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Development of multi-dimensional production simulation test system for natural gas hydrate and its primary application

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Abstract: In order to study the synthesis and decomposition characteristics of natural gas hydrates, the exploitation performance of the reservoir, and the sand production and control during the mining process of natural gas hydrates, a set of multi-dimensional natural gas hydrate production simulation test system has been developed. The test system is mainly composed of gas injection system, constant pressure liquid supply system, steam or hot water injection system, 1D,2D&3D model, back pressure control system, outlet metering system, data acquisition and control processing system and corresponding auxiliary systems. The main innovations of the experimental system are as follows: 1) The one-dimensional reactor wall made of high-pressure glass and the high-definition camera are combined to achieve visualization for monitoring the synthesis and decomposition of hydrate and the sand migration in the production process under medium and low pressure. 2) The self-developed double-cylinder constant speed and pressure pump is used to control the back pressure valve, so that the pressure in the reactor can be uniformly reduced at a decrement of higher precision during the entire depressurizing production process. Consequently, the gas hydrate reformation is greatly reduced, and the gas production rate becomes more uniform. Using quartz sand of different particle sizes, deionized water and methane gas with a purity of 99.9% as raw materials，the one-dimensional phase equilibrium test and two-dimensional depressurizing production test are conducted. The reliability of the test system is verified based on the primary application results from these tests.

Keywords: natural gas hydrate; production simulation; test system; phase equilibrium; depressurization production

1 Introduction

Natural gas hydrate is an ice like solid formed by natural gas and water under high pressure and low temperature. It is widely distributed in sediments 200−2 100 m below the surface of permafrost and 0−1 500 m below the seabed of continental margin[1]. The reserves of natural gas hydrate are huge all over the world, and the natural gas resource is twice the total carbon content of conventional fuels[2]. Since 1968, when the Soviet Union first developed the world’s first natural gas hydrate deposit, a lot of countries have successively carried out the trial production of deep-sea natural gas hydrate. In particular, China carried out the second round of trial production of natural gas hydrate in Shenhu sea area of the South China Sea in 2020 and achieved remarkable results, marking a step closer to the commercial production of natural gas hydrate. However, the reservoir environment of deep-sea gas hydrate is mostly argillaceous silt, and the porosity and permeability of the reservoir are very low, consequently the gas production rate and gas production in the process of gas hydrate exploitation are limited. Meanwhile, the fine sand particles in the reservoir are very easy to enter and block the wellbore, causing significantly negative impact on the exploitation of natural gas hydrate. Therefore, sophisticated studies of gas production law and mechanism of sand production and control are very important to realize safe and efficient gas hydrate production.

The heat injection method and depressurization method are the most widely studied natural gas hydrate production methods at present. The heat injection method has characteristics of high hydrate recovery, but low energy efficiency, and hence becomes difficult to realize large-scale production[3]. Huang[4] obtained the optimum temperature, speed and time of hot water injection for hydrate production under different saturations and initial temperatures by carrying out hydrate heat injection displacement test. Ma et al.[5] found through experimental research that higher temperature or lower hydrate saturation leads to a greater gap between decomposition and equilibrium states, and the heating

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rate affects the slope of hydrate decomposition curve. The reduction of energy loss, increase of heating range and speed, and improvement of mining efficiency are the key issues in heat injection method. Unfortunately there is no well-developed heat injection mining scheme up to date. The depressurization method can realize the continuous production of natural gas hydrate, but it consumes a lot of reservoir heat, which consequently not only reduces the decomposition rate of natural gas hydrate, but also causes pore water freezing and hydrate secondary generation, resulting in the blockage of reservoir pore throat and reduction of the permeability of natural gas hydrate reservoir. Wang et al.[6], Minagawa et al.[7] and Li et al.[8] respectively studied the effects of free gas saturation, hydrate saturation, depressurization amplitude, depressurization mode, scale and depressurization rate on the depressurizing decomposition characteristics of hydrate. From the results of several trial productions [9–11], the depressurization method also exposes the problem of low mining efficiency. Therefore, establishing a safe and efficient hydrate mining method is an urgent issue to be solved in the commercialization of hydrate resources.

In recent years, complex structure wells represented by horizontal wells and multi branch wells have great application potential in hydrate mining. However, to apply multi branch well technology to hydrate mining on a large scale, it is also necessary to accurately predict and evaluate the productivity of multi branch wells under different mining conditions and formulate reasonable development schemes[12]. In general, due to the limitations of existing equipment and technical conditions, it is difficult to conduct extensive in-situ gas hydrate production tests directly at the deep-sea gas hydrate deposit site, and it is also difficult to obtain the natural gas hydrate reservoir under the original temperature and pressure conditions to study the production characteristics of hydrate. Therefore, the indoor natural gas hydrate production simulation test is regarded as one of the important technical means to solve the problems related to natural gas hydrate production prediction and evaluation because it is easy to realize the original temperature and pressure conditions of natural gas hydrate and obtain accurate production characteristics [13].

At present, many scholars [14–16] have carried out experimental research on natural gas hydrate exploitation. Fan et al.[17] used a one-dimensional piston variable volume reactor to determine the phase equilibrium point of methane gas aqueous solution by constant temperature pressure test method and circle-drawing method, respectively. Kim et al.[18] designed a set of one-dimensional natural gas hydrate rapid synthesis device to directly study the influence of physical factors such as stirring and spray on hydrate formation rate and gas storage capacity. Jiang[19] designed a one-dimensional natural gas hydrate synthesis test system to examine the methods of rapid synthesis of natural gas hydrate and efficient enhancement of hydrate formation. Li et al.[20–21] used the one-dimensional natural gas hydrate production simulation test device to reveal the effects of depressurization amplitude and depressurization rate on gas production rate and final gas production, as well as the effects of initial pressure on gas hydrate production and generation time in porous media. Du et al.[22] developed a two-dimensional natural gas hydrate production simulation system by using the capacitance test method as the detection means for the first time, which is used to record the dynamic characteristics of temperature field, pressure field, distribution state and advancing speed of decomposition front in the process of hydrate formation and decomposition. Huang[4] used the two-dimensional natural gas hydrate synthesis and production simulation test equipment to carry out the synthesis, depressurization and heat injection production tests of natural gas hydrate, and selected the hydrate reservoir production methods under different geological conditions. Zhou et al.[23] developed a three-dimensional natural gas hydrate production simulation test system by using the dimensionless similarity analysis method, and carried out three-dimensional test simulation analysis of natural gas hydrate production methods such as depressurization and heat injection. Based on the three-dimensional natural gas hydrate production simulation system, Gao[24] used multiple gas injection method to study the change law of gas production, ice formation and secondary formation of hydrate in the depressurizing production process of class I, II and III methane hydrate reservoirs with excess gas. In addition, many scholars [25–33] used self-developed test devices to study the synthesis and decomposition behaviors of hydrate. It can be seen that there are many simulation test devices used to study hydrate mining around the world, but there is no multi-functional, full-dimensional and systematic hydrate simulation test system. In addition, there are few reports on the experimental system and related research on the influence of wellbore layout under different mining conditions, especially multi branch well layout on hydrate productivity.

In view of the above understanding, in order to overcome the shortcomings of the existing test system, a systematical study on the synthesis and decomposition mechanism of natural gas hydrate has been carried out. The changes of reservoir physical properties, temperature, pressure, production, sand production and control laws

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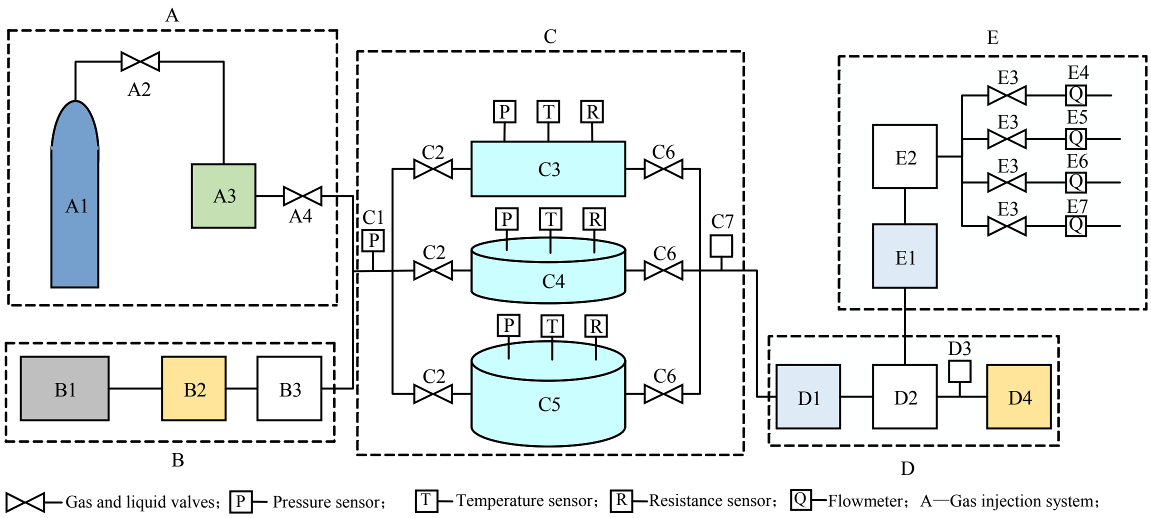
in the process of hydrate production under different production methods and well groups have been investigated, so as to provide test basis for hydrate test production. A set of multi-dimensional gas hydrate production simulation test system has been developed independently. The one-dimensional phase equilibrium test and two-dimensional depressurizing production test were carried out by using the system to study the influence of hydrate skeleton with different particle sizes on phase equilibrium curve and the influence of different well layouts on depressurizing production characteristics of gas hydrate. The reliability of the test system is verified via the above procedure, and then a test foundation is lain for the further study of natural gas hydrate production characteristics.

2 Simulation test system for natural gas hydrate production

2.1 Composition of test system

The simulation testing system of developed multi-dimensional natural gas hydrate production is shown in Fig.1. The main function of the testing system is to realize multi-dimensional natural gas hydrate production simulation. Its main components are one-dimensional/ two-dimensional / three-dimensional model, complete with gas injection system, stabilized pressure liquid supply system, steam (chemical reagent) injection system, back pressure control system, outlet metering & data acquisition system, control & processing system and auxiliary systems such as process cabinet and console.



P— Pressure sensor; T—Temperature sensor; R—Resistance sensor; Q—Flowmeter; A—Gas injection system; B—Liquid supply system with stable pressure; C—One-dimensional/ two-dimensional/three-dimensional models; D—Back pressure control system; E—Outlet metering system; A1—Gas cylinder; A2—Pressure reducing valve; A3—High pressure storage tank; B1—Air pump; B2—Constant speed constant pressure pump; B3—Piston container; C1—Inlet pressure sensor; C2—Inlet valve; C3—One dimensional model; C4—Two dimensional model; C5—Three dimensional model; C6—Outlet valve; C7—Outlet pressure sensor; D1—Gas solid liquid separator; D2—Back pressure valve; D3—Back pressure sensor; D4—Back pressure pump; E1—Gas liquid separator; E2—Electronic balance; E3—Exhaust valve; E4—30 mL/min gas flowmeter; E5—300 mL/min gas flowmeter; E6—1 000 mL/min gas flowmeter; E7—0.5 m^3/h wet flow meter

Fig. 1 Schematic diagram of multi-dimensional natural gas hydrate production simulation test system

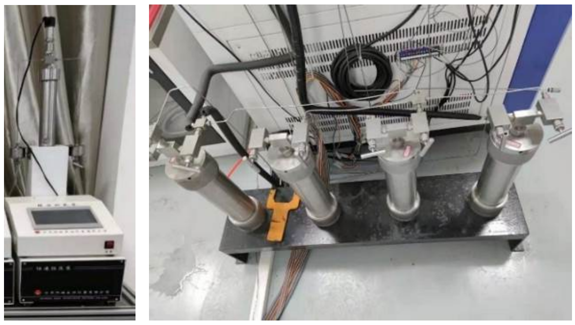
One dimensional / two-dimensional / three-dimensional model is one of the main parts of the testing system, as shown in Figs.2−4. The one-dimensional model is mainly used for different tests of one-dimensional hydrate samples. The model mainly consists of one-dimensional reactor, high and low temperature incubator and full visual outer wall. The one-dimensional reactor has the sample size ϕ600 mm ×300 mm, the pressure resistance value is 25 MPa, and the temperature range is −15−200 ℃. Four measuring points are evenly distributed along the axis, each is shared by temperature sensor, pressure sensor and resistance sensor. The temperature incubator (Type KDHD-II) has the temperature control range between −30−200 ℃, as shown in Fig.2. The full visual outer wall, which is made of quartz glass, has the sample size of 30 mm×200 mm and pressure resistance value of 15 MPa. The two-dimensional model is mainly used for different tests of two-dimensional hydrate samples, mainly consisting of two-dimensional reactor and high and low temperature incubator. The reactor has the sample size of 600 mm×50 mm and the working temperature of −15−200 ℃. The pressure resistance value is 25 MPa. It has 49 temperature measuring points, 13 pressure measuring points, 49 pairs of saturation measuring points, 13 vertical well pattern interfaces and 6 horizontal well pattern interfaces. The high and low temperature incubator (KDHWD-II type) has the temperature control range of −30− 200 ℃, as shown in Fig.3. The three-dimensional model is mainly used for different tests of three-dimensional hydrate samples, and the model mainly consists of three-dimensional reactor, and the cold storage for three-dimensional reactor, as shown in Fig.4. The reactor has the size of 600 mm×500 mm, pressure resistance value of 25 MPa and working temperature of −15−200 ℃. It is configured with 147 temperature measuring points, 27 pressure measuring points, 147 pairs of saturation measuring points, 13 vertical well pattern interfaces, 9 horizontal well pattern interfaces, 3 pairs of ultrasonic probes and 3 sampling ports. In the one-dimensional / two-dimensional/ three-dimensional model, each measuring point is arranged on the reactor following a designed manner and maintains different distances from the vertical/ horizontal wellbore collecting the produced gas, so as to monitor the state of hydrate reservoir at different distances from the production wellbore.

The gas injection system is used for the injection of test gas. The system consists of gas booster pump, silent air pump, pressure reducing valve, high-pressure gas storage tank, gas flow controller and pressure regulating valve. The stabilized pressure liquid supply system serves for the injection of solution and carbon dioxide, consisting of constant speed and constant pressure pump and a piston injection system composed of multiple piston containers, as shown in Fig. 5.

Fig. 2 One-dimensional model

Fig. 3 Two-dimensional model

Fig. 4 Three-dimensional model



(a) Constant speed and pressure pump (b) Piston container

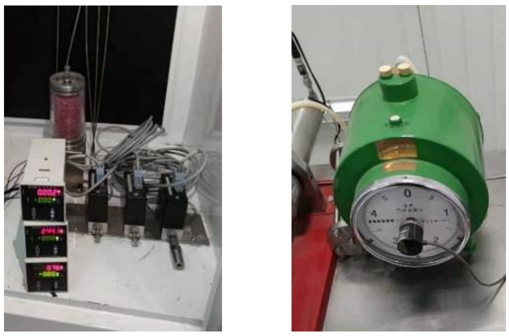
Fig. 5 Stable pressure liquid supply system

The back pressure control system controls the gas pressure at the outlet of the reactor. The system consists of horizontal manual back pressure pump, automatic back pressure pump, back pressure valve (pressure control accuracy is 0.05 MPa) and back pressure vessel (pressure resistance value =40 MPa, volume =500 mL), as shown in Fig. 6.

(a) Horizontal manual back pressure pump (b) Back pressure valve (c) Automatic back pressure pump

Fig. 6 Back pressure control system

The outlet metering system is introduced for measuring the amount of gas, liquid and solid discharged. It mainly consists of gas-liquid separator, gas-solid-liquid three-phase separator, high, medium and low range flowmeters (measuring ranges of 30, 300 and 1 000 mL/min, respectively), electronic balance and wet flowmeter with measuring range of 0.5 m^3 /h, as shown in Fig.7.



(a) High, medium and low range flowmeter (b) Wet flowmeter

Fig. 7 Outlet metering system

2.2 Main functions of testing system

The main functions of the one-dimensional model are as follows: to study the physicochemical properties, growth kinetics, formation/ decomposition process and sediment response of gas hydrate. To observe and monitor remotely the formation and decomposition of hydrate by using visual design such as camera, and to measure the changes of temperature, pressure and saturation at different positions in porous media in one-dimensional model during mining. To obtain the pressure temperature equilibrium conditions of natural gas hydrate in different media, that is to say, by using the temperature pressure detection technology, the formation and decomposition law of hydrate is determined by analyzing the changes of temperature and pressure curves in one-dimensional porous media as well as the small difference of temperature between gas phase and porous media. To measure and examine the dynamic characteristics of hydrate sample decomposition process, that is to say, under the condition of controlling the depressurization or thermal injection decomposition of hydrate sample, the dynamic evolutions of gas, water permeability, gas-water relative permeability and thermal conductivity of hydrate-bearing sediments during hydrate decomposition are measured and studied; meanwhile, the synthesis and decomposition of hydrate and the migration of sand particles in the mining process are monitored through the visual window.

The main functions of the two-dimensional / three-dimensional model are as follows: it is mainly used to study the production characteristics of natural gas hydrate. The pressure monitoring device, resistance monitoring device, temperature monitoring device and acoustic monitoring device in the model can simulate logging exploration technology to monitor the formation process of hydrate in sediments. The high and low temperature incubator matched with the device is used to control the temperature of hydrate synthesis and decomposition in the reactor. The device comes complete with a gas-liquid injection module that can accurately control the gas-liquid mobility ratio so as to monitor the medium ratio of gas and liquid and give the measurement precisely. The device is designed with a controllable metering high-pressure pump, also known as constant speed and constant pressure pump. The pump is a set of high-precision, high stability and fast pump control system. Using the equipment, the fluid can be injected at constant pressure or constant speed to accurately control and measure the hydrate formation conditions, and realize the injection of multiple mixed modes through the control parameter setting and time setting of the pump. The designed CO_2 quantitative injection system and outlet CO_2 metering system make it possible to realize CO_2 replacement mining. Combined with the export metering system mentioned above, it can accurately measure the replacement amount of CO_2 (buried amount) as well as the exploitation amount of CH_4 in the replacement mining process. In addition, the three-dimensional model has the function of applying axial pressure, which can simulate the exploitation of natural gas hydrate under different occurrence depths (formation pressure), and then study the process and mechanism of submarine landslide by monitoring the deformation of the overlying layer of natural gas hydrate reservoir.

3 Preliminary application of test system

In order to verify the reliability of the deep-sea gas hydrate production simulation test system, the preliminary application effect of the test system is introduced by taking one-dimensional phase equilibrium test and two-dimensional production simulation test as examples. Quartz sand with different particle sizes, deionized water and methane gas with purity of 99.9% were used as raw materials to prepare one-dimensional and two-dimensional sediment samples containing natural gas hydrate by constant volume method.

3.1 Experimental study on one dimensional phase equilibrium

The research on hydrate phase equilibrium is mainly to determine the critical temperature and pressure conditions for hydrate synthesis and decomposition, and provide basic data support for the research related to hydrate mining. The main methods of hydrate phase equilibrium determination are observation method and graphic method. Graphical method is a hydrate phase equilibrium measurement method with high precision. The pressure and temperature parameters during hydrate synthesis and decomposition are recorded and stored through the data acquisition system, the pressure−temperature curve during hydrate synthesis and decomposition is plotted, and the phase equilibrium point of hydrate is determined through the intersection of the curve[34], as shown in Fig. 8. The phase equilibrium measurement method selected in this paper is the graphic method. In this paper, the effects of different particle sizes of quartz sand and different initial pressures on the phase equilibrium curve of natural gas hydrate are studied by means of one-dimensional model.

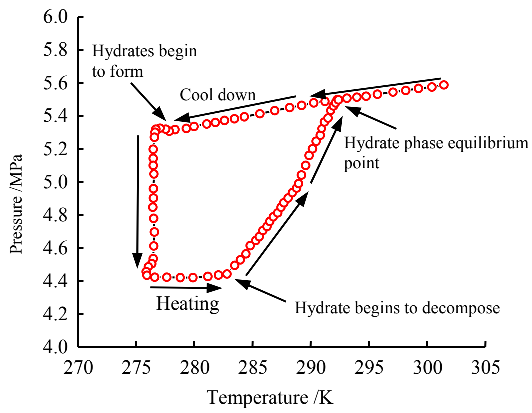


Fig. 8 Determination of hydrate equilibrium point by graphic method

3.1.1 Test procedure

The test process mainly includes four steps: sample preparation, raising temperature and injecting, cooling synthesis and warming decomposition, and gas injection and pressurization, which are described as follows.

(1) Sample preparation

Use the electric vibrating sieve machine and standard sieve as shown in Fig. 9 to screen a sufficient amount of quartz sand (particle sizes: 0.250, 0.105 mm) for the test, then mix the sieved quartz sand with deionized water according to a certain proportion and fully stir, finally fill the evenly mixed sand−water mixture into one-dimensional reactor and tamp it in layers, as shown in Fig. 10.

(a) Electric vibrating sieve machine (b) Standard sieves

Fig. 9 Electric vibrating sieve machine and standard sieves

(a) Mixing up the materials (b) Sample filling

Fig. 10 Preparation of one-dimensional specimens

(2) Raising temperature and injecting

Install the one-dimensional reactor, connect the temperature, pressure, resistance and other sensors on the reactor, open the incubator and set the temperature to the predetermined value. There is a temperature sensor in the incubator to assist in the setting of initial cooling temperature during hydrate formation and initial heating temperature during hydrate decomposition. After the temperature of each measuring point in the kettle is stabilized, open the gas cylinder and use the pressure regulating valve to adjust the pressure to the predetermined initial pressure. Then, open the inlet valve to inject methane into the reactor, and close the inlet valve after the pressure in the reactor stabilizes at the preset initial pressure value. If the pressure in the kettle can be stabilized at the initial pressure value for a long time (1−2 d), it indicates that the air tightness is good, and the next test can be carried out. Otherwise, leakage detection is needed to perform until the air tightness is good.

(3) Cooling synthesis and warming decomposition

Set the temperature of the incubator as the minimum synthesis temperature of hydrate required for the test. If the temperature and pressure in the reactor retain stable for a long time (more than 3 h), that is, the temperature and pressure values stay constant within the accuracy of the acquisition system (two decimal places), it indicates that the decomposition and formation rates of natural gas hydrate in the reactor have reached dynamic equilibrium. Macroscopically, the saturation degree of hydrate does not change, and the hydrate has been completely formed. Subsequently, in order to ensure the accuracy of the test, the temperature of the incubator is set to the predetermined initial temperature value before cooling. When the temperature and pressure in the reactor return to the initial value and remain stable, it indicates that the natural gas hydrate in the reactor has been completely decomposed. The evolutions of temperature, pressure and resistance at each measuring point in the reactor are recorded during the test.

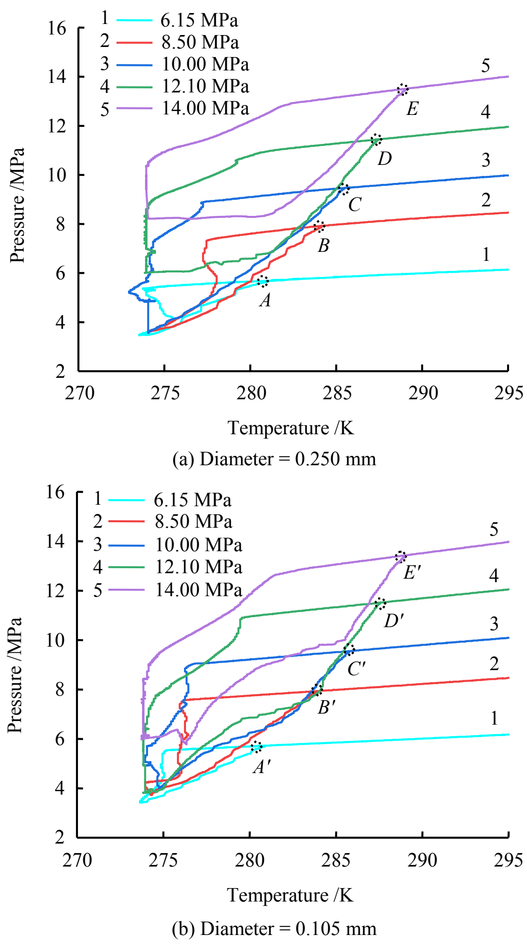
(4) Injecting pressurization

Use the pressure regulating valve to adjust the gas injection pressure to another initial pressure value, and open the inlet valve to continue to inject gas into the reactor to the initial pressure value, so as to change the initial pressure. When the pressure in the reactor stabilizes at the initial pressure value, close the inlet valve and stop gas injection.

Repeat steps (3) and (4) three times according to the test requirements, and conduct one-dimensional phase equilibrium test under three different initial pressures.

3.1.2 Results and discussion

The quartz sand selected in the test has relatively large particle size, large porosity and strong internal connectivity. Therefore, the temperature and pressure values at four measuring points on the one-dimensional model are similar, and only the data of one measuring point is selected for analysis. Figs. 11(a) and 11(b) show the pressure−temperature curves under different initial pressure conditions during hydrate synthesis and decomposition with quartz sand with particle sizes of 0.250 and 0.105 mm as the skeleton, where points *A*, *B*, *C*, *D*, *E* and *A′*, *B′*, *C′*, *D′*, *E′* are the phase equilibrium points of phase equilibrium test with particle sizes of 0.250 and 0.105 mm, respectively.



(a) Diameter = 0.250 mm

(b) Diameter = 0.105 mm

Fig. 11 Experimental pressure−temperature curves of different particle size quartz sands

As can be observed from Fig.11, the phase equilibrium test curve is mainly divided into two processes: synthesis and decomposition. The synthesis process is divided into gas dissolved in water stage, gas-water mixing cooling stage, hydrate induction stage and hydrate stable existence stage, and the decomposition process includes hydrate decomposition stage, gas-water mixing thermal expansion stage and final stability stage[34]. For the phase equilibrium test of quartz sand with the same particle size, with the increase of the initial pressure, the temperature and pressure of the test phase equilibrium point obtained by the graphical method are also increasing, because the initial pressure of the phase equilibrium test in this paper is mainly provided by methane gas. More methane gas is injected into the reactor under higher initial pressure, it indicates that the stronger supersaturation state of methane gas in the reactor results in the more gas remaining after the reaction under the same temperature reduction. Therefore, the higher required equilibrium temperature is achieved under higher residual pressure.

Figure 12 is a test phase equilibrium curve (particle sizes of 0.250 and 0.105 mm, respectively) and a standard phase equilibrium curve fitted by using the coordinates of the test phase equilibrium point and the standard phase equilibrium point in Fig. 11. The standard phase equilibrium point coordinate is the phase equilibrium point coordinate of pure natural gas hydrate calculated by using the function of phase equilibrium calculation software to predict phase equilibrium pressure. It can be seen from Fig.12 that, compared with the phase equilibrium curve of pure natural gas hydrate, i.e. the standard phase equilibrium curve, the phase equilibrium curve of natural gas hydrate in the sediment deviates slightly to the upper left, which indicates that at the same temperature, the phase equilibrium pressure of hydrate in the sediment is greater than that of pure natural gas hydrate. It is mainly because the capillarity and adsorption of pore media acting as hydrate sediments on water will reduce the water potential energy, making the physical conditions for hydrate formation in sediments more difficult to achieve than those in pure water. Therefore, higher pressure or lower temperature are required [35−36].

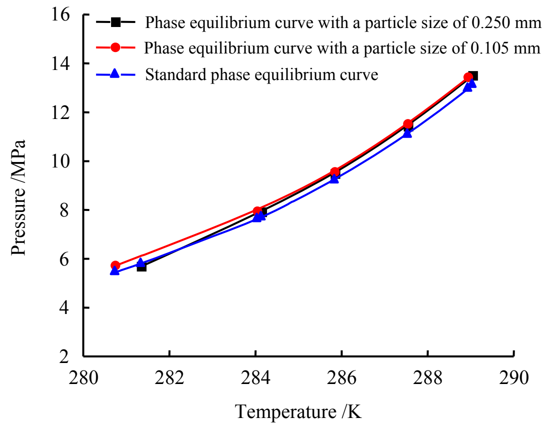


Fig. 12 Experimental and standard phase equilibrium curves

Compared with the test phase equilibrium curve with a particle size of 0.250 mm, the deviation of the test phase equilibrium curve with a particle size of 0.105 mm is greater, because the smaller particle size of hydrate-bearing sediments leads to the decrease of pores between media, the greater the capillary pressure and the greater the surface tension, making the heat transfer process more difficult and the more stringent the physical conditions to achieve phase equilibrium. The overall offset of the phase equilibrium curves of the two particle sizes of quartz sand has little impact, which is in line with the conclusion reached by Chen et al.[37] through the test, in which 58.68 nm has been found the critical value of pore radius of porous media affecting hydrate synthesis reaction, and pores larger than this radius will not significantly hinder hydrate synthesis.

3.2 Simulation test of two-dimensional depressurization mining

The depressurizing production method of natural gas hydrate refers to maintaining the pressure at the bottom of the production well under the phase equilibrium pressure corresponding to the temperature of the storage area through pumping, breaking the phase equilibrium state, which means the free fluid in the storage area flows out of the wellhead under the action of differential pressure, resulting in the pressure drop in the storage area. The hydrate begins to decompose when the pressure is lower than the phase equilibrium pressure[38]. In this paper, a two-dimensional model was used to study the influence of different well layout on depressurizing production behavior. In the test, the pressure difference was realized by controlling the back-pressure valve to discharge a small part of the gas in the kettle through the constant speed and constant pressure pump.

3.2.1 Test procedure

The test is mainly divided into four stages: sample preparation, injecting and cooling, gradient depressurizing, decomposing and producing. The two stages of gradient depressurization and decomposition gas production are carried out alternately. The specific test steps are as follows:

(1) Sample preparation

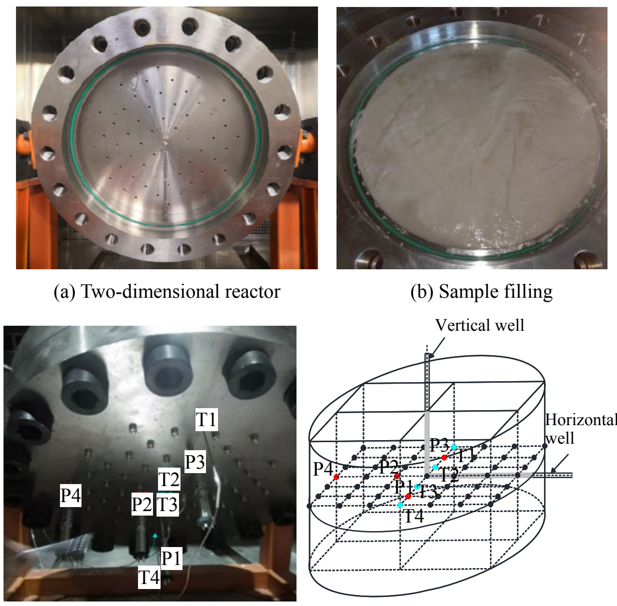
The mixture of quartz sand with particle sizes of 0.250−0.450, 0.125−0.250 and 0.076−0.125 mm is used as hydrate skeleton, and its mass ratio is 1:2:1. It is found that the mixture realized a similar particle gradation to that of quartz sand sampled from the South China Sea via testing. Subsequently, the amount of quartz sand required is determined according to the volume of the reactor. The quartz sand is mixed with deionized water in an appropriate proportion to prepare the sample. As shown in Fig.13 (a), considering the large volume of the reactor, in order to make the prepared samples as uniform as possible, repeat the configuration a few times according to the appropriate proportion. After that, fill the prepared sample into the two-dimensional reactor for compaction, and clean the sealing ring of the reactor to prevent air leakage, as shown in Fig. 13 (b).

(2) Gas injection cooling

As shown in Figs. 13 (c) and 13 (d), the pressure sensor, temperature sensor and production well (single vertical well and single horizontal well respectively) are arranged on the two-dimensional reactor filled with samples according to the test requirements, and a mesh with a mesh diameter of 0.038 mm is used to screen the shaft to prevent quartz sand from entering the shaft and blocking the gas production channel. P is the pressure measuring point and T is the temperature measuring point. After that, open the valve of methane cylinder, pressurize the gas pressure to 12 MPa by booster pump, open the inlet valve to make the gas enter the two-dimensional reactor, and close the inlet valve when the pressure at the four pressure measuring points in the two-dimensional reactor reaches about 12 MPa. If the pressure in the kettle can be stabilized at about 12 MPa for a long time (1−2 d), it indicates that the air tightness is good and the next test can be carried out. Otherwise, leakage detection needs to be carried out until the air tightness is good. Finally, open the incubator and set the temperature to the temperature required for the test, waiting for hydrate synthesis.

(3) Gradient depressurization

After a period of time for stabilization (about 4 d), the pressure and temperature at various measuring points in the reactor have been in a stable state, indicating that hydrate has been completely formed. According to the pressure value in the reactor, the constant pressure mode of the constant speed and constant pressure pump is employed to control the back pressure valve to raise the back pressure slightly higher than the pressure in the reactor. Then change to gradient depressurization mode, and set the predetermined back pressure and depressurization time in multiple stages according to the test requirements, in which the depressurization amount and depressurization gradient should be set up.



(a) Two-dimensional reactor (b) Sample filling

(c) Photo of measuring points layout (d) Schematic of measuring points layout

Fig. 13 Two-dimensional depressurization production test

(4) Decomposition gas production

When the back pressure is lower than the pressure in the kettle, the back pressure valve will open and the gas will be discharged from the kettle, and the discharged gas will reduce the pressure in the kettle to less than the back pressure, thus the back pressure valve will be closed and the first gas production will be completed. Subsequently repeat this process and depressurize in multiple stages until the back pressure and the pressure in the reactor are at the external atmospheric pressure level. Meanwhile, record the changes of pressure, temperature, gas production rate and total gas production in the whole process, as shown in Table 1.

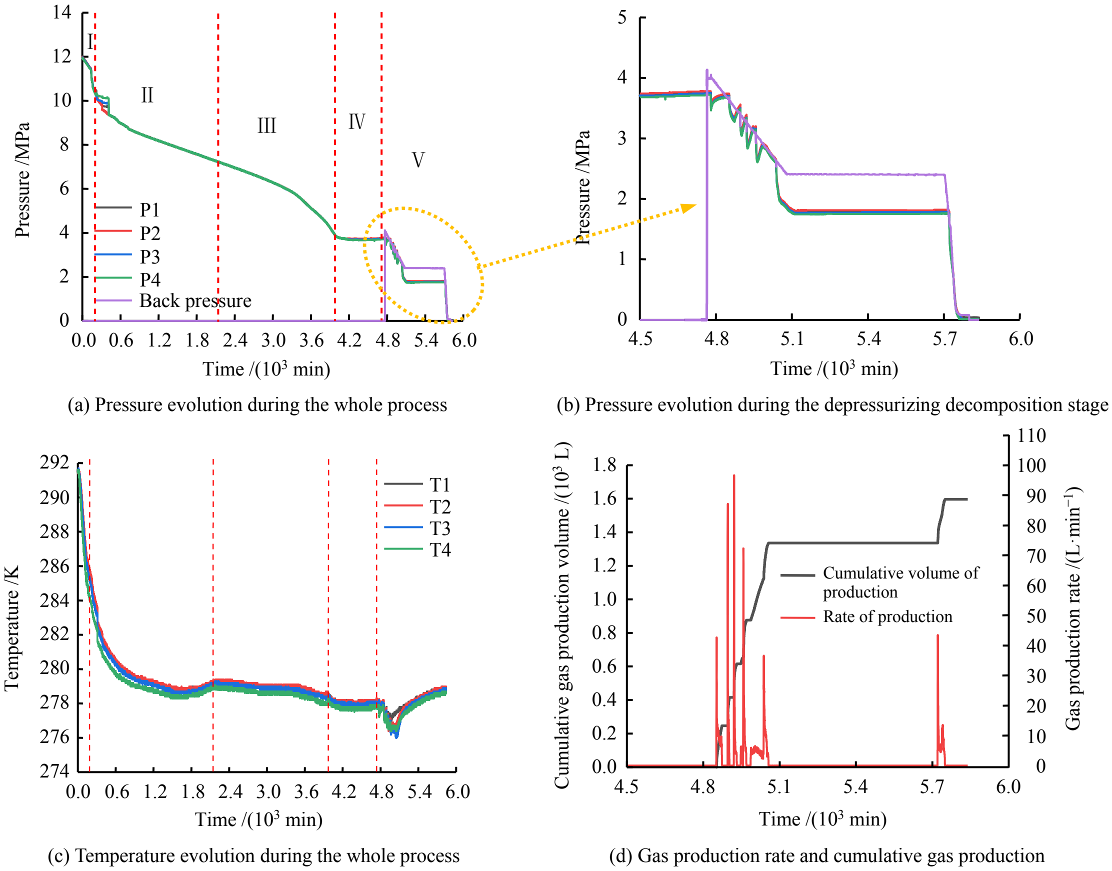
3.2.2 Results and discussion

The cooling synthesis, depressurizing decomposition and gas production characteristic curves of single horizontal well production and single vertical well production are shown in Fig. 14 and Fig. 15. The two-dimensional depressurizing production test can be divided into five stages (from left to right): I gas water mixed cooling stage, II hydrate induction stage, III hydrate continuous synthesis stage, IV hydrate stable existence stage and V depressurizing decomposition stage. In stage I, the temperature in the reactor begins to decrease, and the residual methane gas not dissolved in water in the reactor begins to shrink with the decrease of the temperature in the reactor, thus the pressure at the measuring point shows a linear decreasing trend. In stage II, the methane gas molecules in the pores in the sediment begin to combine with water molecules under the action of temperature and pressure to form natural gas hydrate, but the synthesis of hydrate is not stable at this stage, so it does not have regularity. The pressure continues to decrease, but the curve slope has begun to flatten compared with the cooling stage. However, due to the exothermic synthesis of hydrate, the temperature at each measuring point increases locally in a small range though it is not obvious. In stage III, the formation of hydrate has been basically regular, the temperature in the kettle is stable at the preset temperature value under the influence of the incubator. The pressure continues to decrease, but the curve slope gradually becomes steeper. In stage IV, the hydrate synthesis process has stopped, and the pressure and temperature are stable at a certain value without further change. In stage V, the free gas is discharged first. This leads to the decrease of pressure in the kettle. The hydrate deviates from the phase equilibrium state, decompose massively and absorbs a large amount of heat, resulting in a decrease in the temperature in the kettle. Additionally, due to the hydrate decomposition, a large amount of methane gas is produced, which increases the internal pressure of the reactor without discharge. Then repeat the previous stage until the hydrate is completely decomposed.

As can be seen from Figs. 14 (b) and 15 (b), the whole depressurizing decomposition stage includes two depressurizing processes, each having unique depressurization amount and depressurization rate. The depressurization process is mainly divided into the following two stages. (i) When the back pressure decreases to the pressure value in the kettle, the back pressure valve opens. The free gas in the kettle is discharged, and the gas pressure decreases rapidly. A large number of hydrates decompose, and the temperature of the measuring point in the reactor decreases rapidly and is lower than the temperature of the incubator. (ii) When the pressure value in the kettle is less than the back pressure value, the back pressure valve is closed, the gas exhaust ends, and the hydrate continues to absorb heat and decompose to produce gas. The decomposition speed slows down. The methane gas generated by decomposition begins to increase the pressure at the measuring point, and the heat absorbed by hydrate decomposition at the measuring point is less than the heat input of heat conduction, which increases the temperature at the measuring point. After that, repeat this process until the pressure in the kettle is the external atmospheric pressure. It is noted that the phenomenon that the gas pressure is higher than the back pressure in the whole process, is the back pressure lag phenomenon. It is caused by the accuracy and sensitivity of the back pressure valve and the blockage of the back pressure valve. At the same time, the phenomenon of back pressure "failure" occurred in the two depressurization processes, such as the back pressure stability stage in Fig.14 (b) and the back pressure lag caused by the blockage of the back pressure valve in Fig.15 (b). These two back pressure "failure" stages play the same role in the whole depressurizing decomposition gas production process. The difference between the two is that when the back pressure stability stage of the single horizontal well production test occurs, most of the hydrate has been decomposed, and the saturation of remaining hydrate is low, while for the single vertical well at the same stage, the hydrate is decomposed only a small amount, and the hydrate saturation is much greater than the former, which also leads to the gas production rate of the latter is much higher than that of the former. This observations are the same as the effect of hydrate saturation on the depressurizing production rate[39].

Table 1 First depressurization and gas production of two kinds of production wells

Type of production well	Initial pressure /MPa	Initial temperature /K	Depressurization amplitude /MPa	Depressurization rate /(Pa • s^{-1})	Cumulative gas production volume /L	Gas production rate	
						Peak gas production rate /(L • min^{-1})	Average gas production rate /(L • min^{-1})
Horizontal well	4.04	278.30	1.43	86.87	1 335.96	96.78	6.58
Vertical well	4.01	278.10	0.78	87.09	519.02	136.93	4.76



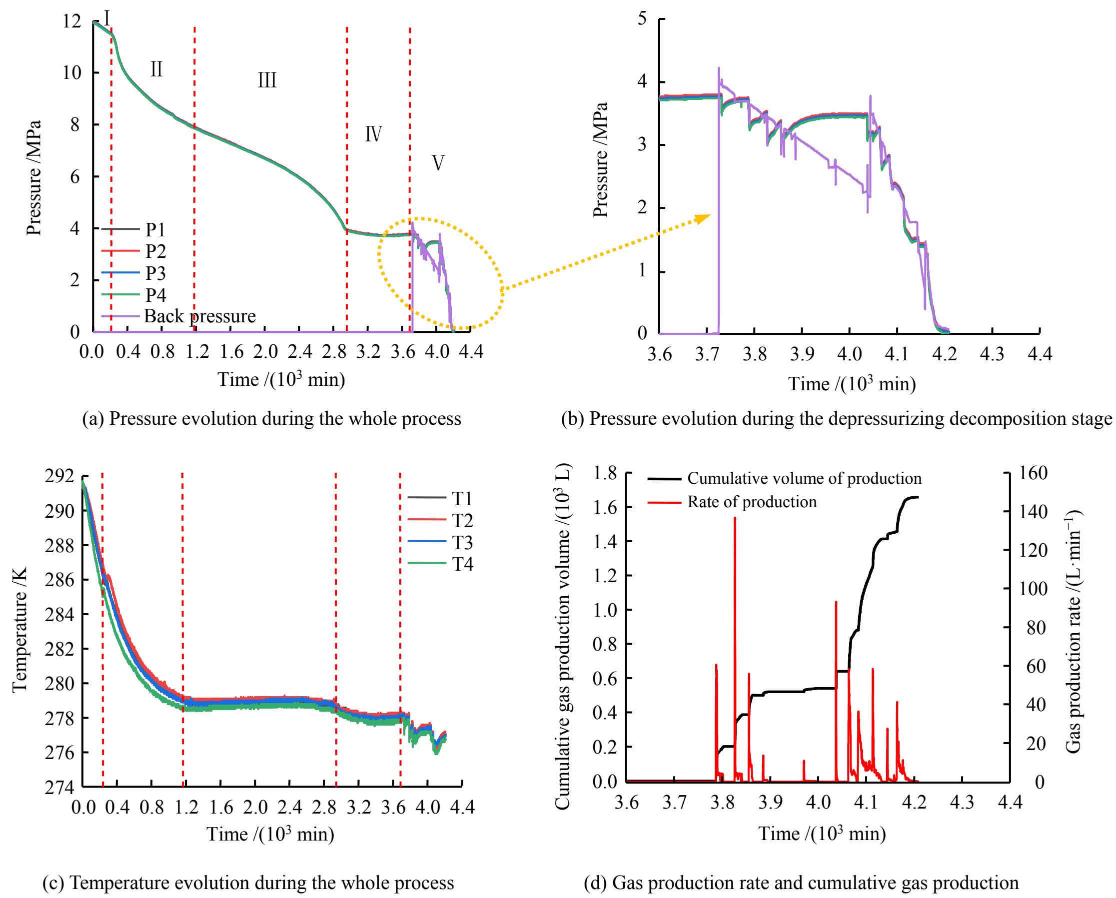
(a) Pressure evolution during the whole process

(b) Pressure evolution during the depressurizing decomposition stage

(c) Temperature evolution during the whole process

(d) Gas production rate and cumulative gas production

Fig. 14 Temperature reduction synthesis, pressure reduction decomposition and gas production characteristic curves of single horizontal well production



(a) Pressure evolution during the whole process

(b) Pressure evolution during the depressurizing decomposition stage

(c) Temperature evolution during the whole process

(d) Gas production rate and cumulative gas production

Fig. 15 Cooling synthesis, depressurizing decomposition and gas production characteristic curves of single vertical well production

The hydrate saturation in the reactor is the same before the first depressurization, the data in the gas production process of the first depressurization is therefore more accurate with less interference factors. This dataset is employed as the basis for analyzing the two-dimensional depressurizing production characteristics. As shown in Figs. 14 (d), 15 (d) and Table 2, although the gas production rate fluctuates due to the instability of gas-liquid two-phase seepage itself and the sensitivity of back pressure valve[34], the gas production rate in depressurizing production test by using constant speed and constant pressure pump to control back pressure is more uniform as compared with manual control of back pressure.

Table 2 Stage production of two kinds of wells

Type of production wells	Stages	Mean gas production rate /($L \cdot min^{-1}$)	Peak gas production rate /($L \cdot min^{-1}$)
Horizontal	1	11.44	24.08
Horizontal	2	21.27	88.06
Horizontal	3	15.93	96.78
Horizontal	4	11.39	74.11
Horizontal	5	4.88	23.77
Horizontal	6	11.70	28.30
Vertical	1	61.57	57.93
Vertical	2	3.58	5.05
Vertical	3	102.78	136.93
Vertical	4	3.12	4.75
Vertical	5	13.29	56.32
Vertical	6	1.87	2.67

According to the comprehensive comparison of the first depressurizing production of horizontal wells and vertical wells, the hydrate saturation, initial pressure and initial temperature of the two wells were the same before depressurizing production. Some previous research results suggested that the gas production rate and total gas production are positively correlated with the depressurization rate[40], which means the greater pressure drop leads to the more gas production. In this paper, the same depressurization rates of the two groups of tests at about 87 Pa/s were measured, but the cumulative gas production and gas production rate per unit pressure drop were found very different. During horizontal well exploitation, the unit pressure drop gas production was 934.24 L /MPa, the peak gas production rate was 96.78 L /min, and the average gas production rate was 6.58 L /min; while during vertical well exploitation, the corresponding values were 665.41 L /MPa, 136.93 L / min and 4.76 L /min. The gas production per unit pressure drop and average gas production rate of horizontal wells were about 1.4 times that of vertical wells, and the peak gas production rate of the latter was about 1.4 times that of the former. In conclusion, from the perspective of the whole depressurizing gas production process, the average gas production rate of horizontal wells is higher than that of vertical wells under the same conditions, but the latter achieves higher peak gas production rate. Compared with horizontal well mining, vertical well mining is more likely to cause the self-protection effect of hydrate around the wellbore. The gas production of horizontal well is more uniform than that of vertical well. The reason for this characteristic is mainly due to the size of two-dimensional reactor as the horizontal well has longer length buried in the sample and larger contact area on the hydrate. Considering each depressurization and gas production process in the two groups of tests is carried out alternately by two depressurizing stages, the gas production process is therefore also phased. According to Figs. 14 (d) and 15 (d), the first gas production process of horizontal wells and vertical wells is divided into six stages, as shown in Table 2. Moreover, there is a gas production window period of different sizes between every two stages. During the window period, the back pressure valve is closed, the gas in the kettle is not discharged, and consequently the cumulative gas production remains constant with zero gas production rate.

In the whole process of the first depressurizing gas production, the evolutions of the two gas production rate curves of horizontal well and vertical well are shown in Fig. 16. The gas production rate curve of horizontal well performs the path of initial value → peak→trough→final value. The two gas production rate curves of vertical wells follow the trend of initial value→trough→peak→trough→peak→final value. Compared with the rate curve of vertical wells, the rate curve of horizontal wells has less fluctuation, indicating a more uniform gas production. It can be explained that the vertical well is more conducive to the discharge of free gas in the kettle, and thus greater initial gas production rate is reached. The large discharge of free gas in the kettle leads to a large amount of hydrate decomposition. The hydrate saturation

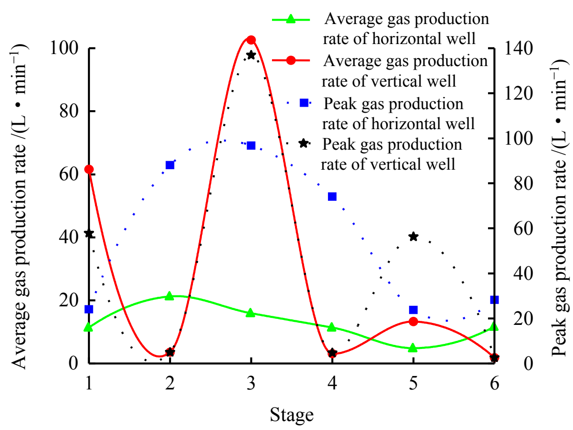


Fig. 16 Phased gas production rate of two types of production wells

responds in terms of rapid decreasing, and the decomposition rate slows down. Furthermore, in the process of rapid gas production, the secondary formation of hydrate around the vertical well also hinders the discharge of gas and reduces the gas production rate until the gas production rate reaches the final value.

4 Conclusion and prospect

In this paper, the multi-dimensional natural gas hydrate production simulation testing system is introduced. A one-dimensional phase equilibrium test and two-dimensional depressurizing production test are carried out to test the reliability of the system so as to provide data support for subsequent natural gas hydrate research. The following main conclusions are obtained:

(1) For the phase equilibrium test of quartz sand with the same particle size, with the increase of initial pressure, the temperature and pressure of the test phase equilibrium point obtained by graphic method are increasing as well, whereas the particle size of quartz sand has little effect on the phase equilibrium curve.

(2) The two-dimensional depressurizing production test can be divided into five stages: I gas water mixed cooling stage, II hydrate induction stage, III hydrate stable synthesis stage, IV hydrate stable existence stage and V depressurizing decomposition stage.

(3) The gas production rate fluctuates due to the instability of gas-liquid two-phase seepage and the sensitivity of back pressure valve. However, compared with manual control of back pressure, the gas production rate of two-dimensional depressurizing production test using constant speed and constant pressure pump to achieve piecewise slow depressurization is more uniform.

(4) The gas production rate curve of horizontal wells evolves following the trend of initial value → crest → trough → final value, while the two gas production rate curves of vertical wells evolve as initial value → trough → crest → trough → crest → final value. At the same time, compared with vertical wells, the rate curves of horizontal wells shows less fluctuation, indicating a more uniform gas production achieved.

In this study, the quartz sand filled in the test and the surrounding environment conduct heat through the model steel cylinder wall. The thermal conductivity of the steel cylinder is large, generally about 50 W/(m • K), so that the system temperature can be maintained at a relatively stable level. In the actual natural gas hydrate reservoir, the thermal conductivity of the rock layer is generally only about 2 W/ (m • K). The decomposition and absorption of heat by hydrate therefore greatly lower the temperature of the surrounding sandstone, resulting in the rapid decomposition of natural gas hydrate. The heat flow from the upper and lower caprocks to the reservoir are not able to supplement the heat loss in time, so that the reservoir temperature decreases rapidly, and it initiates the self-protection effect of natural gas hydrate to prevent the further decomposition of hydrate. The depressurizing production is consequently interrupted. Therefore, it is necessary to select a material with low temperature resistance, high pressure resistance, strong sealing and low thermal conductivity to make the hydrate reactor. In addition, the wellbore layout in this study only involves a single wellbore design. The subsequent research on multi wellbore and different well pattern layout will be carried out. For the exploitation of deep-sea natural gas hydrate safely and efficiently, it is essential to understand its in-situ synthesis and decomposition characteristics. It is known that most deep-sea natural gas hydrates occur hundreds of meters below the seabed. The in-situ synthesis and decomposition characteristics of hydrate are affected by not only pressure and temperature, but also in-situ stress and other factors under this condition. In the prospective study following up this research, the three-dimensional depressurization mining test will be carried out.

Reference

[1] SLOAN E D, KOH C. Clathrate hydrates of natural gases (3rd edition)[M]. Boca Raton: Chemical Rubber Company Press, 2007: 1−10.

[2] JIANG Yu-jing, GONG Bin, WANG Gang. Introduction of methane hydrate production in deep sea[M]. Beijing: Science Press, 2017: 1−10.

[3] ZHU You-hai. Production test from gas hydrate of Mackenzie permafrost, Canada[J]. Advances in Earth Science, 2006, 21(5): 513−520.

[4] HUANG Rui. Experimental study on dissociation of natural gas hydrate by heat injection and depressurization[D]. Qingdao: China University of Petroleum (East China), 2016.

[5] MA S, ZHENG J N, ZHAO J, et al. Effects of temperature holding on methane hydrate decomposition process by thermal stimulation[J]. The Journal of Chemical Thermodynamics, 2021, 159(9): 106487.

[6] WANG Y, FENG J C, LI X S, et al. Pilot-scale experimental evaluation of gas recovery from methane hydrate using cycling-depressurization scheme[J]. Energy, 2018, 160: 835−844.

[7] MINAGAWA H, ITO T, KIMURA S, et al. Depressurization and electrical heating of methane hydrate sediment for gas production: laboratory-scale experiments[J]. Journal of Natural Gas Science and Engineering, 2018, 50: 147−156.

[8] LI D X, REN S R, ZHANG L, et al. Dynamic behavior of hydrate dissociation for gas production via depressurization and its influencing factors[J]. Journal of Petroleum Science and Engineering, 2016, 146: 552−560.

[9] TAKUMA N. About the second methane hydrate marine gas production test, gas production started from the methane hydrate layer[EB/OL]. https://www.jogmec.j-ogmec.go.jp/n-ews_06_000266.html, 2017-5-8.

[10] TAKUMA N. The second offshore production test of methane hydrate stopped decompression and ended gas production[EB/OL]. https://www.jogmec.go.jp/news/release/news_01_000108.html, 2017-6-30.

[11] WU Neng-you, HUANG Li, HU Gao-wei, et al. Geological controlling factors and scientific challenges for offshore gas hydrate exploitation[J]. Marine Geology & Quaternary Geology, 2017, 37(5): 1−11.

[12] MAO Pei-xiao, WU Neng-you, NING Fu-long, et al. Behaviors of gas and water production from hydrate induced by depressurization with different types of wells[J]. Natural Gas Industry, 2020, 325(11): 174−182.

[13] LI X S, YANG B, ZHANG Y, et al. Experimental investigation into gas production from methane hydrate in sediment by depressurization in a novel pilot-scale hydrate simulator[J]. Applied Energy, 2012, 93: 722−732.

[14] ZHOU Jia-zuo, WEI Chang-fu, WEI Hou-zhen, et al. Development and application of multi-functional triaxial test system for hydrate-bearing sediments[J]. Rock and Soil Mechanics, 2020, 41(1): 342−352.

[15] LIANG Wen-peng, ZHOU Jia-zuo, CHEN Pan, et al. An elastoplastic constitutive model of gas hydrate bearing sediments based on homogenization theory[J]. Rock and Soil Mechanics, 2021, 42(2): 481−490.

[16] ZHOU Yuan, WEI Chang-fu, ZHOU Jia-zuo, et al. Development and application of gas hydrate injection synthesis and direct shear test system[J]. Rock and Soil Mechanics, 2021, 42(8): 2311−2320.

[17] FAN Shuan-shi, SHI Lei, GUO Yan-kun, et al. New experimental apparatus and method of testing methane gas hydrate phase equilibrium[J]. Natural Gas Industry, 2001, 21(3): 71−73.

[18] KIM N J, LEE R H, CHO R S, et al. Formation enhancement of methane hydrate for natural gas transport and storage[J]. Energy, 2010, 35(6): 2717−2722.

[19] JIANG Lei-lei. Experimental study on rapid synthesis technology of natural gas hydrate[D]. Chengdu: Southwest Petroleum University, 2018.

[20] LI Shu-xia, CHEN Yue-ming, HAO Yong-mou, et al. Experimental research on influence factors of natural gas hydrate production by depressurizing in porous media[J]. Journal of China University of Petroleum (Edition of Natural Science), 2007, 31(4): 56−59.

[21] LI Shu-xia, CHEN Yue-ming, WANG Rui-he, et al. On the influence of initial pressure on natural gas hydrate formation in a porous medium[J]. Journal of Experimental Mechanics, 2009, 24(4): 313−319.

[22] DU Yan, HU Shi-hui, HUANG Chong, et al. Experimental studies of natural gas hydrate formation and dissociation in porous media with 2D experimental system[J]. Journal of Chemical Industry and Engineering (China), 2008, 59(3): 673−680.

[23] ZHOU Shou-wei, LI Qing-ping, CHEN Wei, et al. Research on 3D experiment technology of natural gas hydrate exploitation[J]. China Offshore Oil and Gas, 2016, 28(2): 1−9.

[24] GAO Yi. Study on mining characteristic of multiclass methane hydrate deposits by depressurization method[D]. Dalian: Dalian University of Technology, 2019.

[25] FENG Jing-chun, LI Xiao-seng, WANG Yi, et al. Three-dimension experimental investigation of hydrate dissociation by the combined method with dual horizontal wells[J]. Geoscience, 2016, 30(4): 929−936.

[26] WONMO S, HYUN K. Experimental investigation of production behaviors of methane hydrate saturated in porous rock[J]. Energy Sources, 2003, 25(8): 845−856.

[27] SUNG W M, LEE H S, YANG H J. An experimental study for hydrate dissociation phenomena and gas flowing analysis by electric heating method in porous rocks[J]. Korean Chemical Engineering Research, 2004, 42(1): 115−120.

[28] HAO Wen-feng, FAN Shuan-shi, WANG Jin-qu. Effects of stirrer on methane hydrate formation[J]. Natural Gas Chemical Industry, 2005, 30(3): 5−7.

[29] KONO H O, NARASIMHAN S, SONG F, et al. Synthesis of methane gas hydrate in porous sediments and its dissociation by depressurizing[J]. Powder Technology, 2002, 122(2-3): 239−246.

[30] ZHANG Chun-sun, FAN Shuan-shi, GUO Yan-kun, et al. Effects of various surfactants on natural gas hydrate formation[J]. Natural Gas Industry, 2003, 23(1): 91−95.

[31] BUFFETT B A, ZATSEPINA O Y. Formation of gas hydrate from dissolved gas in natural porous media[J]. Marine Geology, 2000, 164(1-2): 69−77.

[32] BOOTH J S, WINTERS W J, DILLON W P. Apparatus investigates geological aspects of gas hydrates[J]. Oil & Gas Journal, 1999, 97(40): 63−70.

[33] SUN Zhi-gao, SHI Lei, FAN Shuan-shi, et al. Study of the measuring methods of gas hydrate phase equilibrium[J]. Chemical Engineering of Oil and Gas, 2001, 30(4): 164−166.

[34] LIANG Hai-feng. Natural gas hydrate depressurization production theory and technology[M]. Beijing: Chemical Industry Press, 2014.

[35] CLAYTON C R I, PRIEST J A, BEST A I. The effects of disseminated methane hydrate on the dynamic stiffness and damping of a sand[J]. Géotechnique, 2005, 55(6): 423−434.

[36] CLENNELL M B, HENRY P, HOVLAND M, et al. Formation of natural gas hydrates in marine sediments: I. conceptual model of gas hydrate growth conditioned by host sediment properties[J]. Annals of the New York Academy of Sciences, 1999, 104(1): 22985−23003.

[37] CHEN Qiang, YE Yu-guang, LIU Chang-ling, et al. Research on formation kinetics of methane hydrate in porous media[J]. Marine Geology & Quaternary Geology, 2007, 24(1): 111−116.

[38] WANG Y, LI X S, LI G, et al. A three-dimensional study on methane hydrate decomposition with different methods using five-spot well[J]. Applied Energy, 2013, 112(4): 83−92.

[39] LI Shu-xia, LI Jie, JIN Yu-rong, et al. Depressurizing dissociation of natural gas hydrate with different saturations[J]. CIESC Journal, 2014, 65(4): 1411−1415.

[40] LI Shou-ding, SUN Yi-ming, CHEN Wei-chang, et al. Analyses of gas production methods and offshore production tests of natural gas hydrates[J]. Journal of Engineering Geology, 2019, 27(1): 58−71.