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The World's First Experimental Simulation Technology and System of Solid Fluidization Exploitation of Marine Non-diagenetic Natural Gas Hydrate

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Abstract—With huge reserves, marine natural gas hydrate is one of the most potential unconventional alternative energy sources after shale gas, coalbed methane and tight gas. The research and pilot engineering of natural gas hydrate exploitation technology mainly adopts the depressurization method at home and abroad, all of which refer to the exploitation technology of conventional oil and gas. However, if the depressurization method is used to exploit the weak cementing and unstable non-diagenetic marine natural gas hydrate, the hydrate will be decomposed disorderly and uncontrollably, and 6 great risks will be faced. Therefore, the project team led by Academician Zhou of the Chinese Academy of Engineering divided the hydrate into the kind of diagenetic and non-diagenetic, proposed the technological strategy of 6 "utilize", firstly created the technological principle of solid fluidization exploitation of non-diagenetic natural gas hydrate and the technological process of hydrate mining, crushing, ejection and fluidization of seawater, separation and backfill of sand, slurry lift and deep separation and re-backfill in the platform, and achieved the safe and green exploitation which let nature take its course, turned the harm into a benefit, and turned the uncontrollable into controllable. Based on this principle, Southwest Petroleum University invented the experimental simulation method and technology, cooperating with China National Offshore Oil Corporation and Sichuan Honghua Petroleum Equipment Co. Ltd. The overall process simulation of solid fluidization exploitation with water depth of 1500 m and pipeline length of 4500 m is achieved. The world's first large physical experimental simulation system of solid fluidization exploitation of marine natural gas hydrate is researched and developed, which has full independent intellectual property rights and includes 3 modules and 12 subsystems of sample preparation of hydrate, crushing and slurry modulation, high-efficient pipeline transportation and separation of slurry, image capture in real-time, data collection and automation of security control and so on. Moreover, the experiment of solid fluidization exploitation is carried out systematically for the first time, which provided an important basis for the formulation of the test scheme, the optimization design of the process and the research and development of downhole tools, supported the world's first successful test exploitation of solid fluidization method, and proved the scientific feasibility of the principle and the technology of solid fluidization exploitation. The experimental simulation technology and system, as well as the first testing results, were reported in the Journal Science. The successful research and development and the further upgrading of the system are expected to promote the technology of solid fluidization exploitation of marine non-diagenetic natural gas hydrate to become a disruptive

technology leading the world's frontiers, and are expected to accelerate the commercial development of natural gas hydrate in China and even the whole world.

Keywords—marine non-diagenetic natural gas hydrate; solid fluidization; exploitation; physical simulation; experimental system; test scheme

I. INTRODUCTION

Natural gas hydrate, commonly called combustible ice, is a kind of ice-like cage crystal compound formed by hydrocarbon gas such as methane and water in the condition of high pressure and low temperature. It mainly distributes in the permafrost zone of the land and the coastal continental shelf with water depth of 300～3000 m [1-2]. It is estimated that the total amount of methane hydrate in the world is $1 \sim 5 \times 10^{15}$ m^3 (Milkov and Sassen, 2002) [3], and the total amount of marine resources is about 2.83×10^{15} m^3 (Boswell and Collett, 2011) [4]. The natural gas hydrate resources in the sea area of China are about 1×10^{14} m^3 [5], and the resources in the 11 hosting areas in the South China Sea are about 0.85×10^{14} m^3 [6]. Natural gas hydrate is one of the most potential unconventional alternative energy sources after shale gas, coal bed gas and dense gas. Especially, the safe and efficient development of marine natural gas hydrate is an innovative technology field in the world.

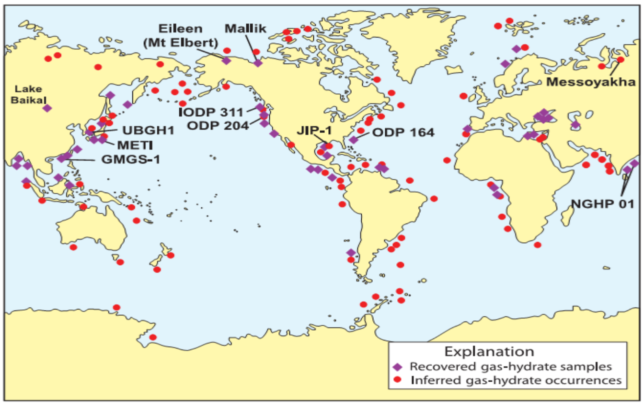


Fig. 1. The distribution of natural gas hydrate worldwide

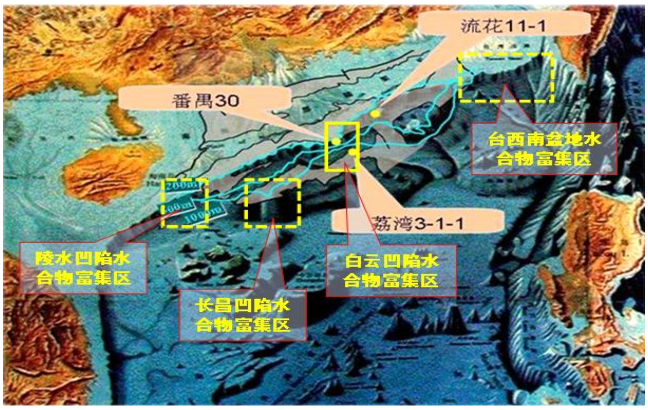


Fig. 2. The distribution of natural gas hydrate in South China Sea

II. OCCURRENCE CHARACTERISTICS AND EXPLOITATION RISKS OF NATURAL GAS HYDRATE

According to the natural gas hydrate's occurrence state of sandstone type, sandstone fissure type, vein block type, fine grain fissure type and dispersed type, Hydrate types can be divided into permafrost sandstone hydrate, marine silty mudstone hydrate, marine vein massive hydrate and marine argillaceous rock hydrate (as shown in Fig.3), of which marine hydrates account for more than 90%. Compared with conventional oil and gas reservoirs, most of the marine gas hydrate hosting areas are characterized by shallow burial depth, loose mineral deposits, weak cementation or no cementation, instability, no tight cap rock, and no well-developed source-reservoir-cap rocks. Therefore, marine natural gas hydrates are classified as diagenetic and non-diagenetic hydrates as shown in Fig.4: 1) Diagenetic gas hydrates fill pores and fissures in rocks with certain traps structures and rock skeletons. 2) Non-diagenetic gas hydrate has no rock skeleton and hydrate itself is "rock skeleton", it's weakly cemented and unstable, and it's easy to collapse and be decomposed disorderly affected by external influence. Compared with conventional oil and gas reservoir types, marine non-diagenetic gas hydrate hosting areas are characterized by shallow burial depth, weak cementation, no tight cap rock and well-developed source-reservoir-cap rock. Marine non-diagenetic natural gas hydrates account for more than 85% of marine hydrates and 76.5% of total resources.

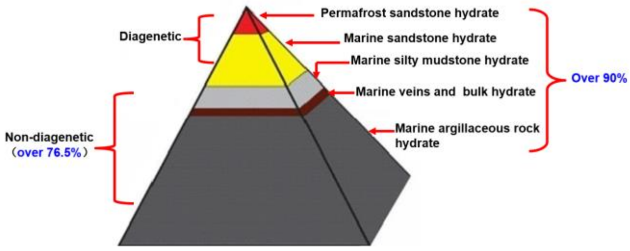


Fig. 3. Distribution pyramid of natural gas hydrate resources in different occurrence states

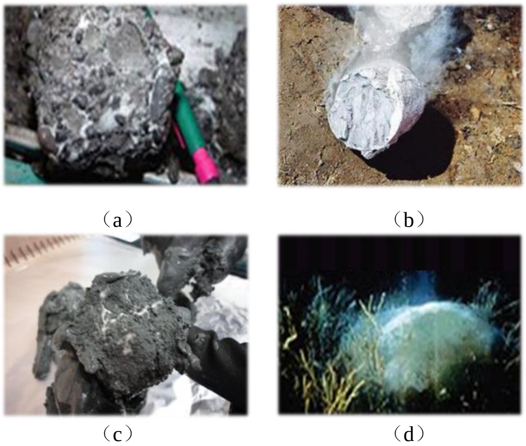


Fig. 4. Diagenetic (a、b) and non-diagenetic (c、d) natural gas hydrate

The main research and test projects of natural gas hydrate exploitation technology at home and abroad are as follows: The former Soviet Mezzoja permafrost region of Siberia, Canada's Mackenzie tundra (twice), Frozen ground on Alaska's north slope, Sea area of Aichi Prefecture, Japan (3 times), Shenhu area, South China Sea (China Geological Survey), Shenhu area, South China Sea (CNOOC, SWPU etc, solid fluidization exploitation). Except for the solid fluidization method, the depressurization method is the main method, and the conventional oil and gas production technology is used for reference. The depressurization exploitation for both diagenetic hydrates and non-diagenetic hydrates is short-term scientific research test and mining. Because of the short time of test exploitation, the environmental safety, equipment safety, production safety and engineering geological risks faced by long-term mining are neglected.

As shown in Fig.5, using the depressurization method to exploit the non-diagenetic gas hydrate, the undersea hydrate decomposes in situ, partly flows to the bottom of the well, and escapes into the sea water in large quantities, and the hydrate will face the following six risks if it decomposes disorderly and can not be controlled. 1) Plugging and shutting down caused by mud and sand entering well. 2) A large amount of decomposed gas is dissipated into the sea water, resulting in waste of resources, low gas recovery rate and low production. 3) During long term exploitation, hydrate ore body collapses, resulting in stratum instability and submarine landslide, etc. 4) The deformation of seabed structure leads to the instability and loss of control of production equipment, resulting in the risk of production safety. 5) Large quantities of loose natural gas inflated freely, causing disaster to ships at sea and damaging marine ecology. 6) Large quantities of natural gas entering the atmosphere produce greenhouse effect.

Therefore, if the marine non-diagenetic natural gas hydrate is not reasonably exploited, it will cause catastrophic accidents, and the six risks it faces have always been the focus of attention in the development of marine non-diagenetic natural gas hydrate. It is necessary to adopt safe and effective scientific and technological innovation methods for green exploitation of this kind of hydrate resources.

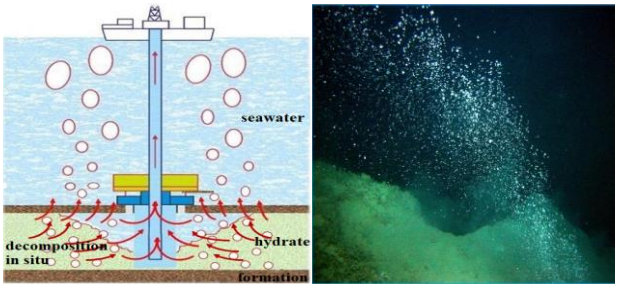
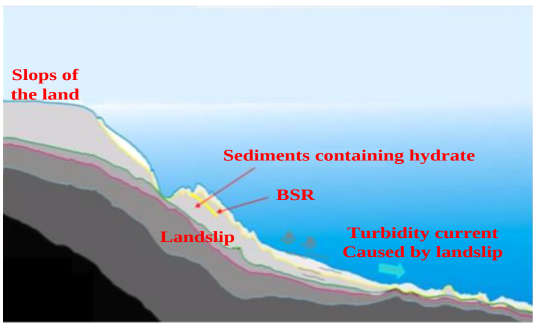


Fig. 5. Depressurization principle (left) and decomposition gasification diagram (right) of marine non-diagenetic hydrate



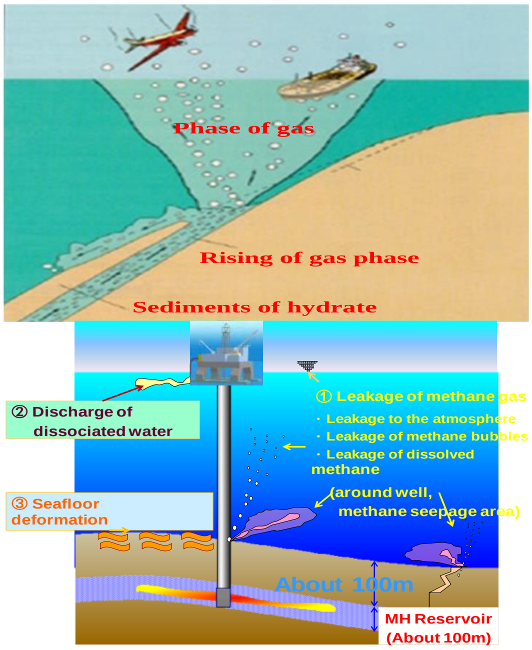


Fig. 6. Depressurization principle (left) and decomposition gasification diagram (right) of marine non-diagenetic hydrate

III. SCIENTIFIC THOUGHT ON SOLID FLUIDIZATION EXPLOITATION OF MARINE NON-DIAGENETIC NATURAL GAS HYDRATE

In December 2012, the project team headed by Zhou Shouwei, Academician of Chinese Academy of Engineering, firstly put forward solid fluidization exploitation method of marine non-diagenetic natural gas hydrate in the “Shuangqing Forum”. The new approach was further elaborated at the 9th International Methane Hydrate R&D Workshop conference in India in November 2014. It has realized 6 “utilize” technical strategies: 1) Utilize the geological characteristics of shallow burying, loose, and easiness to crush and fluidize of non-diagenetic hydrate in the shallow layer. 2) Utilize the seabed environment conditions of which the sea bed temperature and pressure are relatively stable and difficult to be separated. 3) Utilize the natural rise of temperature and natural decrease of pressure from the ocean floor to the ground. 4) Utilize the difference of specific gravity between hydrate and sediment and the convenience of initial swirl separation to achieve partial automatic sand precipitation. 5) Utilize the surface temperature of seawater as the ejection liquid to heat and make it decompose. 6) Utilize the physical characteristics of natural resolution, phase change and gaseous lifting of natural gas hydrate in condition of temperature rise and pressure reduction.

Based on the technical strategy of six “utilize”, the core idea of solid fluidization exploitation is: the solid hydrate is first broken up, then fluidized into hydrate slurry, and then enters into a closed pipeline to initially decompose, lifts to the offshore platform for deep decomposition, and starts the separation of gas, liquid and solid, so as to obtain natural gas. Furthermore, the technological process of solid fluidization exploitation of marine non-diagenetic natural gas hydrate is established as shown in Fig.7, including: undersea excavation of the hydrate, pulverize and refine, leading jet and fluidization of seawater, separation and backfill of sand, fluidization and lift of the slurry, deep separation and backfill on the platform and other units. Its scientific essence is to transform the non-diagenetic uncontrollable hydrate reservoir into the controllable hydrate reservoir in the closed pipeline, realizing the controllable and orderly decomposition of the natural gas hydrate in the closed pipeline, and realizing the safe and green exploitation.

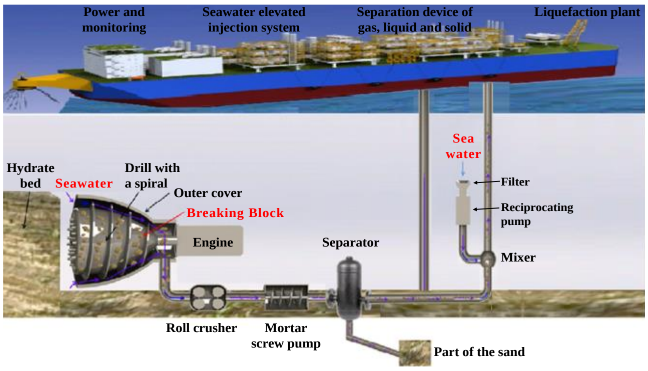


Fig. 7. Depressurization principle (left) and decomposition gasification diagram (right) of marine non-diagenetic hydrate

Is the principle of solid fluidization exploitation scientific and feasible? Can solid fluidization exploitation process be realized? How to carry out the test exploitation project of solid fluidization exploitation? In order to answer the above three questions, the project team carried out comprehensive research on the development of natural gas hydrate, invented and developed a large-scale physical simulation experimental system for solid fluidization exploitation of marine non-diagenetic natural gas hydrate with completely independent intellectual property rights. The whole process simulation of the process of solid fluidization exploitation was designed and developed, and the first marine non-diagenetic natural gas hydrate exploitation laboratory in the world was established.

IV. LARGE-SCALE PHYSICAL SIMULATION EXPERIMENT SYSTEM OF SOLID FLUIDIZATION EXPLOITATION OF MARINE NON-DIAGENETIC NATURAL GAS HYDRATE

On April 28, 2015, the world's first marine non-diagenetic gas hydrate solid fluidization exploitation laboratory was inaugurated at Southwest Petroleum University. The world's first large-scale physical simulation experiment system of marine non-diagenetic natural gas hydrate solid fluidization exploitation with completely independent intellectual property rights has been successfully invented and developed, as shown in Fig.8. The system consists of 3 modules of rapid preparation of large samples, fragmentation and slurry modulation, high-efficient pipeline transportation and separation of slurry, and real-time image capture, data collection and safety control and 12 subsystems of preparation, fragmentation, slurry modulation, screw pump conveying, horizontal pipeline transportation and decomposition, vertical pipeline transportation and decomposition, multistage depressurization, multistage heating, sample analysis of on-line automatic preservation of heat and pressure, three-phase separation, operation monitoring, and image capture and data test and analysis.

Fig. 8. The world's first large-scale physical simulation experiment system of solid fluidization exploitation of marine non-diagenetic natural gas hydrate

Large-scale physical simulation experiment system of solid fluidization exploitation of marine non-diagenetic natural gas hydrate has realized the simulation of the whole process of solid fluidization exploitation of 1500 m water depth and 4500 m pipe length, including:

1) Experimental method and technology of "trinity" of rapid preparation of large samples, fragmentation and slurry modulation of hydrate. Breaking through the bottleneck of rapid preparation of large sample in situ, the hydrate formation process in the environment of pressure of 0～16 MPa, temperature of 2～5 ℃ was simulated, realizing the preparation of world's largest sample size of 1062 L, and making the preparation time less than 20 h. Breaking through the bottleneck of fragmentation technology in situ, up-and-down movable and rotating crushing tools was invented to achieve crushing simulation in situ. Breaking through the bottleneck of slurry modulation technology, the seawater and mud and sand were mixed quantitatively, and the hydrate slurry was modulated precisely.

2) Method and technology of fidelity migration of hydrate slurry to pipeline transportation system. Breaking through the bottleneck of heat preservation, pressure-holding, granularity keeping and safe migration of hydrate slurry, circulate sea water with high pressure and low temperature to the pipeline transportation system by using a stable pressure and refrigeration system to reach the temperature and pressure of the preparation kettle, utilize the stable pressure system to make up the pressure of the preparation kettle automatically, utilize the filter system to ensure hydrate size to be required for experiment, and utilize pressure differential plugging removal system to automatically ensure safe movement of hydrate slurry.

3) Experimental simulation method and technology of pipeline transportation of hydrate particles, mud and sand, decomposed gas, and complex slurry with prepared sea water in the way of piecewise combination, point by point encryption, multiple cycles, multiple depressurization, and multiple heating at the horizontal section of 56 m, and vertical section of 30 m. Breaking through the bottleneck of phase change non-equilibrium simulation technology, simulate the natural decomposition and gas lifting of gas hydrate. Breaking through the technical bottleneck of continuous regulation of temperature and pressure in the condition of material balance, it adopts whole process simulation process of piecewise combination, point by point densification, multiple cycles (simulate the height of gas hydrate slurry transported up the pipeline each time), multiple depressurization (submarine high pressure decreases

to low pressure on the sea surface step by step), and multiple heating up (submarine low temperature rises to the temperature on the sea surface step by step). Breaking through the technical bottleneck of high slippage, high solid phase and high suction port pressure of multiphase pump, apply screw pump to reduce slippage, apply high eccentricity of stator and rotor to realize high particle size and high solid phase conveying, and apply mechanical and rotary seal to increase inlet pressure. Experimental simulation method and technology of pipeline transportation of hydrate particles, mud and sand, decomposed gas, and complex slurry with prepared sea water is invented, realizing whole process simulation of pipeline transportation from seabed to sea surface in solid fluidization exploitation with 1500 m water depth and 4500 m pipe length.

V. Simulation Experiment of Solid Fluidization Exploitation of Marine Non-Diagenetic Natural Gas Hydrate

Based on the formation physical properties of natural gas hydrate reservoir in the target area of test production with water depth of 1310 m, and buried depth of 117～192 m, such as argillaceous silty sand, loose argillaceous cementation, non-diagenesis, average porosity of 43%, and average saturation of 40%, the simulation experiment of solid fluidization exploitation of marine non-diagenetic gas hydrate is carried out supported by the large-scale physical simulation experiment system, and the flow chart is as follows:

1) Simulate and prefabricate gas hydrate (sand included) samples based on marine gas hydrate composition. After the hydrate ore body is formed in the preparation kettle, it is broken in situ, and quantitative seawater is added when it is broken to precisely prepare the hydrate slurry needed for the experiment, and then it is safely migrated to the high-efficient pipeline transportation and separation module of hydrate slurry without changing the temperature, pressure, and granularity.

2) Through multiple cycles (30 m height rising in vertical pipeline of each simulated solid fluidization exploitation), multiple pressure regulation (submarine high pressure to low sea surface pressure), and multiple heat transfer and temperature rise (submarine low temperature to sea surface temperature), the experimental data of each group is synthesized to complete the whole process of pipe flow simulation.

3) The dynamic images and experimental data such as temperature, pressure, flow rate and particle size are collected and stored automatically in the whole process of the experiment, and the experimental analysis and processing are carried out.

A. Simulation experiment on rapid preparation of large samples of marine non-diagenetic natural gas hydrate

Large samples of non-diagenetic natural gas hydrate (Fig. 9) were prepared experimentally, the variations of resistivity, acoustic velocity and hydrate saturation with different particle size, compaction degree, shale content and other parameters of the samples were tested and analyzed, as shown in Fig. 10 and Fig. 11.

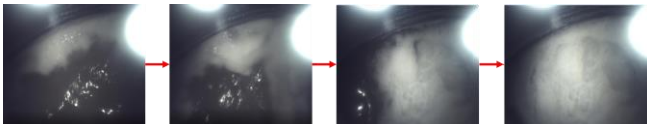


Fig. 9. Preparation of large samples of non-diagenetic natural gas hydrate

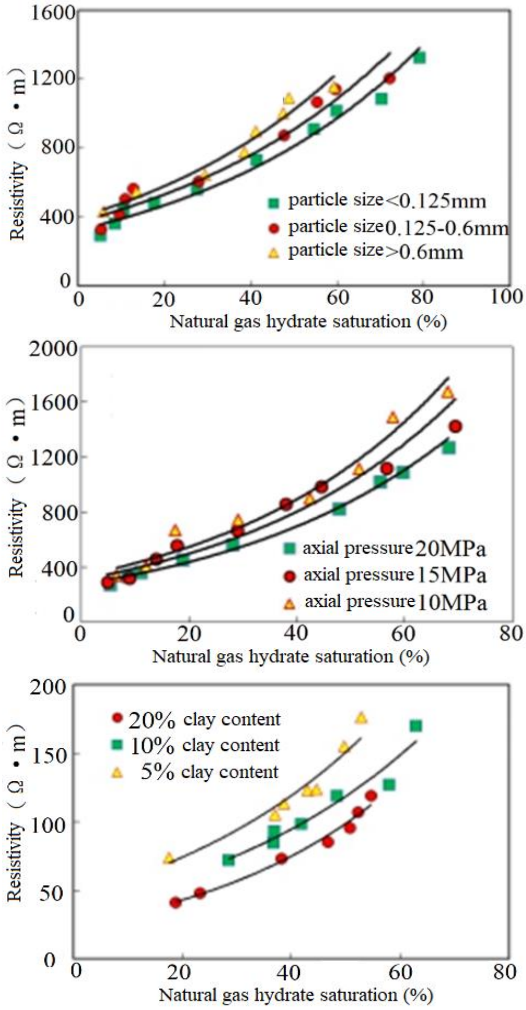
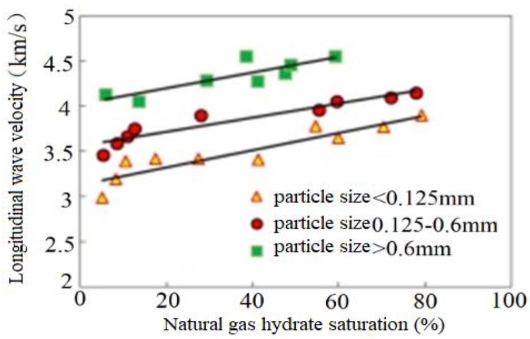


Fig. 10. Variations of resistivity and hydrate saturation with different particle size (left), compaction degree (middle), and shale content (right)



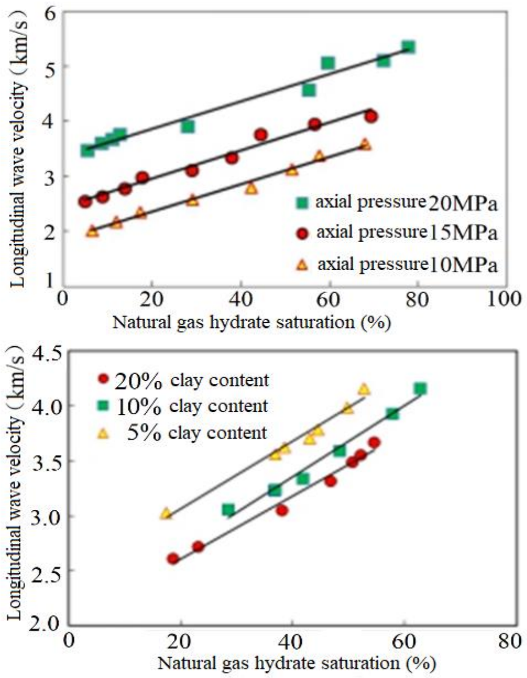


Fig. 11. Variations of acoustic velocity and hydrate saturation with different particle size (left), compaction degree (middle), and shale content (right)

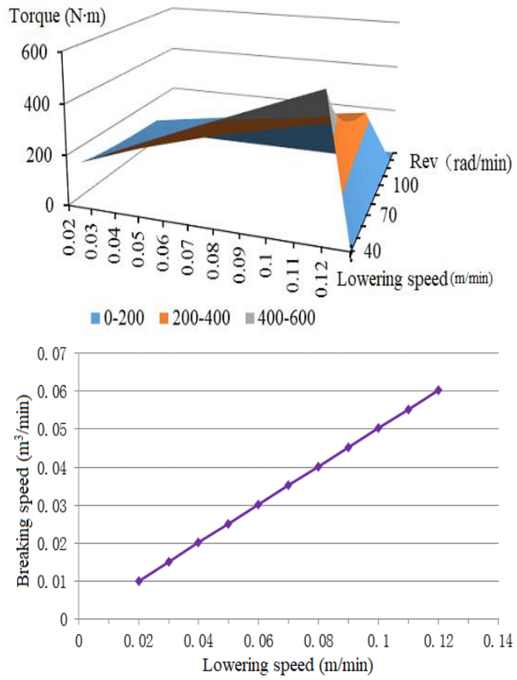
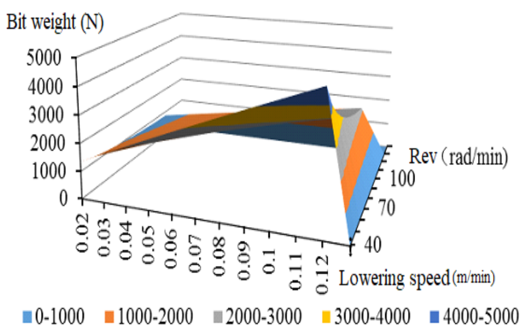


Fig. 12. Variation regularity of weight loss (left) torque (middle) and crushing efficiency (right) along rotating speed and lowering speed in mechanically fractured hydrates

It can be seen from Fig.10 that the saturation of marine non-diagenetic natural gas hydrate calculated through the preparation experiment of large samples has a certain exponential relationship with the resistivity in different particle size, compaction degree and shale content. And it can be seen from Fig.10 that: in the preparation experiment of large samples with different particle size, compaction degree and shale content, the P-wave velocity increases with the increase of hydrate saturation and has a good linear relationship. When the saturation is constant, the resistivity and P-wave velocity increase with the increase of sediment grain size, and decrease with the increase of axial pressure and shale content.

B. Crushing experiment of marine non-diagenetic natural gas hydrate samples

The effects of different mechanical crushing parameters (velocity is 0.02～0.12 m/min, rotation speed is 40～120 rpm) on the breakage of non-diagenetic natural gas hydrate are simulated and evaluated experimentally (Fig. 12), and the mechanical crushing engineering plate of marine non-diagenetic gas hydrate sample is established.



It can be seen from Fig. 12 that when the rotary speed of the cutter head is fixed, the bit weight increases gradually with the increase of the lowering speed, and with the increase of the rotating speed, the bit weight decreases gradually with the increasing rate of the lowering speed; When the lowering speed is fixed, the bit weight of gas hydrate broken by cutter head decreases gradually with the increase of rotating speed; When the rotating speed of the cutter head is fixed, the torque increases with the increase of the lowering speed, and with the increasing of the rotating speed, the torque decreases gradually with the increasing rate of the lowering speed; When the lowering speed is fixed, the torque of breaking gas hydrate with cutter head decreases gradually with the increase of rotating speed; The efficiency of crushed orebody increases linearly with the increase of lowering velocity.

C. Experiment on high-efficient pipeline transportation and separation of marine non-diagenetic natural gas hydrate slurry

The phenomena of vertical pipeline transportation and the variation of rock carrying capacity before and after hydrate decomposition were obtained by experiments [24-25], as shown in table I and Fig.13. It can be seen that with the increase of displacement, the solid particles in the vertical pipeline in turn experienced several kinds of movement states, such as downward movement, partial suspension, suspension, partial upward movement, upward movement, and a large amount of upward movement. Before hydrate decomposition, the solid particles of 2 mm in diameter suspend at the critical displacement of 0.912 L/s, while the solid particles of 5 mm in diameter do not suspend until the critical displacement comes to 1.440 L/s. It shows that the smaller the solid particles are in the process of vertical pipeline transportation, the smaller the particle size is, and the easier it is to transport. After hydrate decomposition, the solid particles will move up when gas phase passes through, and then move down again after the passing through of gas phase because of the carrying effect of gas phase rising. On the whole, the critical displacement required for solid particle suspension is 0.960 L/s, smaller than that in the absence of gas phase in the wellbore.

TABLE I. EXPERIMENTAL PHENOMENA OF VERTICAL PIPELINE TRANSPORTATION AND THE VARIATION OF ROCK CARRYING CAPACITY BEFORE AND AFTER HYDRATE DECOMPOSITION

Displacement, L/s	***corresponding liquid velocity, m/s***	***before hydrate decomposition （2 mm in diameter）***	***before hydrate decomposition （5 mm in diameter）***	***after hydrate decomposition （5 mm in diameter）***
0.768	0.168	Particles move down	Particles move down	
0.864	0.189	Partial particles suspend、a small number of particles move down	Particles move down	Particles move down
0.912	0.200	Particles suspend	Partial particles suspend、partial particles move down	
0.960	0.211	/	/	Particles suspend
1.056	0.232	/	/	Partial particles suspend、partial particles move up
1.440	0.316	Particles move up	Particles suspend	A large number of particles move up
1.920	0.421	A large number of particles move up	Particles move up	/

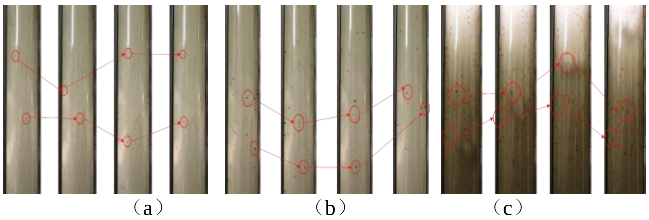


Fig. 13. Experimental phenomena of vertical pipeline transportation before and after hydrate decomposition (a. before hydrate decomposition, with displacement of 0.912 L/s, particles of 2 mm in diameter; b. before hydrate decomposition, with displacement of 1.440 L/s, particles of 5 mm in diameter; c. after hydrate decomposition, with displacement of 0.960 L/s, particles of 5 mm in diameter

Meanwhile experiments were conducted to obtain the phenomena of horizontal pipeline transportation experiments before and after hydrate decomposition and the variation regularity of rock carrying capacity as shown in Table II and Fig. 14.

It can be seen that with the increase of displacement, the solid particles in the horizontal pipeline experienced several motion states such as deposition, starting of small particles, starting of large particles, migration of both large and small particles, and a large number of particles moving rapidly. Before hydrate decomposition, the solid particles with a diameter of 2 mm start at a displacement of 0.960 L/s, while the particles with a diameter of 5 mm start at a displacement of 1.200 L/s. It shows that the smaller the particle size is, the easier it is to transport in horizontal pipeline transportation. After hydrate decomposition, due to the influence of decomposition gasification, the density of the mixed fluid in the horizontal pipeline decreases. The critical starting capacity of solid particles with diameter of 2 mm is increased to 1.104 L/s, while that of particles of 5 mm with diameter of 5 mm is increased to between 1.200 and 1.440 L/s.

TABLE II. EXPERIMENTAL PHENOMENA OF HORIZONTAL PIPELINE TRANSPORTATION AND THE VARIATION OF ROCK CARRYING CAPACITY BEFORE AND AFTER HYDRATE DECOMPOSITION

Displacement, L/s	***Corresponding liquid velocity, m/s***	***Before hydrate decomposition***	***After hydrate decomposition***
0.720	0.158	No migration of solid particles	-
0.960	0.211	Critical start of small particles (2mm)、no movements of large particles (5mm)	No migration of solid particles
1.104	0.242	/	Critical start of small particles、no migration of large particles
1.200	0.263	Migration of small particles (2mm)、Critical start of large particles (5mm)	Migration of small particles、no migration of large particles
1.440	0.316	Migration of both large and small particles	Migration of both large and small particles

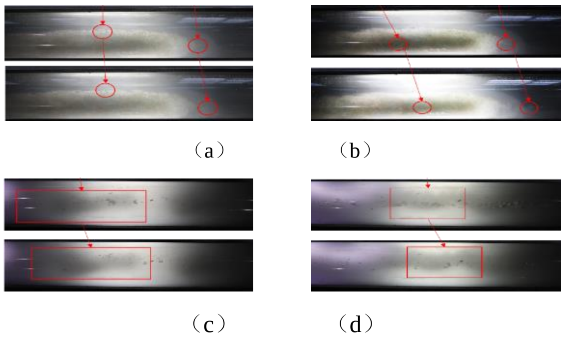


Fig. 14. Experimental phenomenon of horizontal pipeline transportation before and after hydrate decomposition (a. before hydrate decomposition, displacement of 0.960 L/s, critical starting of particles with diameter of 2 mm; b. before hydrate decomposition, displacement of 1.200 L/s, critical starting of particles with diameter of 5 mm; c. after hydrate decomposition, displacement of 1.104 L/s, critical starting of particles with diameter of 2 mm; d. after hydrate decomposition, displacement of 1.200 L/s, no movement of particles with diameter of 5 mm)

In order to analyze the gas-liquid-solid multiphase non-equilibrium flow in solid fluidization exploitation of marine non-diagenetic natural gas hydrate, a mathematical model has been developed [26]:

Continuity equation of gas phase:

$$\frac{\partial}{\partial t}(A\rho_{\rm g}E_{\rm g})+\frac{\partial}{\partial z}(A\rho_{\rm g}E_{\rm g}v_{\rm g})=q_{\rm g} \quad (1)$$

Continuity equation of liquid phase:

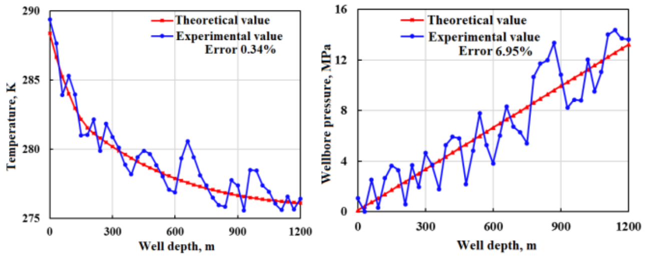
$$\frac{\partial}{\partial t}(A\rho_l E_l)+\frac{\partial}{\partial z}(A\rho_l E_l v_l)=q_l \tag{2}$$

Mixing momentum equation of gas-liquid-solid:

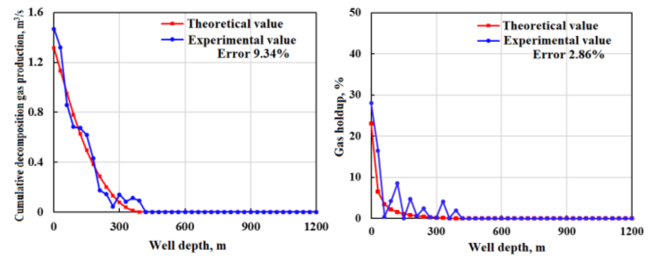
$$\frac{\partial}{\partial t}(\rho_l v_l E_l+\rho_g v_g E_g+\rho_s v_s E_s)+\frac{\partial}{\partial z}(p+\rho_l v_l^2 E_l+\rho_g v_g^2 E_g+\rho_s v_s^2 E_s) \\ +(\rho_l E_l+\rho_g E_g+\rho_s E_s)g+\frac{\lambda\rho_m v_m^2}{2d}=0 \tag{3}$$

Where q_g is the generation rate of methane gas from the decomposition of natural gas hydrate in the control volume, kg/(s m); q_l is generation rate of water from the decomposition of natural gas hydrate in the control volume, kg/(s m); ρ_g, ρ_l, ρ_s and ρ_m are the density of gas, liquid, solid and the mixed phase, kg/m^3; v_g、v_l、v_s、v_m are the flow velocity of gas, liquid, solid and the mixed phase, m/s; E_g、E_l、E_s are the gas holdup, liquid holdup and solid content, dimensionless; A is the sectional area of the wellbore, m^2; p is the wellbore pressure, Pa; λ is the friction coefficient, dimensionless; g is the gravitational acceleration, m/s^2; d is the dimmer of the wellbore, m.

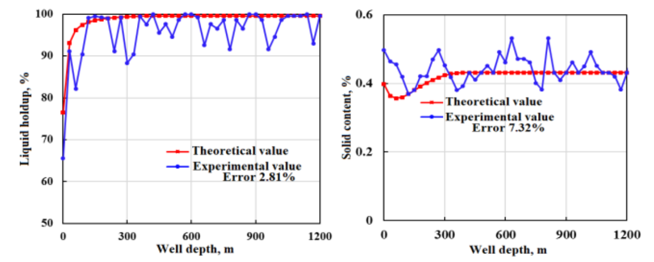
Through the high-efficient pipeline transportation and separation experiments of marine non-diagenetic natural gas hydrate slurry (Fig.15), and the comparison of experimental and theoretical calculation data, it is found that the variation trend is consistent and the error is small, which verifies the accuracy of the mathematical model and lays a foundation for the development of the technology scheme of solid fluidization test exploitation of marine non-diagenetic natural gas hydrate.



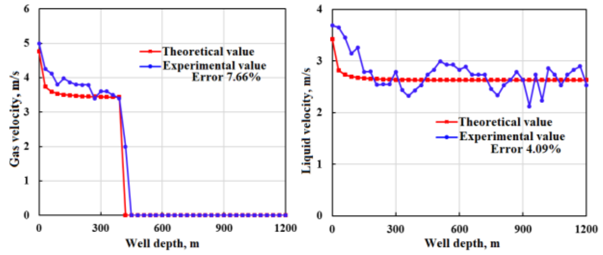
(a) wellbore temperature (b) wellbore pressure



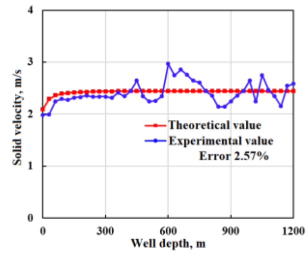
(c) Cumulative decomposition gas production (d) gas holdup



(e) liquid holdup (f) solid content



(g) gas velocity (h) liquid velocity



(i) solid velocity

Fig. 15. Curve of comparison between experimental and theoretical values of wellbore flow parameters with displacement of 12 L/s

VI. TECHNICAL SCHEME OF SOLID FLUIDIZATION TEST EXPLOITATION OF MARINE NON-DIAGENETIC NATURAL GAS HYDRATE IMULATION EXPERIMENT OF SOLID FLUIDIZATION EXPLOITATION OF MARINE NON-DIAGENETIC NATURAL GAS HYDRATE

A. *Analysis of annular phase and multiphase flow in the target well of solid fluidization test exploitation of marine non-diagenetic natural gas hydrate*

The wellbore structure of the test well for solid fluidization exploitation of marine non-diagenetic natural gas hydrate is shown in Fig. 16:

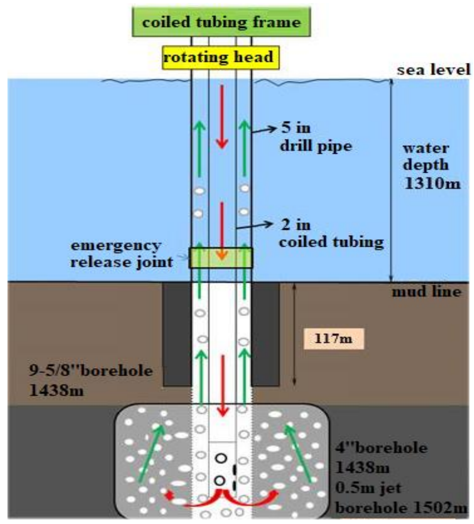


Fig. 16. Wellbore structure of the test well for solid fluidization exploitation of marine non-diagenetic natural gas hydrate

Based on the formed experimental technology, theory and wellbore structure of solid fluidization exploitation of marine non-diagenetic natural gas hydrate, the annular phase state and multiphase flow of the target well for solid fluidization exploitation of marine non-diagenetic natural gas hydrate are analyzed. The multiphase flow parameters in annulus with different liquid discharge, liquid density, wellhead back pressure, gas production and jet diameter (as shown in Figs. 17～22) have been obtained, and the prediction of characteristic parameters has been formed:

1) With the increase of liquid discharge, the gas holdup and the solid content in the annulus decrease, but the liquid holdup increases, and the gas, liquid and solid velocities increase. 2) With the increase of density of liquid phase, the content of solid phase decreases and the velocity of solid phase increases, the gas holdup and gas and liquid phase velocities in the upper well section decrease slightly, while the liquid holdup and solid phase velocity increase slightly. 3) With the increase of wellhead back pressure, gas holdup and gas phase velocity decrease, liquid holdup increases and solid phase velocity increases in the upper well section after hydrate decomposition. 4) With the increase of gas production, the solid content and liquid holdup in the lower section increased, while the gas holdup and the gas and liquid velocities in the upper section increased, and the liquid holdup and the solid velocity decreased. 5) With the increase of the jet diameter, the liquid and solid phase velocities in the annulus decrease, and the volume fraction of the solid phase in the annulus increases.

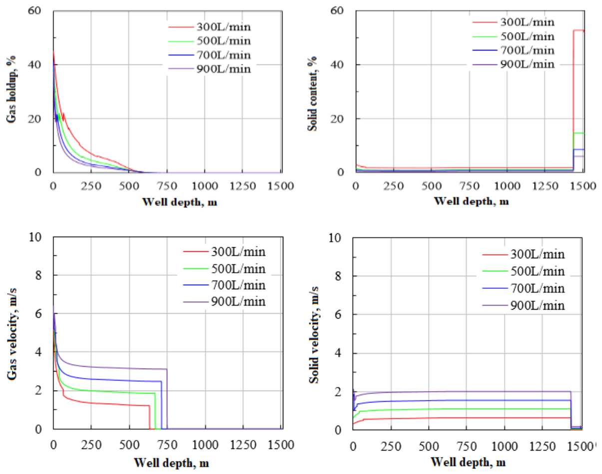


Fig. 17. Distribution of multiphase flow parameters in annulus with well depth in different liquid displacement (300～900 L/min)

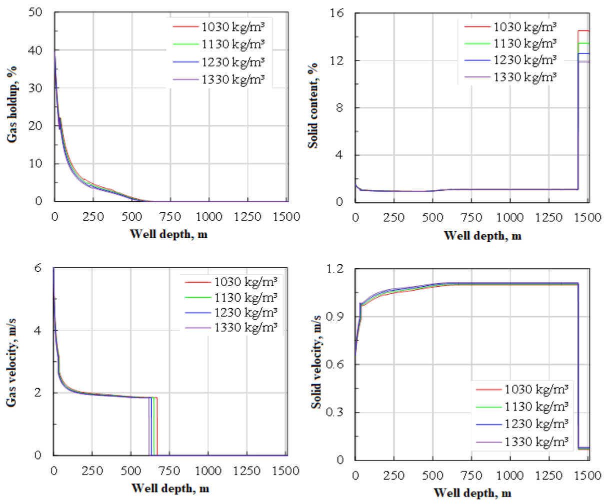


Fig. 18. Distribution of multiphase flow parameters in annulus with well depth in different liquid density (1030～1330 kg/m^3)

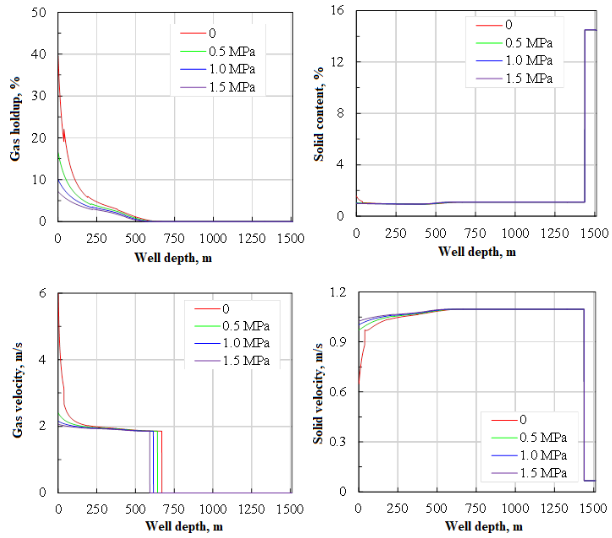


Fig. 19. Distribution of multiphase flow parameters in annulus with well depth in different wellhead back pressure (0～1.5 MPa)

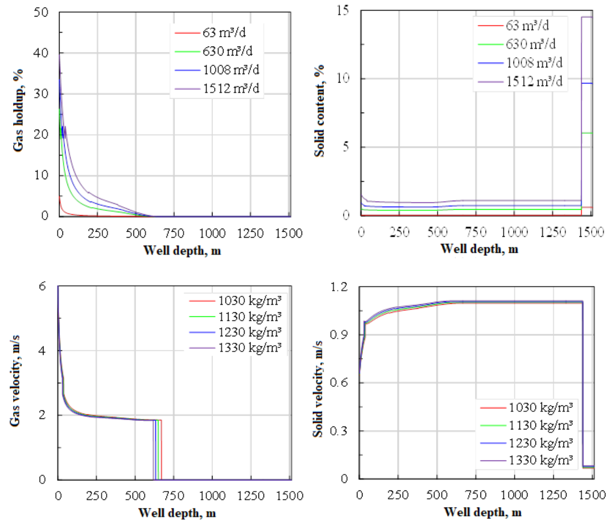


Fig. 20. Distribution of multiphase flow parameters in annulus with well depth in different gas production (63～1512 m^3/d)

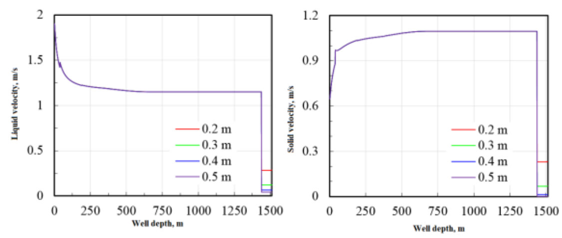


Fig. 21. Distribution of multiphase flow parameters in annulus with well depth in different jet diameters (0.2～0.5 m)

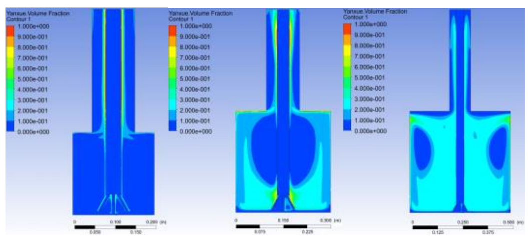


Fig. 22. Cuttings volume fraction cloud images simulated by CFD at jet diameters of 0.2 m (left), 0.3 m (middle) and 0.5 m (right)

B. Development of high pressure jet crushing tool of solid fluidization test exploitation of marine non-diagenetic natural gas hydrate

The idea of high pressure jet crushing technology for solid fluidization test exploitation of marine non-diagenetic natural gas hydrate is researched and put forward: The conventional drilling method is used to drill the collar hole, and then through the coiled tubing, the hydrate is jet broken and fluidized by using the nozzle tool based on hydraulic fracturing in the target zone, and after downhole separation and partial backfill of mud and sand, the hydrate slurry is transported up to the sea surface platform through wellbore annulus, and the natural gas is obtained by slurry separation and hydrate decomposition, and the solid fluidization exploitation of marine non-diagenetic natural gas hydrate is completed. It is not necessary to break the equilibrium state of pressure and temperature of hydrate reservoir by using high pressure jet of nozzle to break the hydrate of target layer, which improves the production efficiency of hydrate exploitation, protects the bottom safety of reservoir, and reduces the energy consumption of hydrate exploitation.

At the same time, as shown in Fig.23, the high pressure jet crushing nozzle tool for natural gas hydrate is researched and developed completely by ourselves, and the range of construction parameters under different crushing aperture and breaking rate is revealed by experiments in the construction of hydrate test exploitation engineering. The process parameters of fluidization test exploitation of target well were optimized, and the parametric plate of fluidization test exploitation of marine natural gas hydrate was established, as shown in Fig.24.

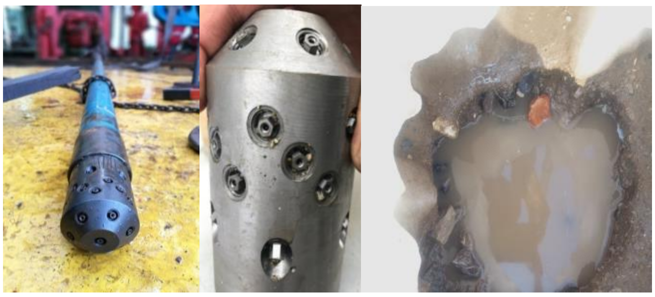
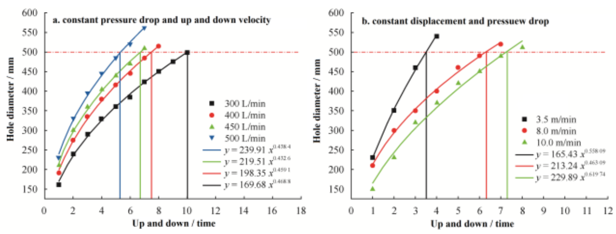
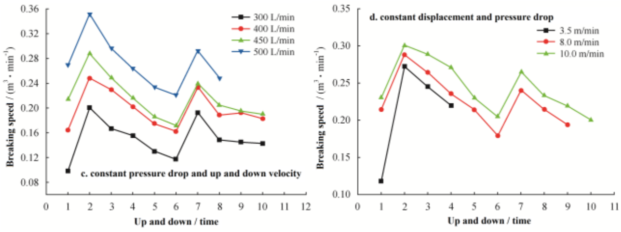


Fig. 23. High pressure jet crushing nozzle tool for natural gas hydrate and indoor experiment phenomenon



（a） （b）



（c） （d）

Fig. 24. Parametric plate of fluidization test exploitation of marine natural gas hydrate (construction process parameters under different crushing apertures and velocities)

C. Optimization of key parameters for target well operation of solid fluidization test exploitation of marine non-diagenetic natural gas hydrate

Based on the analysis of annular phase and multiphase flow in the target well and the development and experimental analysis of the high pressure jet crushing tool, the optimization of the key parameters in the operation of the target well for the solid fluidization test exploitation of natural gas hydrate is carried out, as shown in Table :A graph within a graph is an "inset", not an "insert". The word alternatively is preferred to the word "alternately" (unless you really mean something that alternates).

TABLE III. THE OPTIMIZATION OF THE KEY PARAMETERS IN THE OPERATION OF THE TARGET WELL FOR THE SOLID FLUIDIZATION TEST EXPLOITATION OF MARINE NON-DIAGENETIC NATURAL GAS HYDRATE

No.	***Production rate, m^3/d***	***Wellhead back pressure, MPa***	***Displacement, L/min***	***Liquid density, kg/m^3***	***Jet diameter, m***	***Critical decomposition position, m***	***Maximum gas holdup, %***	***Maximum gas velocity, m/s***	***Maximum solid content, %***	***Minimum solid velocity, %***
1	63	0	500	1030	0.3	650	4.980	1.995	0.602	0.067
2	630					659	26.302	3.781	6.043	0.067
3	1008					664	33.518	4.749	9.668	0.067
4	1512					670	39.545	6.042	14.502	0.067
5	1512	0	500	1030	0.3	670	39.545	6.042	14.502	0.067
6		0.5				642	16.510	2.403	14.502	0.067
7		1				615	10.017	2.155	14.502	0.067
8		1.5				592	7.180	2.061	14.502	0.067
9	1512	0	500	1030	0.3	670	39.545	6.042	14.502	0.067
10				1130		650	39.537	6.040	13.442	0.072
11				1230		633	39.531	6.038	12.560	0.078
12				1330		618	39.525	6.036	11.895	0.082
13	1512	0	500	1030	0.2	670	39.545	6.042	9.882	0.232
14					0.3	670	39.545	6.042	14.502	0.067
15					0.4	670	39.545	6.042	41.468	0.013
16					0.5	670	39.545	6.042	/	-0.011

Based on the safety design principles of safe rock carrying, the maximum solid content should not be too large, the maximum gas velocity and gas holdup should not be too large, the optimized results of the key parameters of the target well operation are as follows: the displacement of high pressure jet crushing is about 500 L/min, and the diameter of the jet cavity is not more than 0.5 m.

D. Technical scheme design for field application of high pressure jet crushing of solid fluidization of marine non-diagenetic natural gas hydrate

Based on the analysis of annular phase state and multiphase flow in the target well, the development and experimental analysis of the high pressure jet crushing tool, and the optimization of the key parameters in the operation of the target well for solid fluidization test exploitation, a scheme for the solid fluidization test exploitation of marine non-diagenetic natural gas hydrate is designed, as shown in Fig. 25:

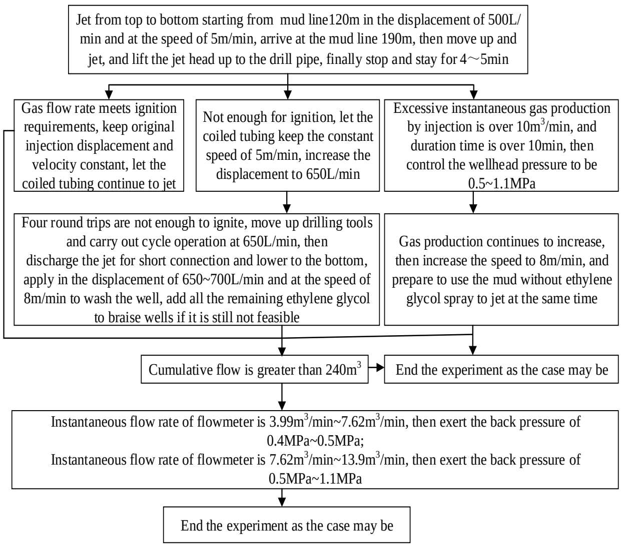


Fig. 25. Technical scheme of solid fluidization test exploitation of marine non-diagenetic natural gas hydrate

E. The world's first successful field application of solid fluidization exploitation of marine natural gas hydrate

In May 2017, relying on the "Offshore Oil 708" Deepwater Engineering Survey Ship, the first global solid fluidization test exploitation project for shallow, weakly cemented and non-diagenetic hydrates was successfully carried out in the Shenhu area of the South China Sea (Fig. 26) [10,15,27]. The results of the experimental system provide an important basis for the development of the scheme, process optimization design and downhole tool development of solid fluidization exploitation of marine non-diagenetic natural gas hydrate.

Fig. 26. "Offshore Oil 708" Deepwater Engineering Survey Ship and the world's first successful solid fluidization test exploitation project

On May 31, 2017, 11 academicians and experts from Chinese Academy of Engineering, Chinese Association of Science and Technology, and National Nature Foundation and other organizations unanimously held the view that "The integrated engineering design and implementation of target exploration, drilling sampling and solid fluidization test exploitation of marine hydrate have been completed by using the technology, equipment and process independently developed in China. It is of great significance to the exploitation of natural gas hydrate resources in the world." [15,27]. In December 2017, the US Science magazine reported the experimental simulation technology, the systematic research progress and the results of the first test exploitation on solid fluidization exploitation of marine non-diagenetic natural gas hydrate with the title of "Latest Achievement of SKL of SWPU" in "Breakthrough of the year", Vol. 358 No. 6370. [12].

VII. Conclusion

(1) The technology of solid fluidization exploitation of marine non-diagenetic gas hydrate is put forward, which realizes the safe and green exploitation of "letting nature take its course, turning harm into profit, and changing uncontrollable into controllable". Natural gas hydrates are divided into diagenetic and non-diagenetic hydrates. Based on the characteristics of non-diagenetic hydrate, six "utilize" strategies are proposed. The principle of hydrate solid fluidization exploitation technology and the technology of hydrate excavation, fragmentation, jet diversion of seawater, separation and backfilling of mud and sand, slurry lifting, and deep separation and refilling on the platform are first developed. Its scientific essence is to transform non-diagenetic and uncontrollable hydrate reservoirs into controllable hydrate reservoirs in sealed pipelines.

(2) Experimental simulation methods and technology of solid fluidization exploitation of marine non-diagenetic natural gas hydrate have been invented, and the whole process simulation of solid fluidization exploitation with 1500 m water depth and 4500 m pipe length has been realized. It includes the experimental methods and technology of "trinity" of rapid preparation of large samples, fragmentation and slurry modulation of hydrate, through which the largest hydrate sample of 1062 L in the world can be prepared within 20 h. Method and technology of fidelity migration of hydrate slurry. Experimental simulation method and technology of pipeline transportation of hydrate particles, mud and sand, decomposed gas, and complex slurry with prepared sea water in the way of piecewise combination, point by point encryption, multiple cycles, multiple depressurization, and multiple heating at the horizontal section of 56 m, and vertical section of 30 m. In addition, the invention and development of the first large-scale physical simulation experiment system of solid fluidization exploitation of marine non-diagenetic natural gas hydrate in the world with completely independent intellectual property rights has been successfully developed. It includes 3 modules and 12 subsystems of rapid preparation of large samples, fragmentation and slurry modulation, high-efficient pipeline transportation and separation of slurry, and real-time image capture, data collection and safety control.

(3) The experiment of solid fluidization exploitation of marine non-diagenetic natural gas hydrate is carried out systematically for the first time, which provides an important basis for the development of test exploitation plan, process optimization design and downhole tool development, and supports the first successful solid fluidization test exploitation in the world.

(4) The invention and development of the large-scale physical simulation experiment system, and the conduction of simulation experiment provides the key parameters for the formulation of the technical scheme and the design of the

operation flow of the first successful solid fluidization test exploitation of marine natural gas hydrate. It is proved that the principle of solid fluidization exploitation is scientific and feasible, and the exploitation technology is feasible. The successful research and development and further upgrade of the system are expected to promote the solid fluidization exploitation technology of marine non-diagenetic gas hydrate to become a leading edge of a subversive technology in the world. It is expected to accelerate the commercial development process of natural gas hydrate in China and even in the world.

ACKNOWLEDGMENT

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