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Review

Ultrasonic-Assisted Rock-Breaking Technology and Oil and Gas Drilling Applications: A Review

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Abstract: High-efficiency rock-breaking is a problem that has long been studied in the oil- and gas-drilling industry. The successful use of ultrasonic technology in related fields has prompted us to study how to introduce ultrasonic technology into rock-breaking in oil and gas drilling. This paper introduces and discusses the successful cases of ultrasonic breaking technology in related fields, summarizes the three basic forms of ultrasonic action on rocks, namely, resonance, impact and cavitation, expounds the factors and laws that affect ultrasonic-assisted rock-breaking, and summarizes the research results reported in recent years. It is believed that, at present, the application of ultrasonic-assisted rock-breaking technology in the oil- and gas-drilling industry still faces some problems and challenges: first, the downhole high-temperature and high-pressure conditions will affect the effect of ultrasonic-assisted rock-breaking, and the related mechanisms and research are not clear; second, the impact of circulating media on ultrasonic-assisted rock-breaking is not clear; third, the problem of ultrasonic propagation and utilization in the downhole has not been well-solved; fourth, the stability of drilling tools and circulating media caused by high-frequency characteristics has not been well-solved. Therefore, it is suggested to increase research on the mechanism of ultrasonic-assisted rock-breaking with oil- and gas-drilling characteristics and the transmission and utilization of downhole ultrasonic energy in the future, and increase the development of supporting products to support the application of this technology in the oil and gas industry.

Keywords: oil and gas drilling; efficient rock-breaking; rock-breaking in deep well; ultrasonic; resonance-enhanced drilling; percussion rock-breaking; ultrasonic cavitation

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1. Introduction

The deep and ultra-deep oil and gas resources are rich, widely distributed, and occur in various types of reservoirs. In recent years, important breakthroughs have been made in terms of exploration [1]. As of 2008, China had cumulative, proven oil geological reserves exceeding 3×10^{10} barrels; cumulative production exceeded 4.2×10^{9} barrels, the cumulative proven natural gas geological reserves at nearly 5×10^{12} m^3, and cumulative natural gas production exceeded 4.3×10^{11} m^3. A series of deep and ultra-deep large oil and gas fields were successively discovered in the Tarim Basin and the southern margin of the Junggar Basin in Northwest China and the Sichuan Basin in Southwest China. Therefore, the exploitation of deep oil and gas resources is particularly important [2,3]. Due to its high density, high hardness and poor drillability, it is very difficult to drill and break rock. Efficient, deep well-drilling and rock-breaking methods have become a key technology for oil and natural gas exploitation.

Ultrasound is a soundwave with a frequency of greater than 20 kHz, which has the characteristics of a high frequency, short wavelength, long propagation distance, concentrated direction, etc. Its penetrating ability is strong, and it can produce ultrasonic cavitation in liquids [4]. Relevant research results have been widely used in medical, manufacturing, aerospace and other fields, and achieved good results and high economic value. The successful experience and research results regarding ultrasonic application in the above fields also provide a good reference for the oil- and gas-drilling industry, and provide new ideas for the development of efficient rock-breaking methods.

By reviewing the developmental history of ultrasonic-assisted crushing technology, this paper expounds the technical characteristics and evolution of ultrasonic-assisted crushing and the technical basis and advantages of ultrasonic-assisted crushing in the oil and gas industries. Additionally, it summarizes the basic action forms and influences of ultrasonic-assisted rock-breaking. The research status of related factors to the ultrasonic-assisted rock-breaking effect is summarized, and the progress of ultrasonic-assisted rock-breaking laboratory test research in recent years is also summarized. The authors analyze the deficiencies in the current research on ultrasonic-assisted rock-breaking technology and the technical challenges faced by oil- and gas-drilling field applications, and they put forward the future research prospects on ultrasonic-assisted rock-breaking technology, which is to be realized in oil and gas drilling as soon as possible.

2. Development History of Ultrasonic-Assisted Crushing Technology

An ultrasonic wave is a type of mechanical wave that generally produces mechanical effects, thermal effects and electromagnetic effects in the process of propagation in solid media, and cavitation effects in the process of propagation in liquid media [5–7]. With good directionality, it is widely used in auxiliary machining and planetary drilling, as well as oil- and gas-layer plug removal and auxiliary production stimulation.

2.1. Development History of Ultrasonic-Aided Machining Technology

Ultrasonic-assisted processing technology is a processing method that uses ultrasonic high-frequency vibration to make abrasives impact, polish, and hydraulically impact the surface of the workpiece at a high frequency, so that the material is gradually broken and peeled off. This is used for high-hardness and high-brittleness materials that are difficult to process using traditional methods, such as drilling [8].

The original ultrasonic machining-drilling technology (USM) [8–10] only uses the vibration characteristics of an ultrasonic wave to transfer the mechanical energy of the ultrasonic wave to the abrasives between the machining gaps, so that the abrasives have a high-frequency impact on the processed materials. In this processing method, due to the small amplitude of the tool head, the output energy cannot be used efficiently. When processing materials such as ceramics and other hard rocks, the tool head wears to a high degree, and other tool parts are also easy to wear, so the processing accuracy and efficiency are reduced, and large-scale promotion is difficult. With the further development of this technology, Rotary Ultrasonic Machining (RUM) [11] emerged; in this, in addition to the axial vibration, the tool head also performs a high-speed circumferential rotational motion. This machining method improves work efficiency and can even perform a quick machining complex of three-dimensional contours. In recent years, a more advanced multi-frequency ultrasonic processing technology has been developed [12], which mainly draws on the planetary drilling sampler technology, and a free mass is connected to the connecting rod between the driver and the tool head. The mass block can reciprocate and irregularly strike the driver, which drives the top of the drill pipe to impact the contact surface between the material and the tool head, speeding up the processing speed and improving the processing accuracy.

2.2. Development History of Ultrasonic-Assisted Extraterrestrial Planet Drilling and Sampling Technology

Soil and rock research on extraterrestrial planets is crucial to understanding the origin and development of the universe. The installations on alien probes launched by humans are used to obtain soil and rock samples from extraterrestrial planets. However, compared with the earth, alien planets often have the characteristics of weak gravity and low environmental gravity [13]; therefore, it is necessary to electrically drive the ultrasonic generator to generate the vibration that is needed to assist to complete the sampling work of the drill. According to the working mode and principle, existing extraterrestrial planetary ultrasonic drills can be divided into three types: impact ultrasonic drills, rotary-impact combined ultrasonic drills and rotary-impact integrated ultrasonic drills.

The impact ultrasonic drill was first developed for obtaining the soil and rock of outer planets by the National Aeronautics and Space Administration. Scholars from the University of Paderborn in Germany [14,15] transformed the disk-shaped free block into a spherical one, effectively solving the problem of free block swinging, and carried out the high-frequency shock process of the free block. Nonlinear dynamics research was carried out, and this kind of impact ultrasonic drill was considered to have a very good effect. The impact ultrasonic driller developed by the Russian Bisk Ultrasonic Technology Center and the Institute of Space Research of the Russian Academy of Sciences [16] can drill into the simulated lunar soil at a maximum drilling rate of 25 mm/min. The United States used this drill on the end effector of the Mars rover Spirit, which was launched to obtain soil and rock samples on Mars [17].

The principle of the rotary-impact ultrasonic drill is to combine the longitudinal impact of the impact drill with the rotary motion of the traditional electric drill and, at the same time, realize the purpose of chip removal through the rotation of the drilling tool, to improve drilling efficiency. Honeybee Robotics [18,19] developed an ultrasonic drill based on this mechanism. In indoor tests, it can drill to a depth of 2 m on limestone samples. A depth of about 3 m was drilled for the rock of 40 MPa.

The rotary-impact coupling-integrated ultrasonic drill was arranged with multiple spiral grooves on the horn of the drill. This structure enabled the horn to convert part of the longitudinal vibration into torsional vibration while the horn is longitudinally vibrating, increasing the impact force. Scholars from Harbin Institute of Technology [20] made use of this principle to produce a prototype of a rotary-impact, coupled, integrated ultrasonic drill. When working, the small-diameter end of the horn longitudinally vibrates to transfer the force to the drilling tool to achieve impact motion. At the same time, the cover plate adopts a V-shaped structure to realize torsional vibration and the coupled motion of rotation and impact. The test results show that the drilling effect of the impact-coupled ultrasonic drill is obviously better than that of the impact-type ultrasonic drill [21].

2.3. Development History of Ultrasonic-Assisted Enhancements of Oil and Gas Production

In the development of oil and gas fields, the oil and gas layers are prone to plugging due to the perennial injection and production, which reduces the oil and gas recovery rate. With the help of an ultrasonic wave, the blocked oil and gas layers can be unblocked, and the permeability of the oil and gas layers can be improved to achieve the purpose of auxiliary production. When the ultrasonic wave propagates in the rock medium, the impurities blocked in the rock will vibrate, which will destroy the cohesion between the blocking particles and the reservoir rock, and increase the number of microcracks in the oil and gas reservoir [22]. Ultrasonic cavitation can subject the asphalt, colloid, waxy and other macromolecular compounds in crude oil to shearing and crushing. In addition, the thermal effect of ultrasonic waves in the rock medium reduces the viscosity and accelerates the flow rate of the produced fluid, thereby improving the oil layer's permeability and increasing oil and gas reservoir production. This technology has the characteristics of a simple process, convenient construction, strong layered processing ability, low cost and quick effect [23–25]. In the 1960s, the United States first carried out research on ultrasonic-assisted oil-well plug removal and production enhancement technology [26,27], and China also started research in the field of auxiliary oil and gas field development, such as ultrasonic plug removal and production enhancement technology, at the end of the 20th century [22,28,29]. With the successful research and development of high-power ultrasonic equipment, and the development and application of new materials, this technology has been tested in the United States, Russia, China's Daqing, and Shengli oilfield blocks, and has achieved good results. Table 1 compares production before and after the use of this technology in different oilfield blocks in China and abroad. The table shows that the output of each block increased to varying degrees after the ultrasonic-assisted production increase measures were adopted. Figure 1 is a bar chart comparing the production growth in each block before and after using this technology. The application of ultrasonic-assisted production stimulation technology in the Daqing Oilfield block has increased the production by about 3.5 times, which proves that ultrasonic technology can effectively assist oilfield production and efficiency.

Table 1. Compare initial production and after ultrasonic-assisted production in different locations.

Location	Frequency (kHz)	Power (kW)	Initial Production (Barrels/d)	Production after Ultrasonic Assistance (Barrels/d)
Demkinskoe Oil Field, Russia [30]	19	9	11.17	13.46
Zhongyuan Oilfield, China [28]	-	-	25.16	38.48
Shengli Oilfield, China [28]	-	-	42.92	68.08
Samara region, Russia [26]	15–30	10	85.10	137.64
Oilfields in northern Shaanxi, China [22]	5–30	>10	4.51	9.25
Yanchang Oilfield, China [29]	22	10	53.28	111.00
Western Siberia region, Russia [26]	15–30	10	29.00	61.57
Samotlor Oil Field, Russia [27]	10	18–27	23.46	56.39
Daqing Oilfield, China [28]	-	-	29.60	103.60

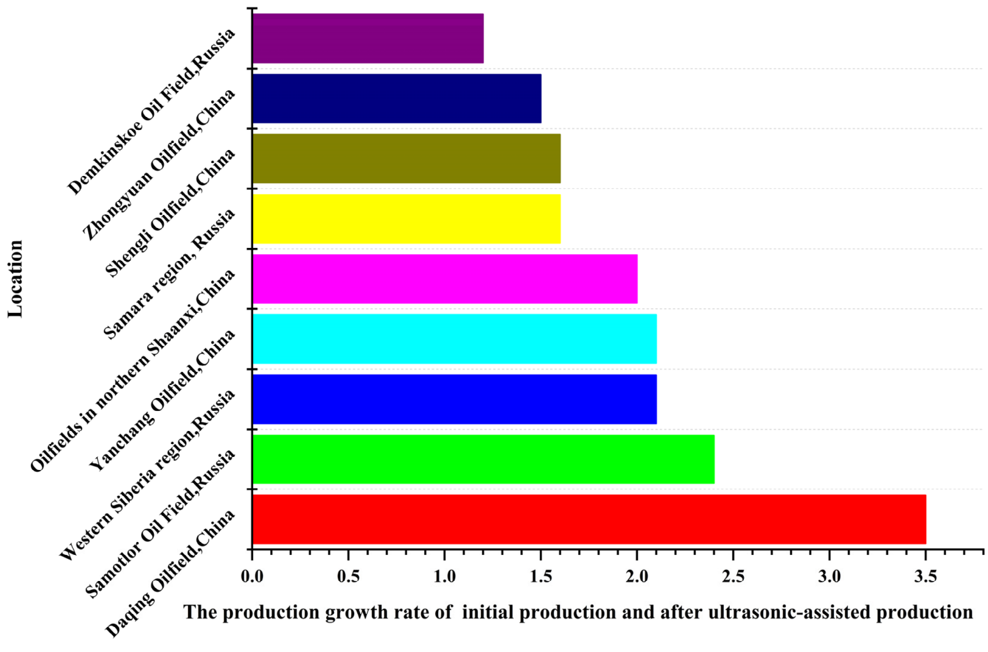

Figure 1. The production growth rate of initial production and ultrasonic-assisted production in different locations.

3. Research Progress on the Mechanism of Ultrasonic-Assisted Rock-Breaking Technology

Ultrasonic is a high-frequency soundwave with a frequency above 20 kHz, which has high-energy characteristics and can transmit energy in the form of a mechanical wave in the medium [31]. When it acts on the rock medium, it can cause two-phase or multi-phase media to interact. This can have thermal, electromagnetic and mechanical effects on the rock medium and can also lead to some chemical changes.

3.1. Effect Forms

At present, it is generally accepted in academic circles that rock-crushing mainly depends on the mechanical effects of the ultrasonic wave in the medium propagation, which include resonance effects, impact effects and cavitation effects [32].

3.1.1. Resonance Effect

When the ultrasonic wave acts on the rock, the rock is forced to vibrate. When the frequency of the rock's forced vibration is the same as the natural vibration frequency of the rock itself, the rock will have a resonance effect. At this time, the amplitude of the crystal particles inside the rock is the largest. Then, the crystals inside the rock are prone to fracture, resulting in cracks inside the rock. In this case, the rock is easily damaged [33–35]. With the help of the transducer, the electrical signal in the ultrasonic generator is converted to mechanical vibrations, and the vibration frequency of the ultrasonic generator is adjusted to be consistent with the natural frequency of the rock in the formation. Therefore, high-efficiency rock crushing can be achieved in engineering [36].

Since the 1980s, ultrasonic resonance has been applied in the field of engineering crushing. The United States and other western developed countries [37] have successively developed PB400 and RB500 ultrasonic-excitation resonance crushers according to the characteristics of ultrasonic resonance. These are widely used in road pavement construction and have achieved good results. In terms of resonance rock-breaking, researchers from the University of Aberdeen in the United Kingdom demonstrated the feasibility of resonance rock-breaking in indoor physical tests for the first time, and believed that, under resonance conditions, the rock-breaking speed was 10 times that of ordinary rock-drilling [38,39]. In recent years, scholars in China and abroad [40–45] have explored the mechanism of resonance rock-breaking, the expansion process of rock cracks and the distribution of cracks and other rock-crushing processes under resonance, and provided a theoretical model of resonance rock-breaking. The means of resonance enhancement, drilling and rock-breaking efficiency were evaluated under different resonance frequencies, amplitudes, action times, static load pressures and other conditions. A variety of resonance rock-breaking tools were designed for engineering operations, mining development, oil and gas drilling and other fields.

3.1.2. Impact Effect

Impact effect is a common action method in engineering. It mainly uses the force-applying object to generate a huge impact load in an instant, causing the force-bearing object to produce a rapid change in the state of motion over a short period of time, so that the force-bearing object produces deformation and changes in properties' dynamics [46]. The rock fracture process under the effect of impact load is very complicated. Due to the original, natural cracks and defects in the rock, under the huge impact load at the moment of external force, the stress distribution inside the rock becomes extremely uneven. Stress concentration occurs in some local locations. When a huge impact load occurs in a short time, the stress generated at the tip of the tiny crack in the rock is very large. When the stress at the tip reaches the critical value of expansion, the crack rapidly expands. There will be a certain bifurcation phenomenon during the integration surface, and the crack penetration phenomenon will appear when the crack meets the crack. When many cracks start to penetrate, macro-cracks will appear, and the rock will locally break. The periodic high-frequency impacts will lead to rock fatigue, which is more conducive to damage and fragmentation of the rock [47,48].

In order to better analyze and describe the dynamic characteristics of rocks under impact, scholars have constructed macro- and micro-impact loading models of rock media with the help of rock mechanics theory, and introduced discrete element ideas to their studies to simulate impact under discontinuous media conditions. The damage and fracture process of the rock under the shock-wave transmission process, the dynamic response law of the rock under shock action, the crack initiation conditions of the cracked rock, and the mechanical change law of the rock under strong dynamic shock have been studied [49–51] to obtain a better understanding of the mechanism of impact, and the characteristics of change and influencing factors of rocks, during the action process.

3.1.3. Cavitation Effect

Cavitation is a special effect caused by ultrasonic vibration in the liquid medium. Since the ultrasonic wave has an alternating cycle of positive and negative pressure, if the liquid medium contains dissolved gas nuclei in the positive pressure phase, the ultrasonic wave squeezes the liquid molecules, and the gas nuclei shrink accordingly. The molecular density of the liquid phase is sparse, the density of the liquid decreases, and the gas core expands [52]. The violent vibrations of the ultrasonic wave cause the bubbles in the liquid medium to be in a constant dynamic process of expansion and contraction. When the sound pressure is large enough, the bubbles in the liquid phase collapse [53]. The minimum sound intensity at which ultrasonic cavitation occurs is called the cavitation threshold. The magnitude of this parameter is related to the liquid-phase physical parameters of the ultrasonic wave. The cavitation threshold represents the difficulty of ultrasonic cavitation in the liquid medium [54].

The micro-shockwave caused by the repeated expansion and contraction of the cavitation bubble has a high-frequency impact on the rock surface and its collapse produces a micro-jet effect, which damages the rock surface. Studies have shown that the shockwave pressure generated by the rapid collapse of cavitation bubbles can reach 200–350 MPa within 10^{-3} s, and the micro-jets generated by this collapse can reach speeds of over 10^3 m/s [55,56].

The cavitation effect is affected by the viscosity of the liquid phase, the gas content and the size of the contained particles. The higher the viscosity of the liquid, the slower the collapse of the cavitation bubble, and the smaller the damage effect. The test results show [53] that there is a critical value for the gas content in the liquid phase. When the gas content is less than this threshold, the gas content is higher, and more damage is caused by cavitation. The addition of solid particles in the liquid phase can also effectively enhance the effects of ultrasonic cavitation. Experiments show that, under ultrasonic cavitation [57], the addition of silica particles to water can lead to surface roughness in sandstone and shale rock samples. Compared with pure water, the surface roughness of rock samples is increased by 20% and 400%, respectively.

3.2. Influencing Factors

The process of ultrasonic-assisted rock-breaking is affected by various forms, and the influencing factors. The factors affecting the rock-breaking effect can be roughly divided into ultrasonic parameters and engineering parameters. The ultrasonic parameters mainly include frequency, amplitude, power, etc., while the engineering parameters mainly include static load pressure and action time.

3.2.1. Ultrasonic Vibration Frequency

Ultrasonic vibration frequency is an important parameter in ultrasonic-assisted rock-breaking, indicating the speed of ultrasonic vibration. The high-frequency cyclic load causes the rock to fatigue, and the cracks inside the rock gradually increase and expand, which reduces the strength of the rock. The faster the cyclic loading frequency, the faster the rock fatigue damage occurs. When the fatigue failure limit is reached, the strength rapidly decreases and the rock suffers macroscopic damage [58]. Xu [59] conducted an experimental study on the characteristics of rock damage in various types of rock samples under different cyclic loads using the SHPB experimental system. Damage also increases with the increasing frequency of cyclic loading. Scholars from the University of Aberdeen in the United Kingdom [38,39] believed, through experimental research, that there is an optimal range of vibration frequency in the process of rock-breaking, and when the vibration frequency does not reach the optimal range, the drilling rate increases with the increase in the vibration frequency. When the vibration frequency is greater than the optimal range, the rock-breaking efficiency decreases with the increase in the vibration frequency.

Sun [60] verified the above conclusion by loading granite with ultrasonic vibration tests of different frequencies. The test results are shown in Figure 2. The results show that when the vibration frequency is close to the natural frequency of the rock, the crushing effect of the rock is the best. At the same time, the test found that frequencies that were slightly lower than the natural frequency of the rock were more conducive to the crushing of the rock. This is because, with the continuous development of internal cracks in the rock, the degree of damage increases and the natural frequency decreases. Ultrasonic cavitation is also affected by the ultrasonic frequency, but the occurrence and cavitation effects are also affected by the ultrasonic amplitude, the physical properties of the liquid phase and the gas content of the liquid phase. Therefore, the ultrasonic frequency alone cannot determine the ultrasonic assistance in the rock-breaking effect [54–56,61,62].

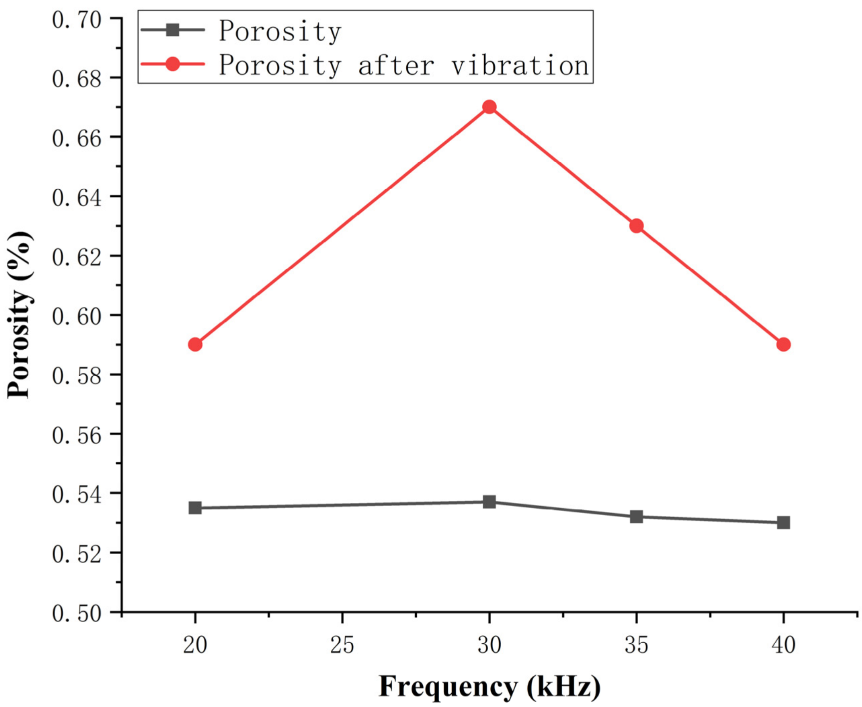

Figure 2. Variation curve of rock sample porosity caused by different frequencies.

3.2.2. Ultrasonic Power

Ultrasonic power represents the amount of energy that an ultrasonic wave can provide and is one of the key indicators in ultrasonic-assisted rock-breaking. The magnitude of ultrasonic power is determined by the frequency and amplitude of ultrasonic vibration. When the frequency of ultrasonic vibration is determined, the magnitude of ultrasonic power is characterized by the magnitude of amplitude, and the magnitude of ultrasonic power is positively correlated with the magnitude of amplitude.

As the ultrasonic power increases, the energy provided by the ultrasonic wave increases. When the vibration frequency is constant, the ultrasonic amplitude increases with the increase in power. The larger the amplitude, the greater the energy with which each vibration acts on the rock, which is more conducive to the crushing of the rock. At the same time, within a certain range, a high power will increase the effect of ultrasonic cavitation, but too high a power intensity will hinder the formation and collapse of cavitation bubbles [54]. Chemical bubbles often implode, limiting the energy stored in the bubbles. Tian [63] took the red sandstone specimen as the research object, carried out ultrasonic vibration crushing tests of the rock sample under the same frequency and different power conditions, and measured the time at which the rock sample was completely broken. The test results are shown in Figure 3, indicating that, with the increase in power, the fragmentation time of the rock sample is significantly reduced, and the rock-breaking effect is improved.

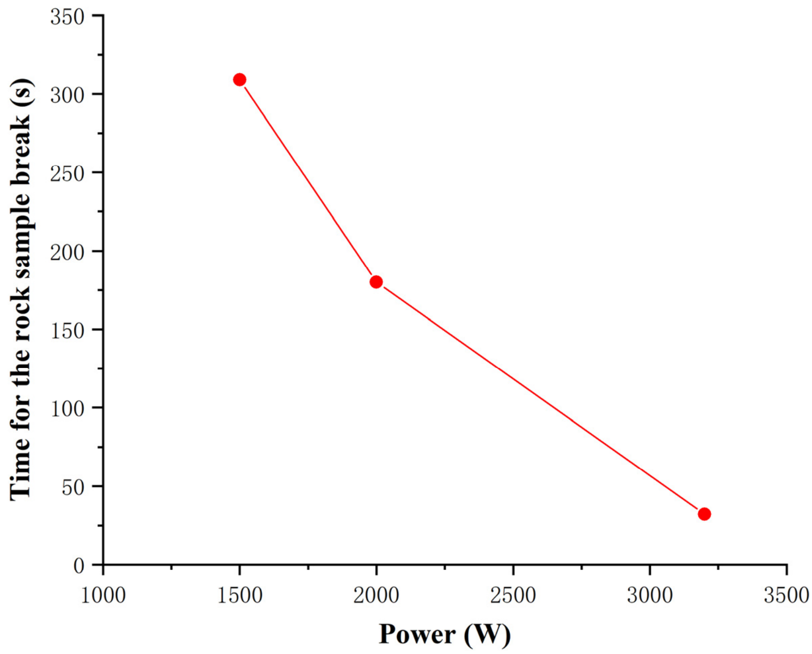

Figure 3. Variation curve of average rupture time of rock samples under different powers.

3.2.3. Static Load Pressure

The static load pressure is the prefabricated constant pressure above the rock. It is expressed by the WOB in actual drilling construction. As an important drilling process parameter, the WOB directly affects the rock-drilling efficiency. From the energy perspective, the static load pressure can temporarily close some micro-cracks and discontinuous positions in the rock, so that the rock medium is in a stable and continuous state, reducing the ultrasonic energy in the discontinuous position. Dissipation increases the utilization efficiency of ultrasonic energy and accelerates the destruction of rocks. With the destruction of the rock, the accumulation of cracks in the rock increases, and the influence of the static load pressure is no longer obvious, and the intrusion of the pressure head into the rock does not proceed smoothly as the pressure increases. However, when the pressure on the rock increases, and the tolerable limit is reached, the bit suddenly intrudes into the rock and the rock suddenly breaks [64]. Therefore, in the process of rock-breaking, it is not that the higher the static load pressure, the better the rock-breaking effect. There is a critical threshold for the static load pressure. When the pressure is greater than this value, the effect of the static load pressure on the rock-breaking efficiency is no longer significant [65–67]. Zhai [68] conducted ultrasonic vibration rock-crushing tests on cylindrical medium-grained granite samples under different axial static load pressures. The rock fragmentation effect is characterized by the change rate of porosity inside the rock after rock-fragmentation and the change rate of the compressive strength of the rock sample. The test results are shown in Figure 4, indicating that there is a threshold value for the axial static load pressure of the rock. When the static load pressure is near this threshold value, the rock-crushing efficiency is significantly enhanced.

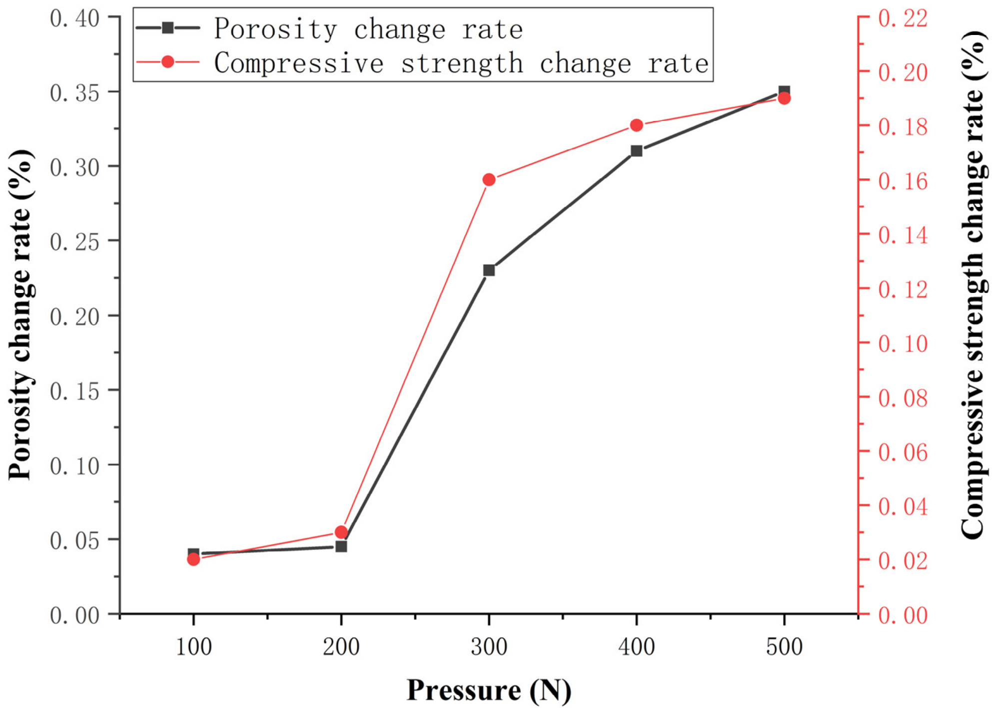

Figure 4. The relationship between static load pressure and rock porosity change rate and compressive strength change rate.

3.2.4. Vibration Time

When the ultrasonic parameters applied to the rock are fixed, the energy provided by the ultrasonic wave for rock-crushing is also fixed. With the increase in the action time and the continuous input of energy, the number of cracks and the extension length of the rock continue to increase, the compressive strength continues to decrease, and the crushing effect improves [69]. However, under the action of an ultrasonic wave, the expansion and strength changes in internal cracks in rocks are not stable and can be roughly divided into four processes: crack initiation, stable expansion, rapid expansion and fragmentation. Yuan et al. [70,71] conducted ultrasonic-vibration crushing tests on granite samples at different times. After the test, the porosity changes in the rock samples were measured by nuclear magnetic resonance technology. The results are shown in Figure 5. When the internal cracks are in the initiation state, the porosity slowly increases, and the rock strength decreases relatively slowly. With the increase in the action time, the internal cracks in the rock have a relatively stable growth stage and then rapidly expand. At this time, the internal porosity of the rock rapidly increases. The strength rapidly drops until the rock breaks apart. The damage that ultrasonic cavitation causes to other materials in the rock surface also exhibits development characteristics over time [72]. In the initial period of time, the surface and mechanical properties of the rock did not much change. After a period of time, micro-craters gradually appeared on the rock surface, and over time, cavities and cracks began to appear on the rock surface.

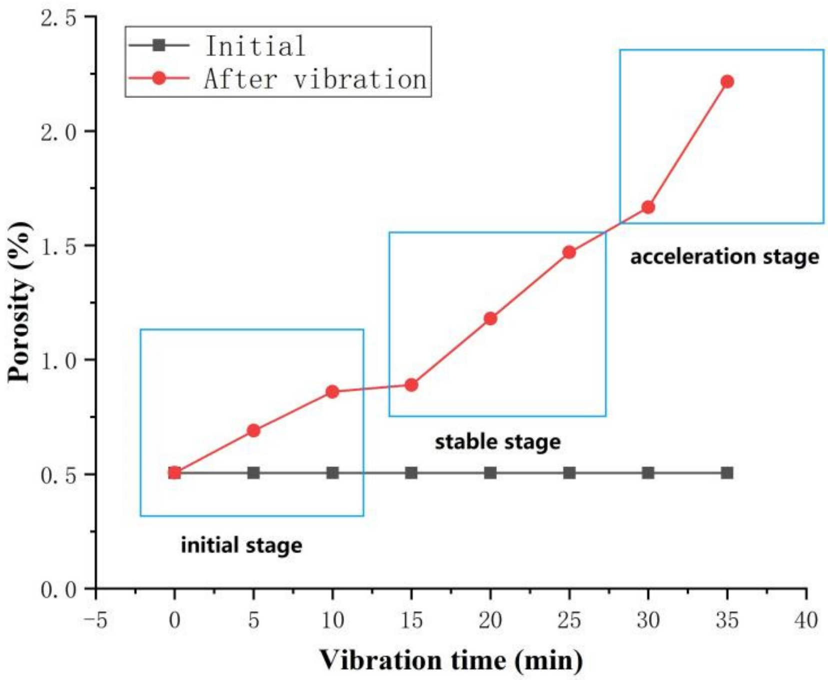

Figure 5. Variation curve of rock sample porosity caused by different vibration times.

4. Research Progress of Ultrasonic-Assisted Rock-Breaking Laboratory Test

At present, reports on the field application and testing of ultrasonic-assisted rock-crushing are extremely rare, and related research is still at the indoor research stage. The researchers tested a variety of lithological rock samples under different experimental conditions, and used some advanced methods to observe and characterize the macroscopic and microscopic changes in the rock samples to explore the change law. Table 2 summarizes the test conditions, test contents and main conclusions of the relevant laboratory test studies reported in the literature in recent years, and summarizes the main action forms of rock breakage in each test.

Table 2. Research progress of ultrasonic-assisted rock-breaking laboratory tests.

Frequency	Test Rock Properties	Test Content	The Conclusion	References
20 kHz	Granite	Under static load pressures of 100 N, 200 N, 300 N, 400 N and 500 N, the cylindrical rock samples were subjected to ultrasonic vibrations for 5, 10 and 15 min, respectively.	The compressive strength of the rock sample did not significantly change at the initial stage of the increase in the static load pressure. When the static load pressure increased from 200 N to 300 N, the compressive strength of the rock sample rapidly decreased. When the static load pressure increased to 400 N, the compressive strength continued to decline. However, the rate of descent slowed down.	[65]
20 kHz, 30 kHz, 35 kHz, 40 kHz	Granite	Under a static load pressure of 300 N, ultrasonic vibration is directly applied to the cylindrical rock sample through the ultrasonic transducer.	The porosity inside the rock is inversely proportional to the compressive strength; when the vibration frequency is 35 kHz, the rock-breaking effects are the best.	[73]
30 kHz	Granite	The ultrasonic vibration test was carried out on the cylindrical rock sample under a 300 N static load, and the infrared radiation temperature of the rock during the whole loading process was observed and measured using an infrared thermal imager.	The rock failure process can be divided into the following three stages: elastic deformation, micro-fracture and yield stage, macro-crack and failure stage; according to the axial temperature distribution of the sample, the rock sample can be divided into a fracture zone, plastic deformation zone and elastic deformation zone. The effective crack depth in the rock sample can reach 10 mm. Fatigue damage caused by ultrasonic vibrations and thermal damage caused by increases in temperature are the main factors used to destroy granite.	[74]

Table 2. *Cont.*

Frequency	Test Rock Properties	Test Content	The Conclusion	References
20 kHz	Sandstone and Shale	Ultrasonic cavitation tests on sandstone and shale samples in pure water and nanoparticle abrasives.	The roughness results show that the erosion effect of abrasive cavitation on shale and sandstone is stronger than that of pure water cavitation; the surface roughness of sandstone and shale samples is increased by 20% and 400%, respectively.	[57]
—	Sandstone, Mudstone and Shale	On the self-designed ultrasonic rock-breaking simulation test bench, the control variable method and the orthogonal test method were used to test the factors affecting the efficiency of ultrasonic high-frequency rotary rock-breaking.	Under normal temperature and pressure conditions in the laboratory, compared with the conventional rotary rock-breaking technology, the ultrasonic high-frequency rotary penetration drilling technology has a higher rock-breaking efficiency, with an average increase of 77.65%; the factors affecting the ultrasonic high-frequency rotary rock-breaking efficiency range from large to small. The order is: WOB, amplitude, bit diameter and rotation speed. WOB and amplitude have the most significant influence on the rock-breaking efficiency of ultrasonic high-frequency rotation, and the greater the amplitude, the higher the efficiency of ultrasonic high-frequency rotation at breaking through rock.	[75]
20 kHz	Sandstone, Shale and Granite	Ultrasonic cavitation tests were performed on cylindrical rock samples in a mixture of distilled water and silica water abrasives.	After the test, several micro-cracks and holes appeared on the surface of the rock sample; the average mass loss of each rock sample was 81.41% (sandstone), 557.38% (shale) and 188.16% (granite).	[76]
20 kHz	Red Sandstone	Under a static load pressure of 35 N, an ultrasonic vibration test is applied to cylindrical rock samples.	After 120 s of ultrasonic vibration, the compressive strength and elastic modulus of the rock samples were reduced by 55.3% and 26.9%, respectively; the natural frequency of the rock samples was reduced by 2.4% due to the changes in mass and elastic modulus caused by damage electron microscope scanning. When ultrasonic vibration occurs in the rock sample, the tensile stress between the rock crystals causes the original cracks in the rock sample to expand and penetrate, forming macroscopic fractures.	[77]
20 kHz, 30 kHz, 35 kHz, 40 kHz	Granite	Through the ultrasonic vibration crushing test of rock samples, the individual and coupled effects of vibration frequency, load and confining pressure on granite damage were analyzed.	The optimal vibration frequency of the sample is 30 kHz, which is close to its natural frequency. The axial static load pressure is the main factor affecting the local fracture degree of the rock sample under ultrasonic vibration. The reason for this is that, when the axial stress of the rock sample is high, the fatigue damage is more serious. The optimal static load pressure value in the test is about 300 N. The confining pressure determines the damage mechanism of the granite specimen under ultrasonic vibration. With the increase in confining pressure, under a confining pressure of about 7 MPa, the damage mechanism of granite changes from fatigue damage to fatigue and shear composite damage, which is further transformed into shear damage at about 9 MPa confining pressure.	[78]
30 kHz, 35 kHz, 40 kHz	Granite	The ultrasonic vibration crushing test was carried out on the rock sample under different parameter combinations, and the optimal coupling parameters of ultrasonic vibration were determined through the nuclear magnetic resonance test and uniaxial compressive strength test.	The optimal combination of parameters for vibration and crushing in the test is as follows: static load pressure of 400 N, amplitude of 100, and frequency of 35 kHz; within the effective resonance frequency range, the primary and secondary order affecting rock crushing is as follows: amplitude > static load pressure > frequency.	[79]

Table 2. *Cont.*

Frequency	Test Rock Properties	Test Content	The Conclusion	References
20 kHz, 30 kHz, 35 kHz, 40 kHz	Granite	Under a static load pressure of 200 N, ultrasonic vibration crushing tests were carried out at different temperatures.	Under the action of ultrasonic vibration, the number of rock cracks will increase with the increase in temperature; the accumulated thermal damage will cause a large number of internal cracks to expand and penetrate, resulting in macroscopic damage to the rock sample. The distribution of cracks in the rock sample has the characteristics of regional concentration, with the cracks' location concentrated near the upper end of the rock sample. When the temperature is lower than 150 °C, the increase in the porosity of the rock sample is not obvious; when the temperature of the rock sample reaches 150 °C, the increase rate significantly and steadily increases as the temperature continues to increase.	[80]

5. Problems and Challenges Faced by Ultrasonic-Assisted Rock-Breaking Technology in Oil- and Gas-Drilling Applications

Research on ultrasonic-assisted rock-breaking technology is at the initial stage, and most research is concentrated in the mining industry. There is little research on the oil- and gas-drilling industry that includes circulating medium and combined conventional rotary drilling under high-temperature and high-pressure conditions in the deep layer and ultrasonic layer, and research on the field application of ultrasonic-assisted rock-breaking is even rarer. Therefore, ultrasonic-assisted rock-breaking still faces many problems in oil- and gas-drilling applications.

5.1. Poor Conditions in Oil- and Gas-Drilling Downhole

Oil- and gas-drilling downhole has the characteristics of "large depth, harsh environment and high rock hardness", especially the deep and ultra-deep wells that are vigorously being developed at present; the downhole temperature can reach more than 300 °C, and the rock is under complex, high-stress conditions. At present, the physical properties and strength properties of the rock are different from those at the surface and at shallow depths, and the rock fragmentation conditions, forms and influencing factors are also different. In the current research on ultrasonic-assisted rock-breaking, the above factors are rarely considered in oil and gas drilling. Therefore, it is necessary to combine the above factors to further explore and improve the mechanism of ultrasonic-assisted rock-breaking.

5.2. The Influence of Circulating Medium

Oil and gas drilling requires the participation of the circulating medium, which can cool and lubricate the drill bit, carry cuttings and balance formation pressure. Except for jet-impact rock-breaking, most circulating media in conventional oil and gas drilling do not directly participate in rock-breaking. However, ultrasonic waves will cause ultrasonic cavitation in the liquid-phase circulating medium, which may damage the rock and affect the rock-breaking effect. Most of the existing theoretical studies do not consider the influence of the circulating medium, and experimental studies are mostly carried out directly in the atmosphere, without considering the participation of the circulating medium, and have not clarified the rock damage caused by the ultrasonic cavitation of the circulating medium in ultrasonic-assisted rock-breaking. The mechanism of action cannot provide a basis for the selection of circulating media in field applications.

5.3. Energy Transfer and Utilization of Ultrasonic Wave

The essence of ultrasonic-assisted rock-breaking is a way to provide additional rock-breaking energy for rock-breaking through ultrasonic wave, and its energy transmission and utilization efficiency have a great impact on the final rock-breaking effect. Ultrasound is essentially a mechanical wave. During its propagation, reflection, interference and other phenomena will occur in the well. The composition of the downhole medium encountered in the propagation is also complex, and a lot of energy will be absorbed or converted into heat energy during long-distance downhole propagation, resulting in high levels of loss. The energy that finally enters the rock medium for rock-breaking is very different from the power output rated by the ultrasonic generator. However, the existing research does not consider the propagation process of the ultrasonic wave, or the loss, and most of them directly use ultrasonic waves. The rated power of the generator calculates the energy provided by the ultrasonic wave, which is not consistent with the actual situation. Therefore, it is necessary to explore the propagation loss law of ultrasonic waves in the actual wellbore of oil and gas drilling, and to determine how to measure the energy of ultrasonic waves that are actually participating in rock-breaking, the actual utilization efficiency of ultrasonic energy, and how to efficiently use ultrasonic energy. The selection of ultrasonic equipment provides the basis for this.

In ultrasonic-assisted rock-breaking, the ultrasonic wave derives from an ultrasonic generator composed of piezoelectric ceramic sheets, etc., and is converted into high-frequency mechanical vibrations through the horn and transmitted through the medium to act on the rock. Sonic drilling rigs are used in mining, the sonic-vibration-generating device is placed at the wellhead, and the mechanical vibrations are transmitted to the bottom of the well through mediums such as a drill pipe to realize the vibration and crushing of the rock. The hole is small, and the rock is relatively hard. If the ultrasonic generator is placed at the wellhead, the high energy will be lost during transmission under long-distance, downhole, complex conditions. Therefore, the rock-breaking process of oil and gas drilling should be based on the characteristics of oil- and gas-drilling technology to reasonably determine the position of the ultrasonic generator.

5.4. Matching Drilling Tools and Products

Ultrasound has the characteristics of "high frequency". High-frequency percussion drilling is the method used in oil and gas drilling at present; however, because the principle of vibration is mostly pneumatic or hydraulic, this so-called "high frequency" mostly refers to the vibration of 10 Hz-level frequency, compared with an ultrasonic wave. In terms of vibration at a frequency of 10^3 Hz, there is a great difference between the two. Therefore, it is precisely because of the high-frequency characteristics of ultrasonic vibration that ultrasonic-assisted rock-breaking is facing many new challenges.

High-frequency vibration has higher requirements regarding the performance of drilling tools. High-frequency vibrations are equivalent to applying high-frequency periodic changing loads to the drilling tools, which makes the metal drilling tools extremely prone to fatigue, resulting in cracks and occurrences in the drilling tools. The fracture greatly reduces the service life of the drilling tool, and it is difficult for conventional drilling tools to meet these requirements. At the same time, the high-frequency impact of the drill bit on the formation causes the cutting teeth of the drill bit to grind more rapidly, and the vibration generated by the stick-slip effect is generated during the rotation of the drill bit and the high-frequency ultrasonic-vibration interaction law, as well as the coupling effect. At present, there are few studies on the characteristic impact on drilling tools, and the relevant influencing factors are not clear, which restricts the application of ultrasonic-assisted rock-breaking technology in oil- and gas-drilling sites.

High-frequency vibration will produce a high-frequency shearing effect on the circulating medium, and an ultrasonic wave will also lead to ultrasonic cavitation in the circulating medium. In addition, the drilling tool will generate a lot of heat under high-frequency vibrations, which will destroy the circulating medium. Its physical properties make the circulating medium function invalid. Therefore, in the rock-breaking of ultrasonic-assisted oil and gas drilling, higher requirements are put forward for the selection and process of the circulating medium, and new challenges are faced.

According to existing reports, the output power of high-power ultrasonic equipment can reach 10 kW, but the high-power output equipment of this power level cannot meet the auxiliary rock-breaking of hard rocks such as deep wells and ultra-deep wells. At the same time, there are many problems in the stable transmission of underground energy. At present, cables suitable for the complex underground environment have been successfully developed and used, which solves the problem of electric energy transmission. However, lowering the cable downhole, especially in deep wells and ultra-deep wells, and ensuring the continuous and stable transmission of electric energy, are urgent problems that must be solved in the field promotion and application of ultrasonic-assisted rock-breaking.

6. Application Prospect of Ultrasonic-Assisted Rock-Breaking Technology in Oil and Gas Drilling

Most of the existing research is focused on the shallow rock-breaking in the field of planetary drilling the mining field. There is little research on the problem of ultrasonic-assisted rock-breaking in oil and gas drilling, especially under more complex deep oil- and gas-drilling conditions. The influencing factors are also unclear. To introduce the advanced ultrasonic technology into the oil- and gas-drilling industry, speed up the drilling of deep and ultra-deep wells, and improve the efficiency of drilling operations, the following three perspectives are proposed.

6.1. Mechanism of Ultrasonic-Assisted Rock-Breaking with Characteristics of Oil and Gas Drilling

According to the characteristics of oil and gas drilling, the relevant factors that affect ultrasonic-assisted rock-breaking with the characteristics of oil and gas drilling are clarified, and factors that have not been considered in previous studies are taken as the key research objects. We focus on the influence of a high temperature, high stress and circulating medium on ultrasonic-assisted rock-breaking. In the future, with the development of test conditions and equipment, if conditions permit, we will carry out experimental research to explore rock crack initiation, and the length of crack propagation until stability. The change laws regarding rocks' physical parameters and strength during crushing, and the influence law of each factor is clarified. Combined with the classical theory, through an analysis of the research conclusions, the quantitative relationship between the rock change characteristics, and various influencing factors under the conditions of oil and gas drilling are established, and the rock fracture equation is established, with ultrasonic parameters as variables.

Through a summary of the test results and the theoretical derivation, the law of ultrasonic-assisted rock-breaking is further revealed, the mechanism of ultrasonic-assisted rock-breaking with the characteristics of oil and gas drilling is clarified, and the influence of rock type is considered. This lays the foundation for the application of ultrasonic-assisted rock-breaking in oil and gas drilling.

6.2. Energy Transfer and Utilization in Ultrasonic-Assisted Rock-Breaking Mechanical Wave

In research, the electrical characteristics and placement position of ultrasonic equipment should be fully considered, the theoretical relationship between the control parameters of ultrasonic generating equipment and the ultrasonic parameters that actually input into the well should be established, and the initial value of the actual energy provided by the ultrasonic generator should be clarified. Considering the characteristics of an ultrasonic wave, the research should use parameters such as the structure of the wellbore during construction, the physical parameters of the drilling fluid, and the characteristics of the formation rock to analyze the propagation path of the ultrasonic wave and the characteristics of the medium encountered by the propagation. The transmission distance and the dynamic changes in the transmission environment, etc., should be used to clarify the energy loss value of ultrasonic waves in borehole propagation. The geological parameters should be considered, including the characteristics of the downhole environment and the physical properties of the rock at the bottom of the well, based on the theories of rock mechanics, material mechanics, vibration mechanics, etc. This should be combined with the mechanism of ultrasonic-assisted rock-breaking and construction technology to determine the energy required for rock-breaking, namely, the ultrasonic actual utilization value.

This study aims to clarify the energy transfer path of ultrasonic-assisted rock-breaking and the main influencing factors affecting energy transfer and utilization, and provide a basis for the selection of ultrasonic generating equipment and the selection of construction parameters.

6.3. High-Power Ultrasonic Generator and Matching Products

Ultrasonic power generators have always been a concern in related fields. In recent years, China has carried out research in this field and achieved some breakthroughs. High-power ultrasonic generators and ultra-high-power ultrasonic generators have been successfully tested. The upper power limit of ultrasonic generators is constantly increasing. The author believes that the further development of technical conditions, especially following the breakthrough in the development of ultra-high-power generators, will vigorously promote the application of ultrasonic-assisted technology in oil and gas drilling. Increasing the research and development regarding supporting drilling tools, so that they have a high performance strength, can help to achieve the characteristics of ultrasonic high-frequency vibration, and lead to success in tests under the complex conditions of downhole oil and gas drilling. Using the premise of clarifying the failure characteristics of the circulating medium in ultrasonic-assisted rock-breaking, the functional characteristics and applicability of the ultrasonic-assisted rock-breaking drilling fluid were studied, and the drilling fluid system and suitable products were developed for ultrasonic-assisted rock-breaking. This provides a reliable hardware guarantee to accelerate the field application of ultrasonic-assisted oil and gas drilling and rock-breaking.

7. Conclusions

“How to carry out high-efficiency rock breaking” is an eternal topic of research and discussion in the oil- and gas-drilling industry. With the successive development of deep wells, ultra-deep wells and difficult-to-drill formations, the development of new rock-breaking methods is particularly urgent. Drawing on the successful experience in related fields, ultrasonic-assisted rock-breaking has great potential in the rock-breaking in oil- and gas-drilling industry as a new rock-breaking method with high efficiency and the possibility of environmental protection.

The development of an efficient rock-breaking method is a systematic project, ranging from mechanism exploration to indoor simulation tests, as well as field tests and the research and development of supporting equipment tools and products. At present, the existing research on ultrasonic-assisted rock-breaking is still at the initial stage, although the feasibility and efficiency of the technology have been verified, and the influencing factors and mechanisms of ultrasonic-assisted rock-breaking have been preliminarily clarified regarding the application of ultrasonic-assisted rock-breaking in oil and gas drilling.

In the future, the laws and mechanism of ultrasonic-assisted rock-breaking under the harsh conditions of deep oil and gas drilling and in a downhole environment should be improved. The energy-transfer path and energy utilization in ultrasonic-assisted rock-breaking should be clarified to improve the energy utilization efficiency in ultrasonic-assisted rock-breaking. The development of matching products should be increased, and combined with the development trend of ultrasonic technology, to form a complete and mature ultrasonic-assisted rock-breaking theory, as well as technology and equipment, and promote the popularization and application of this efficient rock-breaking method in oil and gas drilling. The efficient development of resources should also be increased.

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