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Systematic Review

A Review of Stimulation Technologies for Weakly-Consolidated Natural Gas Hydrate Reservoirs

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Abstract: As an unconventional clean resource with huge reserves and a wide distribution, natural gas hydrates (NGHs) have good application prospects. However, due to limited understanding and available production technology for NGHs, there is still a large gap between current production tests and commercial exploitation. A breakthrough in reservoir stimulation technologies is key to realizing the industrialization of NGHs in the future. Through a comprehensive summary of hydrate production test cases in Japan and China, this paper highlights the difficulties in the transformation of weakly-consolidated reservoirs. By systematically reviewing the theory and technology of hydrate reservoir transformation and engineering applications, this paper elucidates in detail the technical principles and mechanisms of several available stimulation technologies for weakly-consolidated reservoirs, and assesses the feasibility of their application to increase the production of NGHs. Existing problems and challenges are summarized and future prospects are discussed. Finally, suggestions are put forward for research and development of transformation technology for weakly-consolidated NGHs reservoirs in the future.

Keywords: NGHs; weakly-consolidated; reservoir stimulation; hydraulic fracturing; hydrojet; hydraulic dilatancy; hydroelectric effect; electromagnetic wave; dipole moment

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1. Introduction

As an inclusion compound formed by water molecules and guest molecules associated with them, natural gas hydrates (NGHs) exist in the form of crystals under low temperature and high pressure. NGHs in nature mainly refer to methane hydrate occurring in permafrost areas and deep-sea sediments under low temperature and high pressure. The decomposition of methane hydrate per unit volume can produce 150–180 standard volumes of methane gas and 0.8 standard volumes of water. NGHs have the advantages of huge reserves, wide distribution, shallow burial depth and high energy density. It is estimated that the organic carbon stored in the form of NGHs on the Earth accounts for 53% of total global organic carbon [1,2], which is twice the total carbon content of coal, oil and natural gas. Therefore, NGHs are considered an ideal clean alternative resource for the 21st century and have good application prospects.

Since 2002, production testing and research into NGHs at Mallik Station in the Arctic region of Canada have confirmed that NGHs can be decomposed into gaseous and liquid states by heating and depressurization, representing a prelude to the efficient exploitation of NGHs. A combination of carbon dioxide injection and depressurization was completed in the Alaskan tundra in 2012, and production tests were conducted. In 2012, Japan took the lead in exploration of the offshore South China Sea Trough, aiming to extract NGHs in sandy sediments that had been discovered, and, using depressurization as the main method, carried out the world's first production test of NGHs in this area of the sea. In 2017, a second production test was carried out in this sea area, which determined that there were good prospects for the exploitation of sandy NGHs with high permeability by depressurization [3,4].

However, the vast majority of the world's NGHs occur in clayey silt or silty sediments on the seabed. In 2017, China carried out a production test of NGHs in the Shenhu sea area on the northern slope of the South China Sea, and successfully obtained natural gas from muddy siltstone NGH deposits 203 to 277 m below the seabed of 1266 m. Continuous and stable gas production lasted for 60 days, with cumulative gas production of 309,000 m^3. In 2020, China took the lead in using horizontal well drilling and production technology to carry out the second round of production tests of NGHs in the Shenhu sea area of the South China Sea. After one month of production tests, the total gas production was 861,200 m^3, with a daily gas production 28,700 m^3, which was 5.57 times the daily gas production of the first vertical well production test [5]. The tests demonstrated that muddy siltstone NGHs have good exploitation potential. They also demonstrated that the application of new technology can play an important role in improving the single well productivity of NGHs.

Many hydrate production tests have been carried out throughout the world, and a series of breakthroughs have been achieved, resulting in a degree of consensus on the approach to NGH exploitation. Although the reserves of NGHs are huge, there are complex changes in solid, liquid and gas phases of NGHs and the average daily production of NGHs is still far below the threshold for commercial exploitation. Wu Nengyou et al. [6] compared the gap between the average daily production capacity of NGHs and the threshold production capacity for commercial exploitation, pointing out that there was still a gap of two to three orders of magnitude between current production capacity and the threshold for industrial production (see Figure 1). Rapid increase in daily average production using reservoir stimulation technologies is key to realizing the industrialization of NGHs.

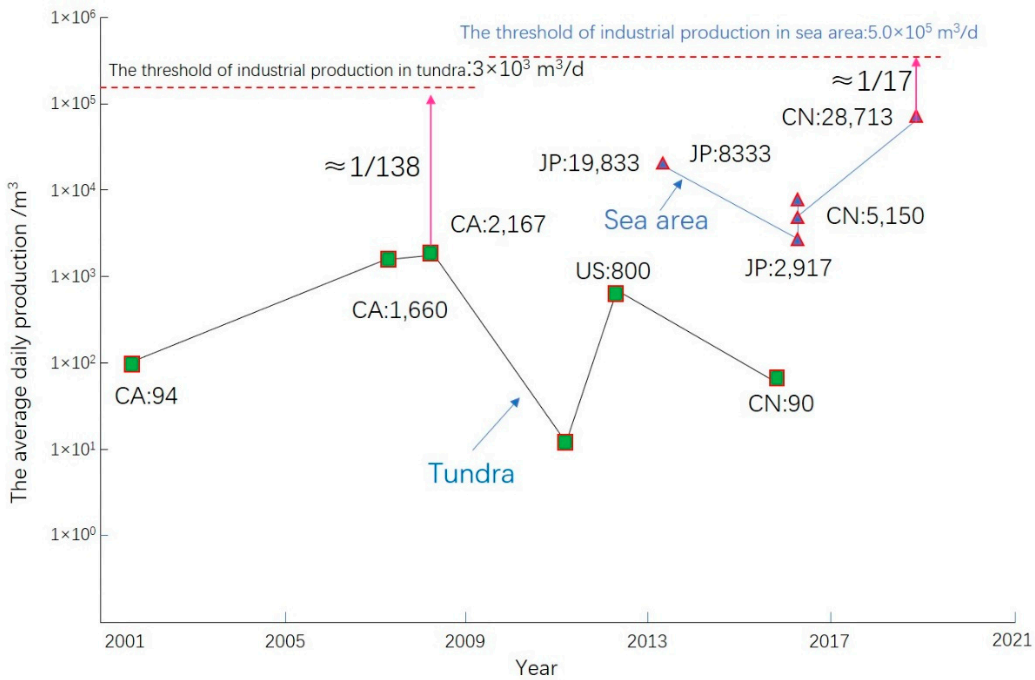


Figure 1. Relationship between average daily production test capacity and threshold of industrial production for NGHs (Reprinted with permission from Ref. [6]. 2020, Wu et al.).

Most research on reservoir stimulation technologies is still at the stage of model construction and numerical simulation, with a lack of corresponding experimental verification and basic support for field implementation, and understanding of how to increase production and reservoir stimulation remains uncertain. Considering the complex phase transitions of NGHs, they are susceptible to the effects of temperature-pressure multi-field coupling factors.

By systematically examining the theory and technology of hydrate reservoir transformation, combined with the assessment of the outcomes of two rounds of NGH reservoir transformation in the South China Sea, this paper highlights the difficulties in the transformation of weakly-consolidated reservoirs, analyzes the methods and basic principles of weakly-consolidated reservoir transformation of NGHs, considers the optimization of several types of transformation technologies for weakly-consolidated reservoirs, and elaborates the principles and mechanisms for each technology. The paper provides a comparative analysis of the feasibility of their practical application, summarizes existing problems and challenges, and discusses the prospects for these technologies. The analysis is anticipated to provide valuable information for the development of efficient and safe NGH mining technology.

2. Difficulties in Stimulation for Weakly-Consolidated Reservoirs

NGHs are mainly distributed in sediments along the continental slope of the deep-sea continental shelf with a shallow burial depth. The reservoir lithology is dominated by weakly-consolidated muddy siltstones with a low temperature and loose structure. Presently, the internationally recognized exploitation methods mainly include depressurization, thermal shock, carbon dioxide replacement and the combined application of these methods [7]. However, through field practice and experimental simulation, it has been confirmed that the depressurization method and the scheme based on depressurization are the best ways to realize the exploitation of NGHs.

NGHs are decomposed by reducing the pressure of their reservoirs below the thermodynamic equilibrium line. Because NGH particles participate in the construction of cementation of reservoirs in solid form, the hydrate crystal skeleton in reservoirs disappears and the cementation capacity among particles decreases along with the decomposition of NGHs. The loose structure of weakly-consolidated NGHs reservoirs makes it difficult to maintain a large production pressure difference, resulting in stress deformation or even the collapse of reservoirs, which block the pressure conduction channel, such that the pressure is unable to conduct, and decomposition of NGHs is terminated. Simultaneously, a great deal of heat is absorbed in the decomposition process, which leads to decrease in the reservoir temperature. In turn, when the temperature decreases to a certain extent, this affects the phase equilibrium of NGHs and promotes the secondary formation of NGHs. To break this thermodynamic equilibrium, it is necessary to continue reducing the reservoir pressure so that the hydrate can continue being decomposed, thus entering a cycle of pressure drop—temperature drop—continuous pressure drop—corresponding temperature drop (see Figure 2).

Based on test results for hydrate-bearing cores, KONO et al. [8] suggested that the existence of hydrate and the change in reservoir pore structure caused by the hydrate decomposition process would significantly affect the permeability of reservoirs. Ruan Xuke, Li Xiaosen et al. [9] simulated the secondary formation of NGHs in the process of depressurization and exploitation in the laboratory. They suggested that the secondary formation of hydrates was mainly limited near the depressurized gas outlet, causing significant changes in the local hydrate saturation, temperature and pressure, and leading to a significant reduction in the gas production rate. Li Yanlong et al. [10] observed that there was a “memory effect” in NGHs, i.e., under certain conditions, the water decomposed from NGHs was more easily able to reform hydrates than water without a hydrate formation history, which led to increased risk of secondary formation blockage in the process of NGH exploitation, as well as decreased efficiency of reservoir seepage.

The decomposition of NGHs is a complex phase transition and seepage process involving interactions among multi-phase, multi-component and multi-physical fields [11]. Both complex morphological changes to gas, liquid and solid phases in the decomposition process and the secondary formation of hydrates lead to changes in pore structure, porosity, permeability, saturation and seepage channels of weakly-consolidated reservoirs. The mutual influence and restriction among these complex phenomena make the application of reservoir stimulation technologies very challenging.

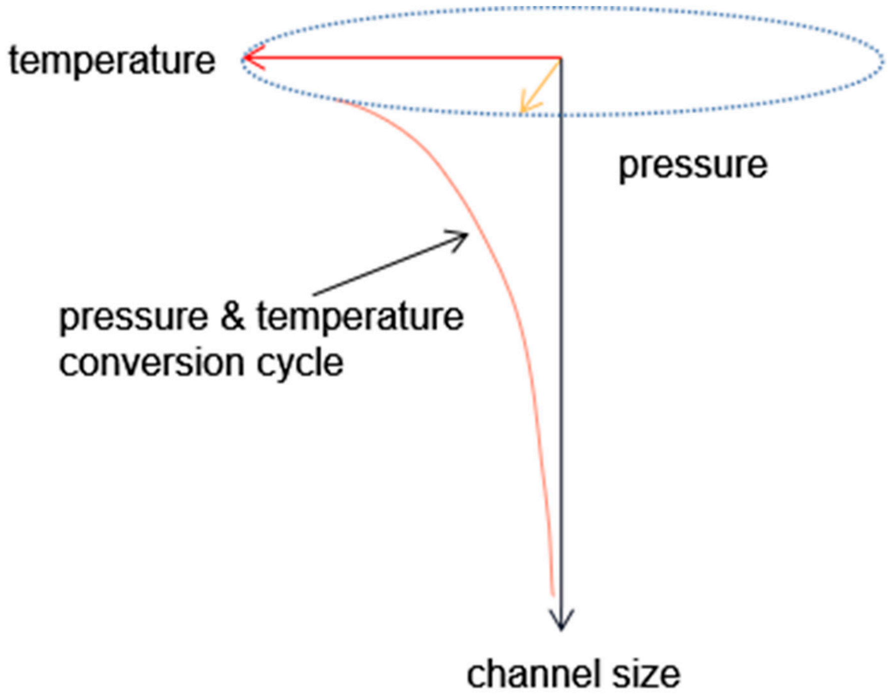


Figure 2. Schematic diagram of pressure and temperature conversion cycle.

3. Stimulation Technologies for Weakly-Consolidated Reservoirs

On the basis that the gas and water produced by the decomposition of NGHs follow the seepage mechanisms of porous media when flowing in reservoirs, methods to achieve increased production of NGHs are mainly divided into three categories: expanding the hydrate decomposition front, enhancing the hydrate decomposition rate and improving the hydrate seepage condition [12]. Based on the first round of production tests, the second round in the Shenhu sea area of the South China Sea in 2020 greatly increased the daily gas production to 28,700 cubic meters using complex structure wells and reservoir stimulation technologies [5]. Therefore, the stimulation of weakly-consolidated hydrate reservoirs should be based on the creation of an artificial fracture network to increase the permeability of reservoirs near the wellhole, enlarging the contact area between the wellhole and NGH reservoirs, accelerating the speed of pressure conduction and improving the seepage capacity of reservoirs. In addition, it is also necessary to remove blockages in pores or fractures, to maintain the geometric size of effective fractures, and to enhance the flow efficiency of reservoir fluids.

3.1. Challenges of Hydraulic Fracturing Technology

In recent years, hydraulic fracturing technology has been well applied, especially in the field of shale gas exploitation in North America. With the increasing development of research and the application of horizontal well multi-stage fracturing technology [13], the technology has been widely used in the fields of unconventional resources, such as ultra-low permeability shale oil and gas reservoirs, low-permeability and tight sandstones, and deep and coalbed methane reservoirs, and has achieved remarkable results. Hydraulic fracturing technology has the advantages of improving the complexity of fractures, expanding the distribution of fractures, greatly increasing the seepage area and enhancing the overall efficiency of exploitation of reserves.

Although it has been recognized that NGH exploitation efficiency by hydraulic fracturing has improved, the mechanism of fracturing technology is still in its infancy, few related monographs have been published, and there is still a lack of in-depth reports on the characteristics of NGHs and their impact on the fracturing effect. Additionally, the feasibility of NGH fracturing is also controversial [14,15]. Through experiments, Too et al. [14] confirmed that sandy reservoirs with an NGH saturation of 50–75% were compressible. Fractures of muddy/sandy interbedded NGH reservoirs tended to extend along the interface of sand-mud interbeds [16]. However, clayey silty NGH reservoirs with low saturation were easily compacted and difficult to fracture [17]. Liu Lele et al. [18] analyzed the permeability of NGH strata and pointed out that the stress sensitivity of NGH strata was strong, and that the strength of NGH reservoirs composed of fine particles, such as fine silt and clay, was much weaker than that of the low-permeability oil and gas reservoir rocks, with the strength of strata after complete hydrate decomposition being reduced to as little as one tenth of the original.

Because of the special physical properties of NGHs, the hydrate crystalline solids not only participate in the construction and cementation of rock skeleton, but are also formed in the pores between reservoir particles to occupy the space of reservoir pore fluid, resulting in the permeability of hydrate storage decreasing to a very low level. However, once NGHs are decomposed, the porosity and permeability changes greatly—the porosity decreases gradually, but the permeability increases sharply. These factors may affect NGH hydraulic fracturing. As a result of the stress change caused by the decomposition/formation of NGHs and the formation and extension of fracturing fractures, the permeability of reservoirs will change greatly. Through numerical simulation, Sun et al. [19] demonstrated that to increase NGH production, hydraulic fracturing has an obvious effect in the early stages of exploitation, but has a limited effect in the middle and late stages of exploitation, and the overall effect of fracturing might change.

The results of two production tests of NGHs in the China Sea area showed that horizontal wells can provide improved exploitation efficiency, with the production of a single well found to be 5.57 times that of a vertical well [5]. In the field of unconventional resources, the multi-stage fracturing technology of horizontal wells has the advantages of greatly increasing the seepage area and improving overall exploitation efficiency. Using horizontal wells, the original single fracture is transformed into complex fractures, and the complex fractures of different scales are further transformed into effective fracture transformation volumes. As a result, the complexity of each fracture is further enhanced (see Figure 3). In this way, the interaction between natural fractures and artificial fractures is made full use of to maximize fracture transformation volumes. Thus, it becomes more and more critical in field applications to make use of horizontal well multi-stage fracturing technology to enhance the hydrate production of a single well.

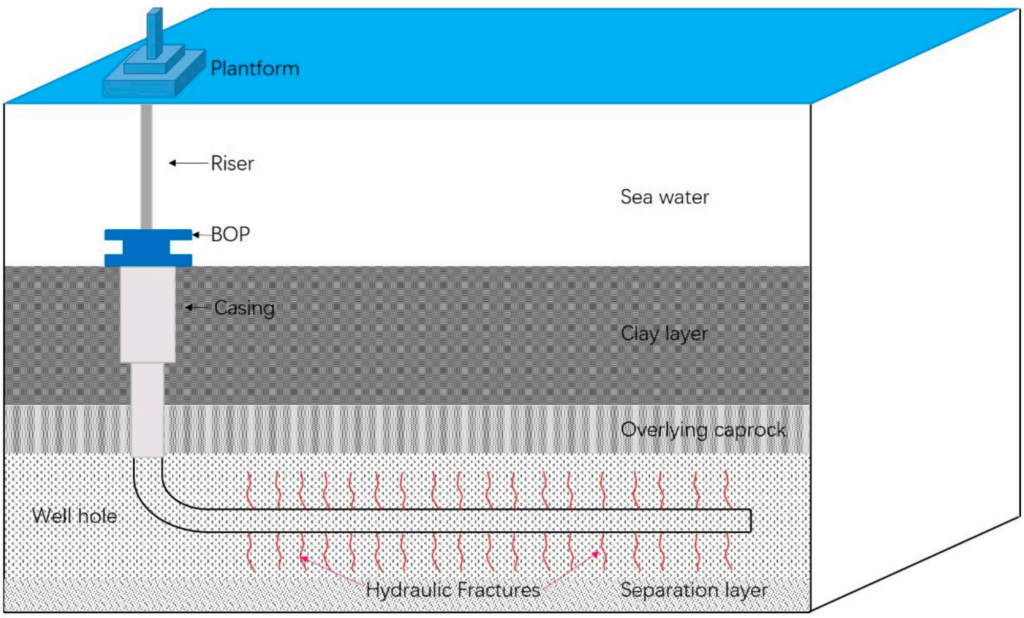


Figure 3. Schematic diagram of physical model for horizontal well fracturing.

For hydraulic multi-stage fracturing in weakly-consolidated reservoirs, it is necessary to determine the feasibility boundary of NGH fracturing, analyze the influence of reservoir type, geomechanical properties and conditions, and stratum sensitivity, and consider fracture initiation and propagation laws. It is also important to carry out research on fracture parameter optimization methods, special perforation technology, multi-stage fracturing tools and methods, multi-scale fracturing process parameter optimization methods, low-damage fracturing fluid and fracture effectiveness maintenance technology. In addition, due to the shallow burial of NGHs, the decomposition and phase transition of hydrates are complex, and the deformation amplitude of strata is large. Therefore, how best to achieve effective multi-stage modification is also one of the technical challenges of hydraulic fracturing.

3.2. Hydraulic Self-Sealing Advantages of Hydraulic Jet Fracturing Technology

Hydraulic jet fracture (HJF) is a new stimulation technology, developed from high pressure abrasive water jet technology based on the transformation relationship among kinetic energy, potential energy and pressure in the Bernoulli equation, which combines hydraulic jet perforation with hydraulic fracturing technology. In 1998, Surjaatmadja of the Halliburton Company in the United States proposed the hydraulic jet fracturing method [20]. For this method, a high-speed fluid generated by a special jet tool with a propping agent is utilized to penetrate the casing and rock to form a hole, and then the fluid generates a pressure higher than the fracture pressure at the bottom of the hole to create a main fracture with a single direction. This increases the seepage area, decreases the reservoir filtration resistance, and provides a good migration path for stratum fluids to enter the wellhole (see Figure 4).

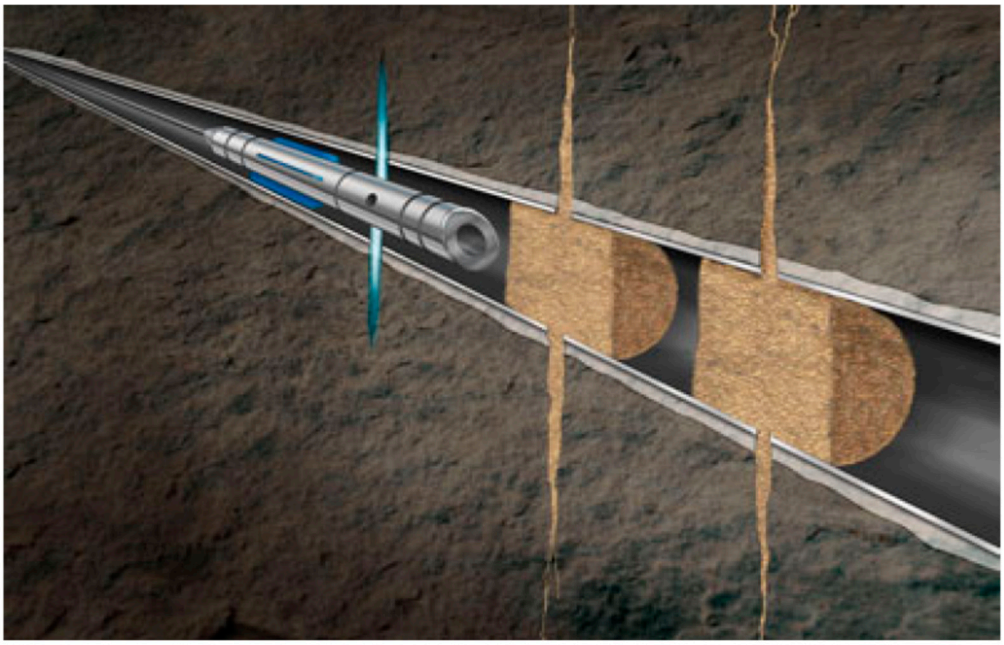


Figure 4. Schematic diagram of hydraulic jet fracturing.

In the late 1990s, the Halliburton Company first carried out field tests and hydraulic jet technology operations in Texas, New Mexico, as well as other oil wells in the United States, and achieved remarkable effects. Subsequently, the technology was successfully implemented in hundreds of wells in North America and the Gulf of Mexico, and, in 2003, it was successfully tested in the 1-RJS. 512HA well in Campus Bay, Brazil [21]. This was the first time that hydraulic jet fracturing technology had been applied to marine stimulation operations. In December 2005, the Halliburton Company cooperated with the Changqing Oilfield Company to successfully complete stimulation operations in the Zhuangping 3 and Jingping 1 wells of the Jing'an Oilfield. This was the first test of this technology in China [22], and it was then widely applied in the Changqing oilfield, the southwest oil and gas field, the Xinjiang oilfield and other oilfields in China. Hydraulic jet fracturing technology is now used in thousands of horizontal wells and tens of thousands of vertical wells all over the world.

For hydraulic jet fracturing, the stratum rock is eroded by a high-speed abrasive jet to form holes, and the low pressure area formed near the high-speed jet entrains the fluid around the holes into the holes, resulting in the pressure in the holes being higher than the stratum fracture pressure, which induces the stratum to crack and achieve hydraulic self-sealing (see Figure 5). Thus, this process does not need to use an additional mechanical sealing device and can carry out the fracture stimulation on the producing layer fast and accurately. This has solved the difficult problem of implementing multi-stage stimulation because the effective sealing cannot be operated in a long, open-hole horizontal well. Therefore, this technology has the advantages of higher construction safety, of a shorter operation cycle, and a wider range of application.

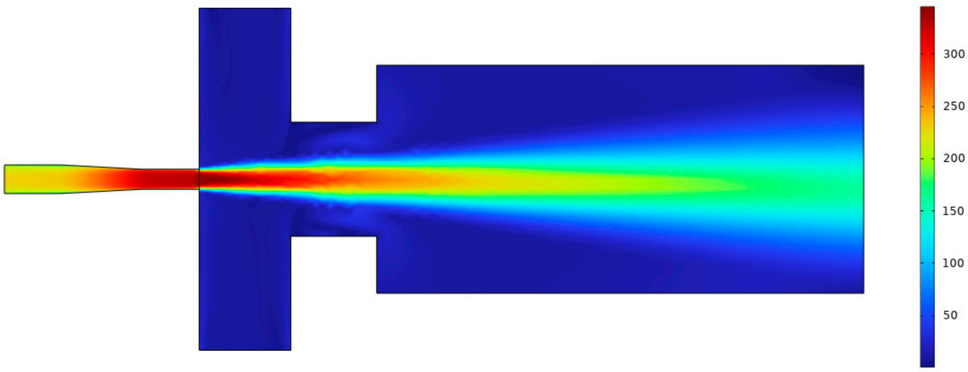


Figure 5. Flow-field analysis of hydraulic jet.

Because of the shallow burial depth and weak rock cementation strength of weakly-consolidated NGHs reservoirs, the conventional mechanical sealing device cannot support the borehole wall stably, and the development of the micro-fracture and the extension direction of the fracture is uncontrollable, which creates significant challenges to the implementation of large-scale reservoir stimulation. On the basis of the fine reservoir characterization and the reservoir stress distribution, and using the hydraulic self-sealing characteristics formed by the high-speed jet, the dominant target reservoir is closely cut, the resistance at the end of the hole is reduced, and the fracturing fluid is forced to follow the principle of minimum resistance and move forward along the dominant channel direction made by the abrasive jet, so as to induce the development of fractures along the set direction, thus achieving control of the fracture direction. This technology provides technical support for the multi-stage stimulation of weakly-consolidated NGH reservoirs, and, currently, is one of the most effective reservoir stimulation technologies. Future research should focus on how to improve the efficiency of stimulation construction, strengthen the intervention and treatment of secondary hydrate formation and sand production in the later exploitation process, and maintain the seepage capacity of dominant channels.

3.3. Fracture Complexities in Weakly-Consolidated Reservoirs Enhanced Using Rock Dilatancy

Dilatancy is an important rock property, referring to the rock deformation phenomenon whereby the total volume of the rock medium increases under the action of shear stress or pore fluid pressure increase when the total stress is still compressive stress. As early as the 1950s and 1960s, Brigeman and Handlin [23,24] studied rock dilatancy. Subsequently, scientists and scholars pursued more systematic studies on this issue, and the process of micro-fissure before macroscopic rupture was also elucidated. In general, when a certain stress combination in the rock medium exceeds a certain limit (the initial dilatancy yielding pressure), part of its deformation is recoverable and the other part is unrecoverable [25]. The former is called reversible elastic deformation and the latter is called irreversible dilatant deformation. Analyzed in terms of the internal structure of rock deformation, dilatancy deformation is an irreversible deformation caused by the sliding of particles and particle interfaces in rocks and the static propagation of micro-fissures, which, from a micro-perspective, can be regarded as the rotation, rolling and rearrangement of rock particles.

The application of rock dilatancy deformation to the field of oil and gas originated from an accidental discovery by the Imperial Oil Company in the treatment of SAGD wells. The production of oil sand wells has been greatly improved following high-pressure injection operations, which has led to the systematic study of the dilatancy of weakly-consolidated sandstones. Dilatancy in oil sands is a combination of shear damage and tensile microfracture. When shear dilatancy occurs, the shear stress on rock particles exceeds the friction strength, and the original structure of rock particles changes due to the disturbance of the particle sliding and rolling, but the particles still contact each other, and, with the continuous injection of high-pressure fluids, tensile fracture occurs. Thus, the particles are separated from each other, which not only increases the total volume of pores in rocks, but also increases the permeability of rocks [26] (see Figure 6a,b).

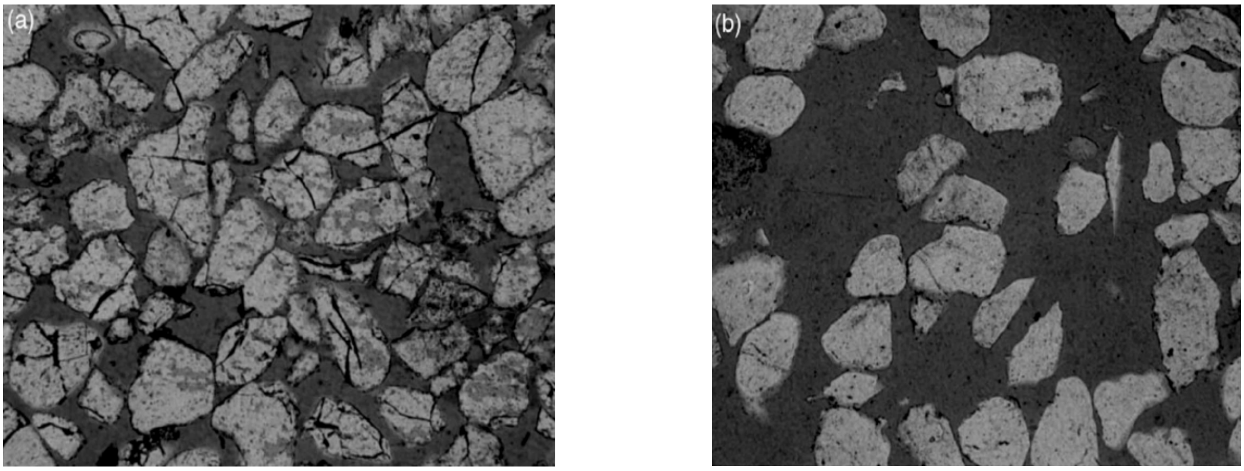
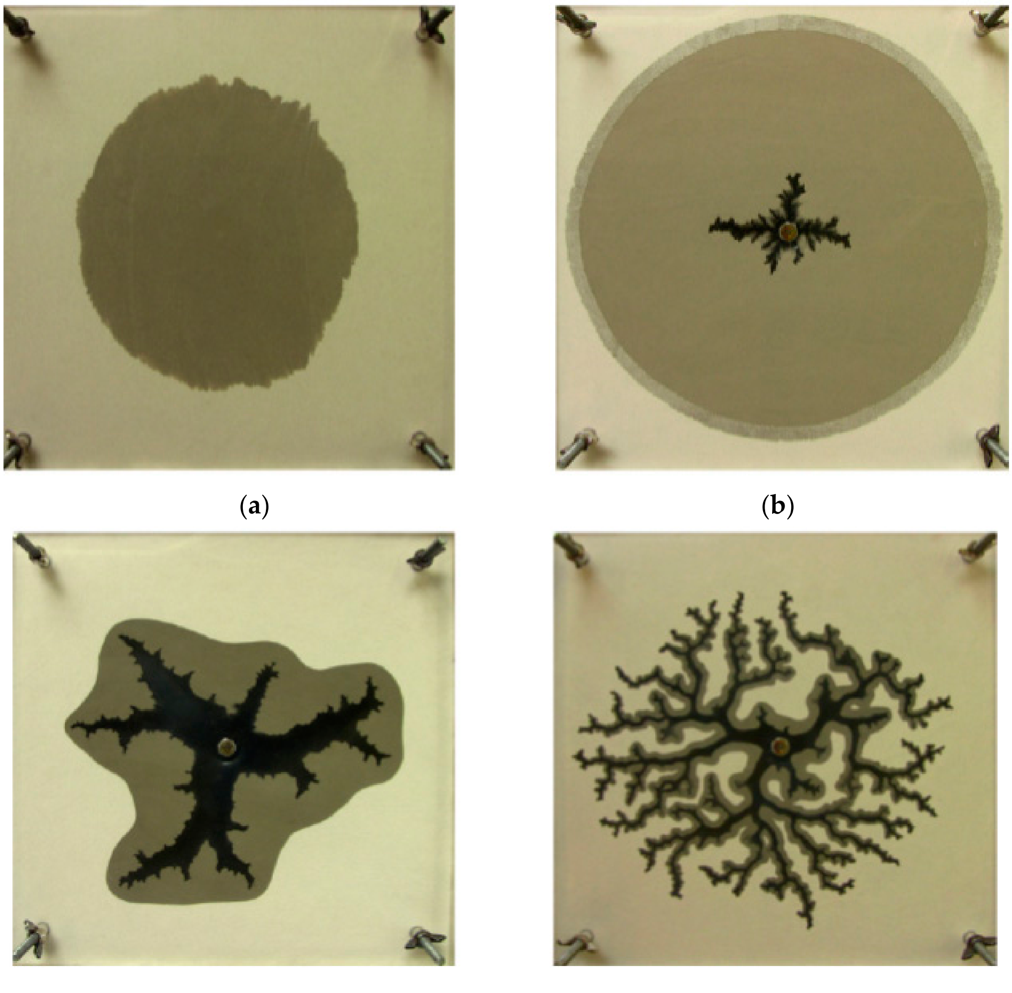


Figure 6. (**a**) Rock micrograph before dilatancy. (**b**) Rock micrograph after dilatancy.

Through rock mass dilatancy, shear expansion zones and independent tensile microfracture areas can be formed around and between wells, which can greatly improve the fluid injection capacity and contact area of injected fluids. Therefore, dilatancy stimulation technology has been tested when transforming water injection wells in the oilfield. Yan Xinjiang et al. [27] carried out cyclic loading triaxial experiments on the sandstone reservoir rocks of the Dongying Formation in the Bohai Oilfield. The mechanical properties and deformation parameters of Dongying Formation sandstones under low confining pressure were tested, the dilatancy angle was measured, and dilatancy simulation of loose sandstones under different conditions was carried out. The test results showed that the loose sandstones were able to produce strong dilatancy under low effective stress, and the dilatancy technology of high-pressure injection was able to form a high-permeability dilatancy fracture network and remove reservoir pollution blockage. Hence, this technology provides a feasible method for the stimulation of water injection wells.

The burial depth of NGHs is shallow, and hydraulic dilatancy technology, as a high-pressure reservoir stimulation process, has a destructive impact on the integrity of the caprock. There is also a risk of local communication of the dominant horizon, which occurred in the early SAGD project. In pilot testing during the Christina Lake SAGD project by the Canadian Cenovus Resource Company, because the pretreatment time was too short, premature dilatancy with large displacement led to the formation of tensile fractures between wells and the communication of bottom water layers, and the results were poor after production. However, this technology was later used successfully after process improvement.

Much experience has been gained in the use of hydraulic dilatancy technology in the treatment of weakly-consolidated loose sandstones, such as oil sands [28]. Through dynamic analysis of the elastic mechanics and thermoelastic mechanics mechanism of porous media, the stress, pore pressure state and water saturation of strata around the well can be adjusted in time, and the rock mass pre-dilated in advance, to form a large volume dilatancy area in the vertical direction. After completion of the dilatancy, the injection pressure and displacement are gradually increased [29], thus achieving dilatancy treatment of the reservoir rock mass (see Figure 7).



(**a**) (**b**) (**c**) (**d**)

Figure 7. Schematic diagram of hydraulic dilatancy process. (**a**) Treatment of pre-dilatancy. (**b**) Formation of dilatancy area. (**c**) Extension of dilatancy area. (**d**) Dilatancy of large volume.

Although NGHs have the same rock mass conditions as oil sands, and are also weakly-consolidated undiagenetic reservoirs, NGH reservoirs, compared with oil sand reservoirs, have fine particles, low permeability, a high mud content and strong adsorption capacity among particles, especially in the Shenhu Sea area of the South China Sea. Because hydrate crystals are hidden in the pores of particles, the pressure in the pores is increased, the permeability of the pores is reduced, and the injected high-pressure fluids have difficulty entering the pores of particles. The mutual dislocation and separation among rock particles are realized by increasing the pressure in the pores and creating a large number of shear micro-fractures for dilatancy. Thus, for diffusion-type hydrates, use of this technology may lead directly to the tensile fracture of the rock mass, and the dilatancy of the rock mass cannot be fulfilled. However, for some leakage-type hydrate reserves, because hydrate crystals participate in the construction of the reservoir skeleton and have larger crystal structures, it is possible to use rock dilatancy deformation to form shear dilatancy zones and independent tensile micro-fractures to increase the porosity and permeability of reservoirs. In this way, the pressure conduction area and the gas production capacity of hydrates are improved. Further investigation and development are needed so that the stimulation of different types of NGHs resources can be achieved using the mechanism of hydraulic dilatancy.

3.4. Stimulation Technology Based on Electro-Hydraulic Effect

When pulse high voltage is applied to a group of electrodes in a liquid, the gaps between electrodes are instantaneously broken down to generate a strong arc spark discharge. High-density electric energy is converted into high-strength light energy, sound energy, electromagnetic energy, mechanical energy and chemical energy in a very short time with the help of high-temperature strong plasmas formed in a discharge channel in the liquid. Many experts and scholars all over the world have carried out theoretical and experimental research on this special discharge phenomenon. In 1955, Yutkin, an engineer in the former Soviet Union, found a way to generate huge levels of mechanical energy by discharging in the liquid. Thus, the mechanical energy produced by the electro-hydraulic effect can be used in the field of engineering applications and is referred to as the "electro-hydraulic effect" [30].

By exciting the arc discharge in a sealed cavity filled with liquids, some of the liquids in the discharge channel are instantaneously vaporized, decomposed and ionized into high-temperature plasmas. These plasmas expand quickly and generate a kind of rapid radial mechanical energy to produce strong shock waves and associated bubbles, which affect the surrounding reservoir rock masses, providing a path for the stimulation of reservoirs [31]. In the 1980s, several tools and technologies developed using the hydro-electric effect were introduced into the field of oil and gas exploitation and were widely used in some countries of the former Soviet Union [32]. As one of the conventional stimulation measures for oil and gas fields, in the 1990s, a number of downhole electric pulse detonation instruments were introduced in China and widely popularized in Xinjiang, Daqing, Ansai and other oilfields, achieving good application results [33]. The Institute of Electrical Engineering of the Chinese Academy of Sciences, PetroChina Exploration, the Development Research Institute, Xi'an Jiaotong University and some oilfields have carried out research for theory development as well as product development and application [34].

Presently, research on the mechanism of the hydro-electric effect have resulted in more systematic understanding. Through discharge in the water medium, high temperature gas and high temperature plasma are produced, resulting in strong shock waves acting on the reservoir rocks and fluids, with acceleration as high as 3000 times the acceleration of gravity [35]. Under the action of the shock wave, the respective point particles of discontinuous media, such as rock and liquid, vibrate violently. Moreover, under the action of the highly-accelerated impact, when the fatigue strength of the rock is exceeded, new micro-fractures or macro-fractures are caused (see Figure 8). At the same time, under the influence of the shock wave, the clay cement on the surface of rock particles is shaken off, and the clay particles filled in the pore throats between the rock particles are loosened or migrated [36]. This results in removal of the blockage of the pore throats, expansion of the pore throat radius and pore connectivity, and improvement in the permeability of reservoirs [37].

Mostly stored in muddy silt deep-sea sediments, NGHs are associated with a weakly-consolidated rock structure with a high mud content. Following the impact of an elastic wave, the continuity of the reservoir media is destroyed, and tensile fractures are easily formed. However, after the shock wave disappears, the fractures close rapidly and exhibit obvious plastic deformation. According to feedback from field applications, the use of the strong blasting ability of the hydro-electric effect is better for dealing with dense rocks with brittle failure characteristics, such as calcareous dolomite, siltstone, etc., and is slightly worse for rocks with relatively strong plasticity, such as mudstone [38]. On the other hand, due to the low cementation strength of hydrate reservoirs, under the action of a shock wave, the fractures formed in rocks expand forward at high speed and become large in scale with a long extension distance, which can be used to achieve deep reservoir stimulation. How to balance the above advantages and disadvantages to provide useful guidance for NGH reservoir stimulation requires further study.

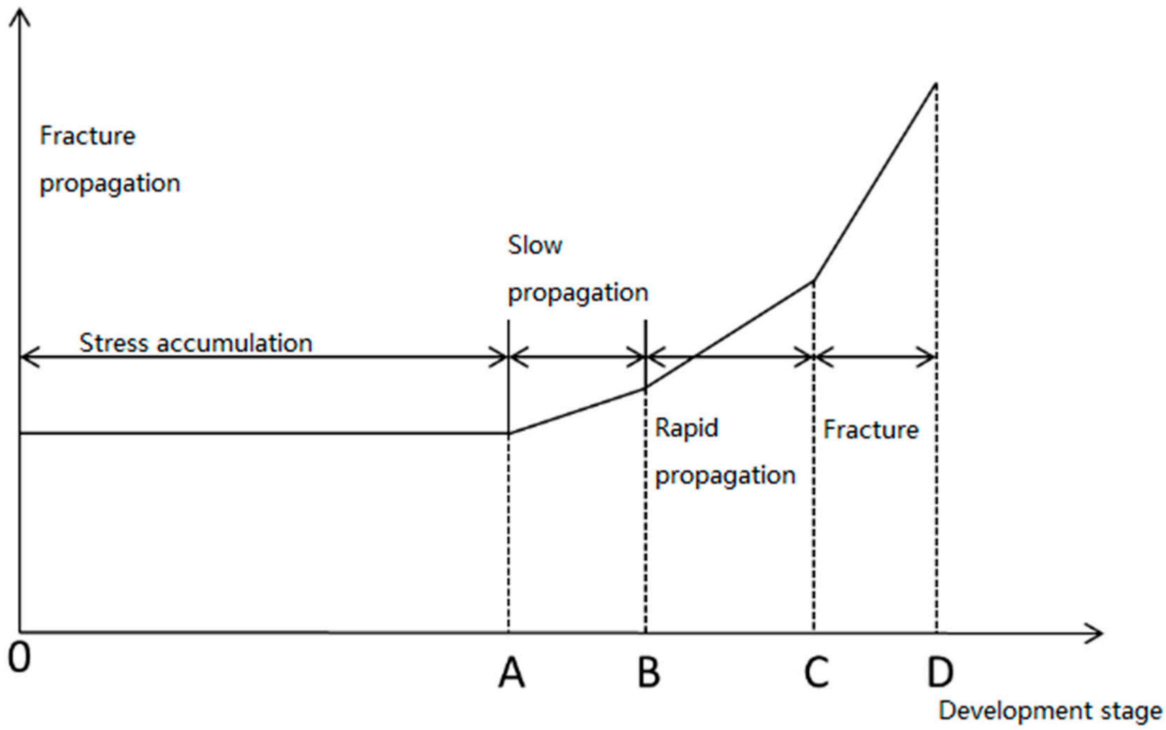


Figure 8. Relationship between fracture propagation and discharge.

In addition to stimulating the reservoir before exploitation, the high-pressure electro-hydraulic pulse stimulation device can be installed in the well for a long time as an auxiliary completion tool (see Figure 9), which will not interfere with the exploitation of NGHs, and can continuously discharge and shock the production layer during the subsequent exploitation process and produce conductive fractures. Additionally, blockage of seepage channels can be removed in time, the smoothness of the high-permeability channel can be maintained, and continuous production of NGHs can be guaranteed.

3.5. Selective Action of Electromagnetic Waves on Polar Molecules

In recent years, when evaluating NGH exploitation methods, a variety of heating modes have been applied to improve the efficiency of thermal stimulation methods. Liang et al. [39] used electric heating to heat hydrate reservoirs and compared the energy efficiency with hot water injection. They concluded that the efficiency of electric heating in vertical wells was higher than that of hot water injection. Rahim I et al. [40] analyzed the role of microwave and plasma radio frequencies in hydrate decomposition. Wang Bin, Zhao Jiafei et al. [41,42] carried out studies on heating hydrates by microwave. M R Davletshina et al. [43] of the Ufa State Petroleum Technological University and Li, D.L. and Liang, D.Q. of the Guangzhou Institute of Energy Conversion Chinese Academy of Sciences carried out experiments on heating hydrates by microwave [44]. It was found that microwaves have a very marked effect on NGH decomposition, and that hydrates can be decomposed in a very short time using low-power microwave radiation. In addition to the obvious "heating effect", electromagnetic waves also have a "non-thermal effect". Jin Youhuang et al. [45] conducted a microwave test on heavy oil cores in the Liaohe Oilfield and the "non-thermal effect" of microwaves on breaking molecular bonds was confirmed. Jeambey et al. [46] used alternating electromagnetic fields with different frequencies, intensities and waveforms acting on oil shale, finding that the hydrocarbons in the samples changed greatly, the molecular bonds of heavy hydrocarbons were broken, and a large number of small molecular hydrocarbons were formed.

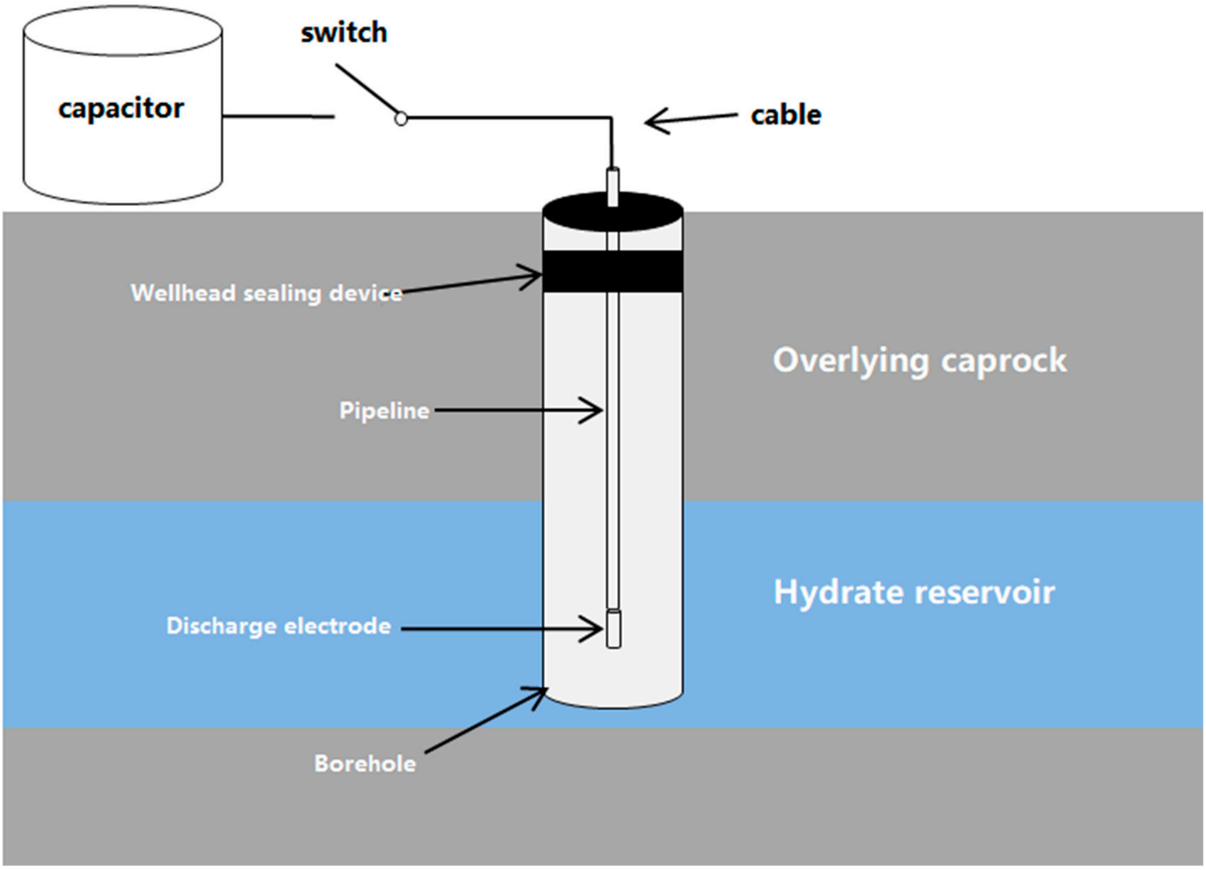


Figure 9. Schematic diagram of high-pressure electro-hydraulic pulse stimulation operation.

Due to the complexity of underground porous media conditions and the differences in the electrical parameters between different interfaces, the waveform path, and the amplitude and intensity of electromagnetic waves, will change in the process of propagation in underground porous media [47]. The frequency change of electromagnetic waves and the electrical characteristics of rocks determine the skin depth. The higher the frequency, the more obvious the skin effect is, and the smaller the penetration distance of electromagnetic waves [48]. The microwave frequency commonly used for heating in industry is 2450 MHz, and its penetration depth is about 0. 5~3 cm [49]. The decomposition effect of electromagnetic waves on hydrates is mainly due to the heating of the surface layer and the transfer of heat. Therefore, it is difficult to use electromagnetic waves to heat large-scale hydrate ore bodies.

NGHs in nature mainly refer to methane hydrate, which is mainly composed of water molecules and methane molecules. Water is a polar molecule in which the positive and negative charge centers do not coincide, so there is a certain dipole moment [50]. Methane is a tetrahedral nonpolar molecule with a dipole moment of 0. At low temperature, the positive and negative charge centers of polar molecules rotate under the action of the electric field to follow the direction of the external electric field [51]. When a large number of disorderly polar molecules are placed in an alternating electric field, the orientation of these polar molecules will change with the polarity of the electric field (see Figures 10 and 11).

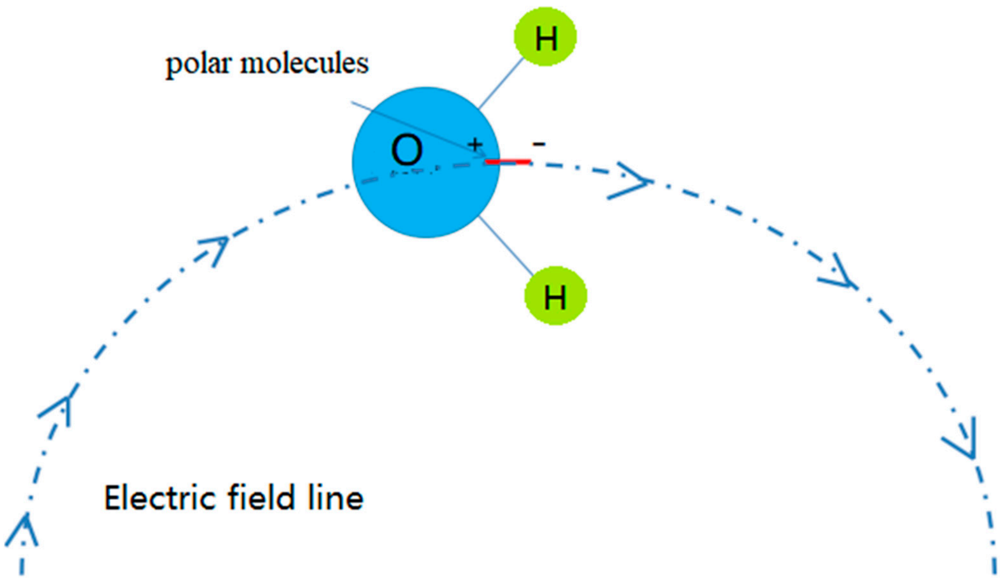


Figure 10. Schematic diagram of dipole moment affected by electric field.

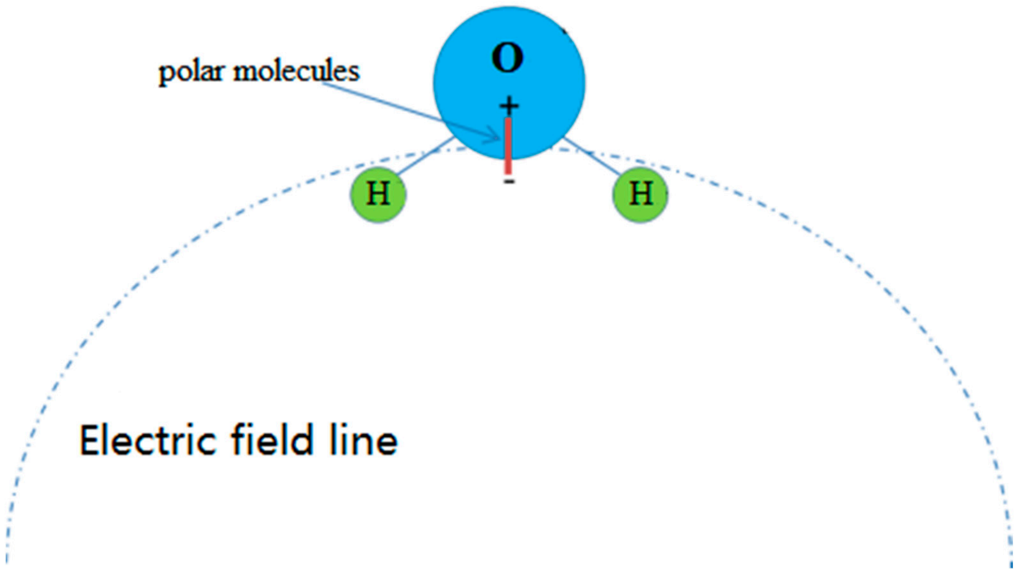


Figure 11. Illustration of deflection of dipole moment under action of electric field.

The application of technologies related to electromagnetic waves may become one of the methods used to more efficiently exploit NGH resources in the future. The transmission characteristics of electromagnetic waves in different media follow Maxwell's equations in the theory of electromagnetic wave propagation [52]. At the same time, the alternating change of magnetic and electromagnetic fields produces radiation of electromagnetic waves in the medium. The lower the electromagnetic wave frequency is, the smaller the influence of the medium, and the greater the distance it travels. In future, we can study and utilize the natural property of the dipole moment of polar molecules, which can strongly absorb electromagnetic wave energy, and the characteristics of non-polar molecules, which do not interact with electromagnetic wave field because of their zero dipole moment, to separate polar molecules from non-polar molecules and apply low-frequency electromagnetic fields directionally to hydrate ore bodies. The stronger the external electric field is, the faster the polarity changes after interacting with the dipole moment of polar molecules. Therefore, the bonds between water molecules are broken, gas molecules can escape from the holes between water molecules, and the gas in NGHs is separated through the non-heating electromagnetic effect.

From the perspective of engineering applications, combined with the geological conditions of NGHs in the South China Sea, this paper compares and analyzes several stimulation technologies suitable for weakly-consolidated reservoirs, and discusses the technical principles and mechanisms, as well as providing an adaptability analysis for the exploitation of NGHs, as shown in Table 1.

Table 1. Comparative analysis of several stimulation technologies.

Technology	Principle	Restrictions	Adaptability Analysis
Hydraulic fracturing	High-pressure pump units are used to inject the fracturing fluid into the wellhole at a rate that exceeds the absorption capacity of the stratum, which is forced to fracture, and then proppant is squeezed in to support the fractured fracture.	1. The operation cost is high, and the construction equipment occupies a large area. 2. There are certain requirements for reservoir thickness and sealing integrity. 3. The fracturing fluid shall be compatible with the physical properties of reservoirs.	The technology is mature, and the support facilities are complete, but the geological requirements are high, and the applicability of unconsolidated plastic rock masses is poor.
Hydraulic jet fracturing	High-pressure abrasive water jet is used to penetrate the casing and stratum to form spindle-shaped holes to relax the stress near the wellhole and increase the seepage area.	1. There is a long construction period. 2. It belongs to the near-wellhole transformation, and the effective distance is limited. 3. It is easy to induce sand production of the stratum.	The construction safety is high, and the application range is wide, but the construction efficiency needs to be improved and the control of sand production needs to be strengthened.
Rock dilatancy	By injecting the high-pressure fluid, the pore pressure is increased, the pore volume of rock masses is increased, and the complex large volume micro-tension-shear fracture area is formed.	1. The physical property of the reservoir is selective. 2. There is a long operation time. 3. It is necessary to carefully control the volume of stimulation.	The action distance is long, the volume of the affected ore bodies is large, no proppant is needed, and the application to weakly-consolidated loose sandstones is mature.
Electrical pulse detonation	The shock wave produced by electrode high voltage discharge is used to shock the reservoir and increase the complexity of wellhole fractures.	1. Accurate stimulation can be carried out for the quasi-reservoir. 2. It can be placed in the well as a completion production string, and the production will not be affected during the stimulation.	It is mainly used near the wellhole to dredge the diversion channel and increase the permeability and has great potential for production and application.
Electro-magnetic wave resonance	The high-frequency resonance of the electromagnetic wave is utilized to drive water molecules to generate heat by friction to increase the heat, and the thermal radiation is utilized to promote the decomposition of hydrates, so that the thermal efficiency is higher.	1. It is effective for open hole wells and cannot be used in casing and screen wells. 2. Electromagnetic waves have a limited penetration distance in the stratum and has a heating effect on the shallow surface of the borehole wall, so it is difficult to heat the hydrate ore body on a large scale.	The reservoir is accurately heated to improve the hydrate decomposition rate; it can be placed in the well as a completion production string, and heating does not affect production.

4. Discussion and Recommendation

In recent years, NGHs, as an alternative resource with huge potential, have attracted wide attention. Several countries have invested huge amounts of money to carry out exploration, production testing and research into NGHs. The breakthrough in the production test projects of NGHs in China and Japan has inspired confidence in exploiting this clean natural gas resource.

However, weak-consolidated NGHs reservoirs have the characteristics of loose structure, weak bearing capacity and easy collapse, which greatly limit the scope for application of reservoir stimulation technologies. With decomposition of the hydrate, physical and mechanical properties of the rock stratum change accordingly. The gas and water generated by hydrate decomposition increase the pore pressure sharply, and the degree of cementation between the clay particles is weakened due to increase in the local stress concentration, and the geomechanical stability of the reservoir reduces significantly [53]. How reservoir transformation and stimulation technology affect the mechanical and physical properties of the formation will be key areas of research in the future.

At present, the exploitation of NGHs has just begun, and no commonly accepted method of exploitation has yet been developed. Most methods focus on the use of stimulation measures in the initial stage of NGH exploitation. Due to restrictions caused by the lack of understanding and research on NGHs, the seepage capacity of NGH reservoirs needs to be enhanced, the migration problems of gas, liquid and solid in reservoirs after the decomposition of NGHs need to be solved, and the mechanism of multi-phase flow in muddy silt reservoirs remains unclear. At present, we cannot effectively improve reservoir seepage capacity, which greatly restricts NGH exploitation efficiency.

Although there is a complex situation of multi-phase transition and multi-field coupling in NGHs, from the macro-perspective, the important factor that determines the decomposition rate of NGHs is the seepage capacity of the stratum. The development of horizontal wells and hydraulic fracturing technology has greatly improved the rate of extraction of shale gas, and has also increased the final recovery of a single well. The level of recovery of production wells has increased to between 15% and 35%, reducing the production cost of shale gas, leading to the industrialization of shale gas, providing inspiration for the industrialization of hydrates. As a result of NGH production testing in the China Sea area, the contact area between the wellhole and reservoir has been increased using complex structure wells. Together with stimulation reconstruction of the reservoir near the wellhole, the increased contact area can greatly increase production. Based on the seepage mechanism in porous media, the permeability of the stratum is increased by expanding the size and total area of the fracture, which, on the one hand, provides a channel for low pressure conduction in the wellhole to promote the continuous decomposition of NGHs, and, on the other, reduces resistance to the migration of decomposed water to the wellhole. These measures are beneficial in improving the decomposition efficiency of NGHs and increase gas production of a single well by improving and maintaining the seepage capacity of the stratum. However, the long-term effect of reservoir stimulation cannot be determined due to the short production test cycle.

The first two rounds of production testing of NGHs in the sea area mainly focused on near-wellhole stimulation, and it is urgently required to carry out more extensive and large-scale controllable stimulation technologies to address the problem of the release of deep NGH resources, and to further improve the effect of increasing and stabilizing the production of a single well. Therefore, it is suggested that, in subsequent production test projects of NGHs in the South China Sea, in light of the above-mentioned reservoir stimulation technologies, that systematic research should be carried out, giving priority to hydraulic dilatancy stimulation technology which can be supplemented by electromagnetic detonation and other technical means to dredge solid particle blockages near the wellhole, focusing on the phase transition dynamic treatment technology of NGHs, and studying well control safety and fracture monitoring technologies in the process of reservoir stimulation. Adaptability evaluation of weakly-consolidated reservoir stimulation technologies should be carried out, and related scientific research and experimental simulation should be conducted to ensure smooth progress of NGH industrialization.

5. Conclusions

(i) The key issues for increasing NGH production are improvement in the decomposition rate of hydrates, expansion of the size of seepage channels and maintenance of the long-term effectiveness of seepage capacity. The breakthrough of the development of reservoir stimulation technology is key to achieving the industrialization of NGHs in the future.

(ii) Several types of weakly-consolidated reservoir stimulation technologies have been optimized, which are suitable for different geological conditions and application scenarios. In the diffusion-based stratum, hydraulic jet fracturing technology has obvious advantages, while in the leakage-based stratum, hydraulic dilatancy technology exhibits better adaptability. Electric pulse detonation technology and electromagnetic wave resonance technology can continuously stimulate the reservoir in the later production process and there is no need to stop production.

(iii) The understanding of, and research into, NGHs is still at a relatively early stage. When exploring different reservoir stimulation technologies, we should pay attention to the combination of geology and engineering, strengthen process quality control, and avoid environmental safety risks.

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