energy loss is generated. When the particle diameter is larger, the mixing efficiency decreases, and the wall

![Flow rate along path and outlet flow rate of single particles with different density](image-url)
FIGURE 11  Trajectories and residence time of single particles with different confining pressure
surface collision probability and wear both decrease. Figure 8 shows the path length and flow rate change of particles with different diameters. From Figure 8, the path lengths of the particles in the cavity increase first and then decrease with increasing particle diameter. The particle outlet flow rate amplitudes are close at the maximum (approximately 65 m/s) when the particle diameter equals 1.0 mm. The flow rate differences between different diameter particles are due to their mass and inertia differences. It can be seen from the above analysis that although the trajectory and outlet flow rate of particles both change with particle diameter, all these particles can be drawn into the self-oscillation cavity and accelerated.

2. Influence of particle density. Figure 9 shows the trajectory and residence time of single particles with different particle density (including $\rho_p = 1500, 2500, 3500,$ and $7500 \text{ kg/m}^3$). When the particle densities are relatively low, the particle trajectories in the oscillating cavity are complex and the residence time is very long. The reason is that the inertia of low-density particles is small and they are significantly affected by turbulence, which intensifies the fluid acceleration of the particles. The fluidity of high-density particles is poor, and the influence of fluid flow on the particle trajectory is small, which reduce the collision probability between particles and the inner cavity wall. Figure 10 shows the path length and flow rate change of particles with different density. From Figure 10, the path lengths of particles in the cavity decrease with increasing particle density, while the flow rate amplitudes for different density particles are almost the same. The longer the path lengths are, the more severe the collision and abrasion between particle and wall are. Fortunately, particles of different density can all be drawn into the self-oscillation cavity and accelerated to considerable flow rate at the outlet.

3. The influence of confining pressure. Figure 11 shows the trajectory and residence time of a single particle under different confining pressure conditions (including $p_c = 0, 2, 4, 6, 8,$ and $10 \text{ MPa}$). From Figure 11, the particle first enters the center vortex zone after it is drawn into the suction port when the confining pressure equals 0 MPa; then, it oscillates and accelerates with the fluid under the effect of a vortex, enters the high-speed jet zone after its flow rate reaches a certain value, and is ultimately ejected from the outlet. Unlike the condition of $p_c = 0 \text{ MPa}$, the particle enters a high-speed jet zone directly when the confining pressure is not equal to zero, and the particle trajectory under different confining pressure is generally the same. The reason for the above phenomenon is that the internal-external pressure difference of the self-oscillation cavity increases with increasing confining pressure, and the initial particle flow rate also increases, making it easier for the particle to get rid of the central vortex region bondage and directly enter the high-speed jet region. Figure 12 shows the path length and flow rate change of particles under different confining pressure. From Figure 12, the path lengths of particles with confining pressure are much shorter than without confining pressure, and the path lengths of particles under different confining pressures are almost the same. The flow rate of the particle at the outlet increases with the increase in confining pressure. The reason is that increasing confining pressure makes the internal-external pressure difference of the self-oscillation cavity increase. Then, the particle can obtain larger impetus, and increasing confining pressure promotes the generation of a primary vortex ring in the self-oscillation cavity and intensifies the self-excited oscillation in the cavity, resulting in larger outlet flow rate.

4. Influence of pump pressure. Figure 13 shows the trajectory and residence times of single particles under different pump pressure conditions (including $p_p = 6, 9, 12,$ and $18 \text{ MPa}$). From Figure 13, the particle trajectories become simpler, and the residence time decreases with increasing pump pressure. Meanwhile, collisions between particles and the cavity wall decrease with increasing pump pressure. Figure 14 shows the path length and flow rate change of particles under different pump pressure. From Figure 14, the particle path lengths decrease with increasing pump pressure, and the flow rate amplitude at the outlet increases (except for $p_p = 12 \text{ MPa}$). The reason is that the total energy of the whole system increases and the particle energy obtained from fluid increases with increasing pump pressure. The results show that particles can be drawn into the self-oscillation cavity and accelerated to considerable flow rate at the outlet under different pump pressure.
3 | ROCK-BREAKING EXPERIMENT

The numerical simulation in Section 22 shows that particles in the annulus can be drawn into the self-oscillation cavity and accelerated to considerable flow rate at the outlet under different conditions, which verifies the feasibility of particle suction. Another important issue is whether the rock-breaking efficiency is acceptable. In this section, rock-breaking experiments with different particles are carried out to show the feasibility of a cuttings jet modulated directly in the bottom hole from the aspect of rock breaking.

3.1 | Equipment details

The experimental setup is shown in Figure 15, including the drill string with particle jet modulation tool, wellbore, and rock. The self-excited oscillation cavity parameters of the particle jet modulation tool are the same as in Figure 2. When the experiment is performed, water is pumped into the drill string from the left end and is ejected out of the modulation tool and then enters the pool through the annulus between the drill string and wellbore. Particles are arranged in the annulus bottom in advance. The particles will be drawn once the self-oscillation generated in the modulation tool cavity and forming particle jet to break the rock. To simulate submerged conditions, a pressure control valve is mounted.

**FIGURE 13** Trajectories and residence times of single particles with different pump pressures

$p_p = 6 \text{ MPa}$

$p_p = 9 \text{ MPa}$

$p_p = 12 \text{ MPa}$

$p_p = 18 \text{ MPa}$
on the wellbore water outlet to adjust the confining pressure by controlling the open area. The length and inner diameter of the simulation wellbore are 1.55 and 0.16 m, respectively. A centering guide with sieve is mounted on the drill string to keep centered, to restrict particle movement, and to stabilize particle circulation in the bottom hole.

The particles for our experiments include steel balls, steel emery, garnet, silicon carbide, and cuttings (see Figure 16). The density and hardness of the steel balls are 7400 kg/m$^3$ and 56~60 HRC, respectively, and different diameter steel balls (such as 0.8, 1.0, 1.4, 1.7, and 2.0 mm) are used. The cuttings at depth of 2047~2055 m from a well in Shengli Oilfield are adopted for the experiment. These cuttings are mainly composed of quartz and feldspar with diameters mainly ranging from 1.25~2.0 mm (<0.6 mm is 0.58%, 0.6~1.25 mm is 16.86%, and 1.25~2.0 mm is 82.56%). The test rock was prepared from grade G oil well cement and sand at a mass ratio of 1:1 and conserved for thirty days at room temperature (see Figure 17). The uniaxial compressive strength of the cement stone is approximately 30 MPa. The erosion time of each test is approximately one hundred eighty seconds, and each test is repeated over three times under the same conditions to ensure the reliability of the experimental data.

### 3.2 | Rock-breaking efficiency results

#### 3.2.1 | Rock-breaking of steel ball

Figure 18(A) shows the relationship of rock-breaking volume and standoff distance with and without confining pressure. Values of 5, 10, 15, 20, 25, and 30 mm are used for the standoff distance, and the other parameters are $p_p = 15$ MPa, $d_p = 1.7$ mm, and $c_p = 5\%$. From Figure 18(A), the rock-breaking volume increases first and then decreases with increasing standoff distance. The reason for this phenomenon is that the particle jet has not been fully developed when the standoff distance is small, which results in a small impact area on the rock. The interaction between jet and the return flow after impacting the rock strengthens and consumes considerable energy. As the standoff distance increases, the rock breaking increases rapidly because the particle jet is fully developed and the impact area becomes larger. As the standoff distance continuously increases, the jet energy attenuates sharply and the impact force decreases, resulting in decreasing rock-breaking volume but larger impact area. The existence of confining pressure (2 MPa) accelerates the attenuation of jet pressure and results in decreasing rock-breaking volume. However, the confining pressure does not influence the relationship between the rock-breaking effect.

![Figure 14](image1.png)

**Figure 14** Flow rate along path and outlet flow rate of single particles with different pump pressures

![Figure 15](image2.png)

**Figure 15** The rock-breaking experimental equipment
and standoff distance. The optimum values of standoff distance are both 15 mm with and without confining distance under the condition herein.

Figure 18B shows the relationship of rock-breaking volume and steel ball diameter with and without confining pressure. Values of 0.8, 1.0, 1.5, 1.7, and 2.0 mm are used for the steel ball diameters, and the other parameters are \( p_p = 15 \) MPa, \( s = 15 \) mm, and \( c_p = 5\% \). From Figure 18B, the rock-breaking volume markedly increases with increasing steel ball diameter. As the steel ball diameter continuously increases, the particle suction volume decreases as the limitation of the suction port diameter and the energy carried by a single particle decreases and the mass of particles increases, resulting in low rock-breaking efficiency. The existence of confining pressure (2 MPa) accelerates jet dynamic pressure attenuation and results in decreasing rock-breaking volume. The optimum values of steel ball diameter are both 1.7 mm with and without confining distance under 6-mm-diameter suction port.

Figure 18(C) shows the relationship of rock-breaking volume and particle concentration with and without confining pressure. Values of 3, 5, 10, 15, 20, and 25\% are used for particle concentration, and the other parameters are \( p_p = 15 \) MPa, \( s = 15 \) mm, and \( d_p = 1.7 \) mm. From Figure 18(C), the rock-breaking volume increases first and then decreases with increasing steel ball concentration. The reason for this phenomenon is that it takes less energy to suck the particle fluid per unit volume into the self-oscillation cavity and because the particles are easily mixed with the water and can enter the center of the self-oscillation cavity at a lower concentration. In contrast, with an increasing steel ball concentration, the particle suction energy consumption increases, and the collision probability between particles also increases. It is difficult for particles to mix evenly with the water jet, and the rock-breaking effect will gradually weaken as the concentration continues to increase. The optimum values of steel ball concentration are both 15\% with and without confining distance under the conditions herein.
Figure 18(D) shows the relationship of rock-breaking volume and pump pressure with and without confining pressure. Values of 4, 7, 10, 15, 17, and 20 MPa are used for the pump pressure, while the other parameters are $c_p = 5\%$, $s = 15\text{mm}$, and $d_p = 1.7\text{mm}$. From Figure 18(D), the rock-breaking volume continuously increases with increasing pump pressure, and there is a threshold pressure (4 MPa herein) for rock breaking. The reason for this effect is that the particle jet flow rate at the outlet and the impact force on rocks increase with increasing pump pressure. The existence of confining pressure (2 MPa) accelerates the attenuation of jet dynamic pressure and results in decreasing rock-breaking volume.

### 3.2.2 Factors influencing particle waterjet rock breaking

Figure 19 shows the influence of different waterjets (including pure water and five kinds of particles) on rock-breaking efficiency.
efficiency. The experimental parameters are $p_p = 15$ MPa, $c_p = 5\%$, $s = 15$ mm, and $d_p = 1.7$ mm. From Figure 19, we see that steel balls have approximately three times the rock-breaking volume of water, and the higher the hardness and larger the edges and corners of the particles, the stronger the cutting and rock erosion capabilities. The order of rock-breaking ability from high to low is as follows: silicon carbide, garnet, steel emery, steel balls, and cuttings. However, the wear of the modulation tool using these high-hardness and irregular particles is more severe. Therefore, it is important to optimize the particle type and select high wear-resistant materials manufacturing tools to improve modulation tool life. Considering the actual situation on site, cuttings and steel balls are the most suitable particles for modulating particle waterjets.

Figure 20 shows the influence of particle concentration on rock-breaking efficiency. The experimental parameters are $p_p = 15$ MPa, $p_c = 0$ MPa, $s = 15$ mm and $d_p = 1.7$ mm. From Figure 20, we see that the rock-breaking efficiency of steel balls is obviously better than that of cuttings. This result occurs because the hardness and density of steel balls are much higher than cuttings. When steel balls impact the rock surface, they are more likely to concentrate in the central region of the jet due to their higher density, which generates greater rock deformation in a very short time and achieves better rock breaking.

Figure 21 shows the influence of confining pressure on rock-breaking efficiency. The experimental parameters are $p_p = 15$ MPa, $s = 15$ mm, $d_p = 1.7$ mm, and $c_p = 5\%$. From Figure 21, we see that the rock-breaking volume and depth decrease with increasing confining pressure for three particle groups. The gradient of rock-breaking volume and decreasing depth under low confining pressure is higher than under high confining pressure. The reason is that the existence of confining pressure accelerates the attenuation of jet energy and results in decreasing rock-breaking volume and depth.

![Figure 20](image1.png)  
**Figure 20** Effects of particle concentration on rock-breaking efficiency: (A) rock-breaking volume and (B) rock-breaking depth

![Figure 21](image2.png)  
**Figure 21** Effects of confining pressure on rock-breaking efficiency: (A) rock-breaking volume and (B) rock-breaking depth
4 | CONCLUSIONS

The feasibility of a cuttings waterjet directly modulated in the bottom hole is discussed from the aspects of cuttings suction and rock-breaking efficiency. The following conclusions are obtained: (a) The particle phase can be continually sucked into the Helmholtz oscillating cavity with two symmetrical suction ports. The cavity interior is divided into five zones according to the particle volume fractions: suction port high, upper high, central low, and vortex ring low concentration areas. The Helmholtz oscillating cavity acts as a cuttings repository during drilling. The velocities of particles and fluid at the Helmholtz oscillating cavity outlet are almost the same, which indicates that the particles can be adequately accelerated in the cavity. (b) The diameter and density have large influence on the trajectory of particles in the cavity and little influence on the velocity amplitude of particles at the outlet, while the confining and pump pressures have large influence on both the trajectory and velocity amplitudes of particles. This finding indicates that the modulation of particle waterjets using a Helmholtz oscillating cavity has better adaptability to particle parameters than drilling operation parameters. (c) The steel ball rock-breaking experiment results show that the optimum standoff distance, steel ball diameter, and concentration are 15 mm, 1.7 mm, and 15%, respectively. The rock-breaking effect increases with increasing pump pressure and decreasing confining pressure. (d) The order of rock-breaking ability for different particle types from high to low is as follows: silicon carbide, garnet, steel emery, steel balls, and cuttings. The rock-breaking efficiency of cuttings first increases and then decreases with increasing cuttings concentration. There is an optimum value (ie, 15%) under the conditions herein. As the confining pressure increases, the rock-breaking efficiency of cuttings worsens.

NOMENCLATURE

\[ d_p \text{, Particle diameter, mm} \]
\[ \rho_p \text{, Particle density, kg/m}^3 \]
\[ T \text{, Time, s} \]
\[ p_c \text{, Confining pressure, MPa} \]
\[ p_p \text{, Pump pressure, MPa} \]
\[ c_p \text{, Particle concentration, %} \]
\[ s \text{, Jetting distance, mm} \]

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