Research Article

Effects of Irreducible Fluid Saturation and Gas Entry Pressure on Gas Production from Hydrate-Bearing Clayey Silt Sediments by Depressurization

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Gas hydrates in the Shenhu area are mainly hosted in clayey silt sediments, which have the relatively high irreducible fluid saturation and gas entry pressure. And then, they will have an impact on gas production from hydrate-bearing clayey silt sediments, which was evaluated by the numerical simulations of SH2 site in Shenhu area in this paper. The results showed that, with the increase in irreducible water saturation and irreducible gas saturation, the amount of water production and gas production was obviously reduced. When the irreducible water saturation increased from 0.10 to 0.50, the cumulative CH₄ production volume decreased from 1668799 m³ to 1536262 m³, and the cumulative water production volume dropped from 620304 m³ to 564797 m³, respectively. When the irreducible gas saturation increased from 0.01 to 0.05, the cumulative CH₄ production volume dropped from 1812522 m³ to 1622121 m³, and the cumulative water production volume dropped from 672088 m³ to 600617 m³, respectively. In addition, the capillary pressure increased obviously with the increase in gas entry pressure, but the effect on gas production was small and the effect on water production could be negligible. In conclusion, irreducible water and gas saturation had an important effect on the gas production from gas hydrate, whereas the effects of gas entry pressure could be ignored.

1. Introduction

Natural gas hydrate (NGH) is an ice-like crystalline compound formed by water molecules and natural gas molecules, such as methane, ethane, and propane, under high pressure and low temperature [1]. NGH is considered one of the potentially clean energies in future, and it is widely distributed in marine sediments and the permafrost regions [2, 3]. It has attracted more and more attentions from researchers all over the world. According to the preliminary estimates, the total amount of energy hosted in the NGH reservoir is two times that of conventional oil and gas resources [4]. However, because of the characteristics of unconsolidated and permeable overburden layer, submarine

hydrate decomposition may cause geological hazards and climate change [5–7].

Different from the production of oil and natural gas resources, gas hydrate should be decomposed into gas and water at first, which is an endothermic phase transition. There are four main methods for hydrate production, including depressurization, thermal stimulation, CO₂-CH₄ replacement, and inhibitor injection [8–10]. In addition, Chinese scientists have proposed a new type of production method called solid fluidization, which transfer natural gas hydrate through mechanical crushing fluidization into a gas-liquid-solid multiphase pipeline [11]. Among them, depressurization method was successfully applied to the offshore gas hydrate production tests in Japan and China. In 2013, Japan's

first marine hydrate production lasted for six days, and the total gas volume reached $1.195 \times 10^5 \text{ m}^3$ [12]. In 2017, two production wells were drilled in Japan's second offshore marine hydrate production test; the gas production of the first production well reached $3.5 \times 10^4 \text{ m}^3$ in 12 days and the total gas production of the second production well was up to $2 \times 10^5 \text{ m}^3$ for 24 days [13]. In July 9, 2017, China successfully completed its first offshore hydrate production test in the Shenhu area, northern South China Sea, which was the first time in the world to produce gas from clayey silt NGH reservoir [14]. The total volume of gas production was up to $3.09 \times 10^5 \text{ m}^3$ in 60 days [13, 14]. In May 2017, China successfully produced 81 m^3 of gas in the northern South China Sea by solid fluidization [11]. From February 17 to March 30, 2020, China's second offshore hydrate production test achieved a total gas production of $1.4986 \times 10^6 \text{ m}^3$ by using a horizontal production well, with an average daily gas production of $3.57 \times 10^4 \text{ m}^3$ [15]. Although these four offshore methane hydrate productions have made great progress, it is far from being commercialized and economical.

China conducted three hydrate drilling expeditions in 2007 (GMGS-1, Guangzhou Marine Geological Survey), 2015 (GMGS-3), and 2016 (GMGS-4) in the Shenhu area, and gas hydrate samples were successfully obtained in these three expeditions [16]. In GMGS-1, gas hydrates were found at sites SH2, SH3, and SH7 [17, 18], and this area is the typical Class 2 hydrate reservoir, which have a mobile water zone under hydrate-bearing layer (HBL). Based on the analysis of core samples, geophysics, and geochemistry, a series of important data, such as hydrate saturation, porosity of sediments, reservoir temperature, and pressure, was obtained. By depressurization experiments to estimate gas hydrate saturation in site SH2, it was concluded that the maximum hydrate saturation could get up to 0.48 [19]. The particle size composition of hydrate-bearing sediments in site SH2 is that silts (0.04–0.063 mm) accounts for 73.94%, clay (<0.04 mm) accounts for 24.68%, and sand (>0.063 mm) accounts for 1.4%, which means gas hydrates are hosted in clayey silt sediments [20]. And the results of X-ray diffraction pattern indicate that the clay minerals in the hydrate layer are mainly montmorillonite (illite/smectite mixed layer), illite, chlorite, and kaolinite [21]. The features of small particle size and high clay content would cause the multiphase flow in the process of gas production more complicated, which mainly includes three aspects. The first is increasing irreducible water saturation. Water will be adsorbed on the surface of sediment particles because of its hydrophilicity [22], and some of the irreducible water is formed by capillarity; in addition, clay will absorb a large amount of water due to strongly hydrophilic [23]. The second is increasing irreducible gas saturation. Previous studies about shale gas have shown that the gas sorption capacity could be influenced by clay mineral composition [24, 25]. The sorption capacity of clays for methane increases in the order illite < chlorite < kaolinite < illite/smectite mixed layer < montmorillonite [25], which means that the clay mineral composition will lead to the different sorption capacities of methane for the different hydrate-bearing clayey silt sediments. In addition, the absorbed gas will decrease with the increase in water saturation [26, 27]. The third is increasing gas entry pressure. Gas entry pressure depends on the radius of the largest

FIGURE 1: Schematic of the simulated NGH reservoir and well design in site SH2.

interconnected pathway through the sediment matrix, the water wettability of the sediments, and the interfacial tension between the fluid phases, so the small particle diameter and high clay content could increase the gas entry pressure [28]. Those changes caused by the small particle size and high clay content could change the gas and water relative permeability and capillary pressure, which would further affect gas production from HBL.

Based on the data obtained from hydrate drilling expeditions in the South China Sea, a lot of numerical simulations were carried out. Su et al. [29] studied the gas production behaviors of the NGH reservoir in site SH3 by depressurization method in a vertical well, and it was found that the gas production could not reach the industrial production according to the relative criterion and the absolute criterion. Li et al. [30] used a single horizontal well in the middle of the HBL to produce gas from the NGH reservoir in site SH7 and found that the gas production rate could reach $3.46 \times 10^4 \text{ m}^3/\text{d}$ when the horizontal well length was 1000 m [30]. Jin et al. [31] investigated the enhancement of hot water injection on gas production from the NGH reservoir in site SH2 and found that the gas production increased with hot water temperature and injection pressure. Sun et al. [32] studied the geomechanical response of the NGH reservoir during gas production under different conditions including hydrate saturation heterogeneity, hydrate formation permeability, and gas formation permeability and found that the largest sea-floor subsidence was only about 0.14 m. Konno et al. [12] simulated Japan's first marine hydrate production through numerical simulation. The simulation results showed that the gas production gradually increased with the expansion of the decomposition area, and the increase in hydrate

TABLE 1: Main hydrate reservoir properties and conditions in site SH2.

Overburden layer thickness, ΔZ_O	30 m
Underlying layer thickness, ΔZ_U	30 m
HBL thickness, ΔZ_H	40 m
Completion interval (L_P)	20 m (in the middle of HBL)
Borehole radius	0.1 m
Initial pressure, P_B (at base of HBL)	14.97 MPa
Initial temperature, T_B (at base of HBL)	14.87 °C
Gas composition	CH ₄
Porosity, Φ (all formations)	38%
Initial saturation in the HBL	$S_W = 0.60$, $S_H = 0.40$
Intrinsic permeability, $k_x = k_y = k_z$ (all formations)	10 mD
Water salinity (mass fraction)	3.05%
Grain density, ρ_R (all formations)	2600 kg/m ³
Dry thermal conductivity, k_{dry} (all formations)	1.0 W/m/°C
Wet thermal conductivity, k_{wet} (all formations)	3.1 W/m/°C
Composite thermal conductivity model	$k_\theta = k_{dry} + \left(\sqrt{S_A} + \sqrt{S_H}\right)(k_{wet} - k_{dry}) + \phi S_I \lambda_I$
Capillary pressure model	$P_{cap} = -P_0 \left[(S^*)^{-1/\lambda} - 1 \right]^{1-\lambda}$ $S^* = S_W - S_{irW}/S_{mxW} - S_{irW}$
λ	0.45
Relative permeability model	$k_{rW} = (S_W - S_{irW}/1 - S_{irW})^n k_{rG} = (S_G - S_{irG}/1 - S_{irG})^{n_G}$
n	3.572 [38]
n_G	3.572 [38]

TABLE 2: Simulation parameters in different cases.

Simulation ID	Parameters	Bottom hole pressure (MPa)	Irreducible water saturation	Irreducible gas saturation	Gas entry pressure (MPa)
1	Irreducible water saturation	3	0.1	0.05	0.1
2			0.3		
3			0.5		
4	Irreducible gas saturation	3	0.3	0.01	0.1
5				0.03	
6				0.05	
7	Gas entry pressure	3	0.3	0.05	0.01
8					0.1
9					0.5

formation permeability increased the ratio of gas to water. Yang et al. [33] studied gas production by depressurization combined with warm water flooding, and the results showed that this method had the characteristics of high efficiency, low cost, and high safety. Ruan et al. [34] investigated the influence of factors such as initial hydrate saturation, permeability reduction index, absolute/relative permeability, and intrinsic porosity on hydrate production, the authors also pointed out the importance of relative permeability model and permeability decay index for numerical simulation. Ma et al. [35] found the increase of water permeability reduction

index from 2.5 to 4.5 could make the total gas production decreases from $1.93 \times 10^6 \text{ m}^3$ to $1.34 \times 10^6 \text{ m}^3$.

Although there are many articles studying the effects of various factors on gas hydrate production through numerical simulation, little research has studied the effects of hydrogeological parameters such as irreducible water saturation, irreducible gas saturation, and gas entry pressure on gas hydrate production. The main purpose of this study is to evaluate the effects of different irreducible fluid saturation and gas entry pressure on gas and water production, gas and water relative permeability, and capillary pressure.

FIGURE 2: Evolution of the pressure distribution P on the 10th day, 365th day, 1825th day, and 3650th day in the case with $S_{irW} = 0.30$, $S_{irG} = 0.05$, and $P_0 = 0.1$ MPa.

2. Simulation Model

2.1. Model Parameters. In this study, Tough+Hydrate was used to conduct the numerical simulations. This software could model the nonisothermal gas release, phase behavior, and flow of fluids and heat in complex geologic media [36]. The schematic of the simulated NGH reservoir and well design in site SH2 in this study is shown in Figure 1. The NGH reservoir in site SH2 could be divided into three layers, including permeable overburden layer, HBL, and permeable underlying layer. The thickness of HBL is assumed to be 40 m, and its intrinsic permeability k_H , porosity, and average hydrate saturation are set to 10 mD [19], 38%, and 0.40 [36, 37], respectively. The thicknesses of the permeable overburden layer and the permeable underlying layer are all set to 30 m, which could satisfy the heat and mass exchange in the process of 10 years' gas production from the NGH reservoir. Other physical characteristics of overburden layer and

underlying layer, such as porosity and permeability, are the same as the HBL [19, 29, 36]. The production well is in the center of this cylindrical hydrate reservoir with a radius of 0.1 m and a special no-flow boundary, which is called the Neumann boundary, is applied at $r_{\max} = 100$ m [37]. The upper and lower boundaries are assumed to be constant temperature and pressure boundary conditions, and these boundaries are permeable. The hydrate used in this numerical simulation is methane hydrate. The salinity of pore water is 3.05% [32]. Other properties and conditions of the numerical model used in this study are listed in Table 1.

As shown in Figure 1, without confining impermeable overburden layer, a large volume of undesirable water will flow into production well, thereby reducing gas production and the effectiveness of depressurization. Meanwhile, the lack of a confining impermeable overburden layer will cause gas leak into the ocean through the overburden layer. In order to prevent gas leaking into the ocean and undesirable water

FIGURE 3: Evolution of the hydrate saturation distribution S_H on the 10th day, 365th day, 1825th day, and 3650th day in the case with $S_{irW} = 0.30$, $S_{irG} = 0.05$, and $P_0 = 0.1$ MPa.

production, the perforated interval does not completely pass through the whole HBL [29, 38]. In this study, the perforation interval has a total length of $L_p = 20$ m, which is located at the middle of HBL [35]. Previous studies have proven that depressurization is the most effective and economical method of hydrate production [39–41], so the method of depressurization is used in this study. The production well has a constant pressure of 3 MPa, which is above the quadruple point of methane gas hydrate. This pressure will accelerate the decomposition of hydrate and avoid the formation of ice [42, 43]. The entire production lasts 3650 days.

The values of irreducible water saturation S_{irW} , irreducible gas saturation S_{irG} , and gas entry pressure P_0 will change with the particle size, clay content, and hydrate saturation. However, the change rule of relevant data with geological parameters is not given in the previous research through experiments. Therefore, in this study, those parameters are

assumed to be fixed values to study the influence of these parameters on hydrate production. The relative permeability model used in this simulation is as follows [44]:

$$\begin{aligned} K_{rW} &= \left(\frac{S_W - S_{irW}}{1 - S_{irW}} \right)^n, \\ K_{rG} &= \left(\frac{S_G - S_{irG}}{1 - S_{irG}} \right)^{n_G}, \\ K_{rH} &= 0, \end{aligned} \quad (1)$$

where K_{rW} , K_{rG} , and K_{rH} are water relative permeability, gas relative permeability, and hydrate relative permeability, respectively, S_W and S_G are water saturation and gas saturation, respectively. Hydrate exists as a solid in pores, so its relative permeability is 0.

FIGURE 4: Evolution of the gas saturation distribution S_G on the 10th day, 365th day, 1825th day, and 3650th day in the case with $S_{irW} = 0.30$, $S_{irG} = 0.05$, and $P_0 = 0.1$ MPa.

The capillary pressure function used is as follows [45]:

$$P_{\text{cap}} = -P_0 \left[(S^*)^{-1/\lambda} - 1 \right]^{1-\lambda}, \quad (2)$$

$$S^* = \frac{S_W - S_{irW}}{S_{mxW} - S_{irW}},$$

$$-P_{\text{max}} \leq P_{\text{cap}} \leq 0,$$

where P_{cap} is capillary pressure, S^* is scaled saturation, and P_{max} is maximum capillary pressure.

In these two models, S_{irW} , S_{irG} , and P_0 are key parameters which could affect the multiphase flow by affecting fluid relative permeability and capillary pressure. In the cases with different S_{irW} , S_{irW} is set to 0.10, 0.30, and 0.50, respectively, while S_{irG} and P_0 are set to 0.05 and 0.1 MPa, respectively; In the cases with different S_{irG} , S_{irG} is set to 0.01, 0.03 and 0.05, respectively, while S_{irW} and P_0 are set to 0.30 and 0.1 MPa,

respectively. In the cases with different P_0 , P_0 is set to 0.01, 0.10, and 0.50 MPa, respectively, while S_{irW} and S_{irG} are set to 0.30 and 0.05, respectively. The parameters in this paper are shown in Table 2.

2.2. Initial and Boundary Conditions. Initial pressure and temperature at the bottom of HBL are assumed to 14.97 °C and 14.87 MPa, respectively, which are also used by other papers [37]. The overburden layer above the HBL is permeable, and the pore water in the stratum could be exchanged with seawater, which means pore water pressure could be determined by hydrostatic pressure formula. So, the following formula is used to calculate the initial pore pressure of whole model:

$$P_{pw} = P_B + \rho_{sw} g \Delta z \times 10^{-6}, \quad (3)$$

where P_{pw} is the hydrostatic pore water pressure in MPa, P_B is the pressure at the bottom of the HBL, and its value is

FIGURE 5: Evolution of the water saturation distribution S_w on the 10th day, 365th day, 1825th day, and 3650th day in the case with $S_{irW} = 0.30$, $S_{irG} = 0.05$, and $P_0 = 0.1$ MPa.

14.87 MPa, and g is the gravity acceleration. Δz is the distance in m from the bottom of HBL, and it is negative above HBL and positive below HBL. ρ_{sw} is the average pore water density, assumed to be 1035 kg/m^3 [30]. The temperature gradient is set to $4.695 \text{ }^\circ\text{C}/100 \text{ m}$. According to the hydrostatic pressure formula and temperature gradient, the temperature and pressure of the upper and lower boundaries could be calculated to initialize the temperature and pressure of the whole simulation domain through the self-balancing function of software.

3. Results and Discussions

3.1. Spatial Distributions of Physical Properties in Reservoir.

Figure 2 shows the evolution of the pressure distribution over time within the entire reservoir in the case with $S_{irW} = 0.30$, $S_{irG} = 0.05$, and $P_0 = 0.1$ MPa under the production pressure of 3 MPa. It could be seen from Figure 2 that pressure distribution has the following characteristics: (1) in the first ten

days of production, the water near the production well flows into the production well under the pressure gradient, and the effect of the depressurization is only within 10 meters; as shown in Figure 2(a), due to the large range of the low-pressure zone below 12 MPa in the initial stage, a large number of hydrates are decomposed, so that the rate of gas production at this stage is high; (2) there is an obvious pressure drop around the production well, and the range of depressurization increases with time; however, because of the low permeability of HBL, the maximum range of pressure drop is within 30 m; (3) it could be seen from the figure that the influence range of the low-pressure zone below 12 MPa increases between 10–365 d, which is due to the gradual extraction of fluid from the reservoir resulting in the expansion of low-pressure zone; but after 365 d, more and more water from the overburden and underlying layers enters the production well, which leads to the increase in water production rate and has a negative effect on depressurization, so the range of the low-pressure area decreases.

FIGURE 6: Relationship between gas, water relative permeability, and water saturation in different cases with different irreducible water saturation S_{irW} .

FIGURE 7: Relationship between capillary pressure and water or gas saturation in different irreducible water saturation cases.

FIGURE 8: Evolution of total gas production rate Q_{PT} and total gas production V_{PT} in three different cases with different S_{irW} .

The location of decomposed hydrate zone could be analyzed by hydrate saturation distribution. The following conclusion could be concluded from Figure 3: (1) during the 3650 days of production, the main range of hydrate decomposition area is limited to 20 meters; the existence of hydrates reduces the effective permeability of the low permeability clayey slit sediments, which affects the range of the depressurization and increases the time of the decomposed gas flows to the production well; (2) the decomposition of hydrates is also accompanied by the formation of secondary hydrates; this phenomenon is mainly due to the fact that the gas generated by hydrate decomposition enters the undecomposed area by diffusion or convection, thereby causing hydrate reformation phenomenon; (3) in the initial stage, the hydrate decomposition zone is mainly concentrated around the production well; and (4) on the 365th day, hydrate decomposition occurs at both the upper and lower parts of the HBL, and the lower part of the HBL decomposes rapidly, which is mainly caused by the high-temperature fluid of the underlying and overburden layers flowing into the production well, and the temperature of the underlying layer is higher than that of the overburden layer [30].

Figure 4 shows the evolution of the gas saturation distribution S_G on the 10th day, 365th day, 1825th day, and 3650th day in the case with $S_{irW} = 0.30$, $S_{irG} = 0.05$, and $P_0 = 0.1$ MPa. The following characteristics could be concluded from Figure 4: (1) the gas saturation in the whole process of

production is almost below 0.2, and the gas saturation gradually decreases with the production; (2) in the early stage of production, gas is mainly distributed around the production well; but when the water from the underlying and overburden layers flows into the production well, the gas is mainly distributed on the lower decomposition edge; and (3) it could be seen from Figure 4(a) and Figure 4(b) that the range of gas is larger than hydrate decomposition area, which confirms the reason for the formation of secondary hydrate.

Figure 5 shows the evolution of the water saturation distribution S_W on the 10th day, 365th day, 1825th day, and 3650th day in the case with $S_{irW} = 0.30$, $S_{irG} = 0.05$, and $P_0 = 0.1$ MPa. It can be seen from the partial enlarged figure in Figure 5(a) that with the increase in the distance from the production well, the S_W in the area near the production well decreases first and then increases. The formation of the area with low water saturation is due to the expansion of the gas produced by hydrate decomposition under the action of pressure reduction, thus displacing the water in the pores. As shown in Figure 5(b), water from the overburden and the underlying layers begins to invade the hydrate decomposed area around the production well. Because the temperature of the water in the pores of the underlying layer is higher than that of the water in the overburden layer, hydrate decomposition in the lower part of the HBL is faster than that in the upper part. As shown in Figures 5(c) and 5(d),

FIGURE 9: Evolution of total water production rate Q_W and total water production V_W in three different cases with different S_{irW} .

with the development of gas production from the hydrate reservoir, the phenomenon of water intrusion becomes more and more obvious.

3.2. The Effects of Irreducible Water Saturation. Irreducible water saturation S_{irW} is one of the fundamental parameters in characterizing reservoirs and also determined as the key factor in reservoir calculation and fluid type identification. High clay content and small particle size could increase S_{irW} . Therefore, the S_{irW} in these three cases are assumed to be 0.10, 0.30, and 0.50, respectively, to evaluate the effect of S_{irW} on gas production from NGH reservoir. In these cases, the S_{irG} is assumed to be 0.05, and the value of the P_0 is assumed to be 0.1 MPa.

Figure 6 shows the variation of relative permeability of gas and water (K_{rG} and K_{rW}) with water saturation in different cases with different S_{irW} . According to the number of coexisting movable phases in the flow process, it could be divided into the gas single-phase flow region (A1, A2, and A3), gas-liquid two-phase flow region (B1, B2, and B3), and water single-phase flow region (C). When the water saturation is less than S_{irW} , the water is adsorbed on the surface of sediment particles or trapped in the pore throat, so it cannot flow. When the water saturation is greater than S_{irW} , the water starts to flow. With the increase in water saturation, the water relative permeability increases gradually. As the

increase in water saturation will occupy the pore space, the gas saturation will decrease, so the gas relative permeability decreases. With the increase in S_{irW} , the region of the gas single-phase flow becomes larger and the two-phase flow region decreases. This is because when the water saturation is low, all water is adsorbed by sediment particles or trapped by small pores or throats, thus becoming irreducible water. Meanwhile, the increase in S_{irW} could increase the proportion of immovable water, thus reducing the relative water permeability. The relative permeability curves of gas and water become steeper with the increase in S_{irW} , mainly because the irreducible water adsorbed by clay particles makes the effective pore diameter smaller.

As shown in Figure 7, with the decrease in water saturation and increase in gas saturation, capillary pressure increases gradually. When the water saturation decreases to a certain extent, the capillary pressure reaches the maximum value, and its maximum value remains unchanged as the water saturation continues to decrease to S_{irW} . The irreducible water occupies the pore space, which makes the pore of the movable water occupied decreases and the slope of capillary pressure increases. In the hydrate-bearing sediments, the particle diameter, clay content (especially montmorillonite content), particle gradation, and consolidation degree of the sediment could change the irreducible water content, thus affecting the change of capillary pressure.

FIGURE 10: Comparison of gas relative permeability K_{rG} , water relative permeability K_{rW} , and capillary distribution P_{cap} between three cases with different irreducible water saturation S_{irW} on the 3650th day.

Figure 8 compares total gas production rate Q_{PT} and total gas production V_{PT} in three different cases with different S_{irW} . It could be clearly seen from Figure 8 that Q_{PT} is obviously declining with the increase in S_{irW} . At the end of 3650 days' production, the total gas production of three different S_{irW} cases is 1668799, 1622121, and 1536262 m^3 , respectively. When S_{irW} decreases from 0.50 to 0.10, the total gas production increases by 8.63%. It could be easily drawn that the whole production could be divided into three stages according to the difference in Q_{PT} between different S_{irW} cases. In the initial stage, the difference in Q_{PT} between different S_{irW} cases is very small, and then in the following stage, the differ-

ences in Q_{PT} between different S_{irW} gradually increase. However, in the last stage of production, the difference in Q_{PT} between different S_{irW} cases gradually decreases. In the initial stage, gas produced by hydrate decomposition could flow into production well more easily as it is close to the production well, which means the gas production rate is less affected by S_{irW} . As production progresses, gas needs to migrate longer distances to reach the production well, so the impact of gas relative permeability on gas production from hydrate reservoir increases. And the gas relative permeability decreases with the increase in S_{irW} , which leads to the decrease in gas production rate in the second stage. In the final stage, the decrease in

FIGURE 11: Relationship between gas, water relative permeability, and water saturation under different irreducible gas saturation.

FIGURE 12: Evolution of total gas production rate Q_{pT} and total gas production V_{pT} in three different cases with different S_{irG} .

FIGURE 13: Evolution of total water production rate Q_W and total water production V_W in three different cases with different S_{irG} .

pressure gradient slows the decomposition rate of hydrate, resulting in lower gas saturation. As could be seen from Figure 6, when gas saturation is low, the difference between gas relative permeability becomes smaller, so the difference of gas production rates between different cases at the end of gas production from hydrate reservoir becomes smaller.

It could be seen from Figure 9 that, as the range of pressure reduction increases gradually, more water flows into the production well, so that the water production rate increases gradually. In the early stage of gas production from the hydrate reservoir, the increase rate of water production rate is faster, and then the increase rate gradually slows down. As shown in Figure 9, the increase in S_{irW} will cause the decrease in Q_W . At the end of 3650 days' production, the total water production of three different S_{irW} cases is 620304, 600617, and 564797 m^3 , respectively. When the irreducible water saturation decreases from 0.50 to 0.10, the water production increases by 9.83%. On the one hand, the water flow into the production well decreases due to the decrease in the movable water proportion in the pore, and on the other hand, the water relative permeability decreases due to the increase in S_{irW} .

Figure 10 shows the comparison of gas relative permeability K_{rG} , water relative permeability K_{rW} , and capillary pressure P_{cap} distribution between different cases with different S_{irW} on the 3650th day. As seen in Figure 10, all the shapes of K_{rG} , K_{rW} and P_{cap} distribution are like a tail, which is con-

sistent with the gas distribution in Figure 4(d). It could be seen from Figures 10(a)–10(c) that the difference of K_{rG} distribution between different S_{irW} cases is very small, which may be the main reason of the small difference of Q_{PT} between different S_{irW} cases in the last stage of production. And it is also could be deduced that K_{rG} decreases as S_{irW} increases in the second stage of production in Figure 8. K_{rG} near the well is higher than other locations, which is mainly due to the fact that more gas accumulate near the perforated section under the influence of depressurization. The low permeability of clayey silt sediments reduces the depressurization effect and fluid flow rate in the hydrate reservoir, resulting in low hydrate decomposition rate and low gas saturation. As shown in Figure 6, low gas saturation could reduce the K_{rG} . Therefore, K_{rG} in Figure 10 is very small, and its value is mainly distributed between 0 and 0.0002, and low K_{rG} is the root cause of low gas production rate in the later period of production. It could be seen from Figures 10(d) to 10(f) that K_{rW} drops significantly with the increase in S_{irW} , which results to the decline of Q_W with the increase in S_{irW} in Figure 9. The increase in S_{irW} leads to the decrease in movable water, so the K_{rW} decreases greatly. K_{rW} near the well is lower than other locations, and this is mainly ascribed that more gas and less water accumulate near the perforated section. In addition, K_{rW} is mainly distributed between 0.45 and 0.95, much larger than K_{rG} . The higher

FIGURE 14: Comparison of gas relative permeability K_{rG} , water relative permeability K_{rW} , and capillary distribution P_{cap} between there cases with different irreducible gas saturation S_{irG} on the 3650th day.

K_{rW} leads to an increase in water production and a decrease in production efficiency. It is worth noting that P_{cap} in Figures 10(g)–10(i), increases moderately with the increase in S_{irW} . This may be due to the fact that the increase in S_{irW} reduces the effective porosity and narrows the fluid flow path, which leads to an increase in P_{cap} .

3.3. The Effects of Irreducible Gas Saturation. Due to the characteristics of higher clay content, small particle diameter, and more small pore throats, clayey silt sediments may contain

more irreducible gas. To study the effects of the increase in S_{irG} on gas production from hydrate reservoir, the values of S_{irG} in three cases are assumed to be 0.01, 0.03, and 0.05. In these cases, S_{irW} is assumed to be 0.30, and the value of the P_0 is assumed to be 0.1 MPa.

In the water relative permeability equation used in this paper, the change of S_{irG} has no effect on the relative permeability of water. As shown in Figure 11, because the gas produced by hydrate decomposition is trapped in the reservoir and could not be a part of movable fluids, increasing S_{irG} will

FIGURE 15: Relationship between capillary pressure and water or gas saturation in different gas entry pressure cases.

decrease the gas relative permeability. When the saturation of water in porous media is greater than 0.6, the relative permeability of gas drops below 0.13.

As shown in Figure 12, when the values of S_{irG} are equal to 0.01, 0.03, and 0.05, Q_{PT} decreases from 1238 m³/d, 1109 m³/d, and 995 m³/d on the 1st day to 330 m³/d, 324 m³/d, and 319 m³/d on the 3650th day, respectively. When the S_{irG} decreases from 0.05 to 0.01, the total gas production in 3650 days increases from 1622121 m³ to 1812522 m³, increasing by about 11.74%. The increase in S_{irG} leads to the decrease in gas production, which is caused by the fact that the increase in S_{irG} causes more free gas produced by hydrate decomposition to remain in the hydrate reservoir. In addition, as the production progresses, the difference of gas production rate between different S_{irG} gradually decreases. There are two reasons for this phenomenon. One is that with the expansion of the pressure reduction range, the pressure gradient inside the reservoir decreases, resulting in the slowing down of the gas flow rate. The second is that the pressure drop of the hydrate decomposition front becomes smaller as the hydrate decomposition front is gradually far away from the production well, so that the decomposition driving force is smaller. Further, this leads to a decrease in gas saturation in the hydrate reservoir, which reduces the difference in K_{rG} between different S_{irG} as shown in Figure 11.

Figure 13 shows a clear comparison between three different cases with different S_{irG} in Q_W and V_W . As shown in the figure, S_{irG} also has a significant impact on water production.

When the S_{irG} decreases from 0.05 to 0.01, the total water production in 3650 days increases from 600617 m³ to 672088 m³, increasing by about 11.90%. The increase in S_{irG} causes a significant decrease in Q_W , which is due to the fact that more gas occupies the pores of hydrate-bearing sediments, thus reducing the reservoir's effective porosity and permeability.

Figure 14 shows the evolution of K_{rG} , K_{rW} , and P_{cap} distribution at different S_{irG} cases on the 3650th day. As the Figure 14 shows, (1) on the 3650th day, the difference of K_{rG} between three different cases is very small, leading to a very little difference in gas production rate in the later stage of production, which is due to the low gas saturation makes smaller difference in K_{rG} ; (2) the increase in S_{irG} reduces K_{rW} , which is due to that the increase in S_{irG} increases gas saturation in the pores of sediments, thus reducing water saturation and K_{rW} ; (3) the increase in S_{irG} makes capillary pressure increase significantly, which is because the irreducible gas occupies pore space, thus making pore throat smaller and increasing capillary pressure.

3.4. The Effects of Gas Entry Pressure. Figure 15 shows the relationship between capillary pressure and water or gas saturation in different gas entry pressure (P_0) cases. Gas entry pressure represents the pressure of gas starting to enter the porous medium, which corresponds to the capillary pressure at the maximum throat. With the increase in P_0 , the range of maximum capillary pressure increases, and the capillary pressure in the same water saturation condition increases.

FIGURE 16: Evolution of total gas production rate Q_{PT} and total gas production V_{PT} in three different cases with different gas entry pressure P_0 .

FIGURE 17: Evolution of total water production rate Q_W and total water production V_W in three different cases with different gas entry pressure P_0 .

FIGURE 18: Comparison of gas relative permeability K_{rG} and water relative permeability K_{rW} distribution in three different cases with different gas entry pressure P_0 on the 3650th day.

When the gas entry pressure is 0.5 MPa, the capillary pressure increases rapidly to the maximum value with the increase in water saturation, which means the diameter of pore throat is smaller. When the gas entry pressure is 0.01 MPa and 0.1 MPa, the capillary pressure rises slowly and then rapidly to 1 MPa, in which the slowly rising stage represents the larger pore throat diameter.

Figure 16 compares Q_{PT} and V_{PT} in three different cases with different gas entry pressure P_0 . It could be seen from the figure that the increase in P_0 could slightly increase gas production. When the P_0 increases from 0.01 MPa to 0.1 MPa, the gas production in 3650 days is only reduced by 0.46%, which could be ignored; when the gas entry pressure increases from 0.1 MPa to 0.5 MPa, the gas production in 3650 days is only reduced by 2.36%. The gas produced by hydrate decomposition will occupy the original space of the hydrate preferentially. Then, the gas will expand under the effect of depressurization. When the gas pressure exceeds the sum of water pressure in the pore throat and the capillary pressure, the water will drive the water in the capillary tube to flow. In this paper, the gas expansion effect is obvious due to the large depressurization amplitude in the hydrate reservoir, which is easy to overcome the flow resistance caused by capillary pressure. At the same time, the gas entry pressure has no effect on the gas relative permeability and reservoir permeability in this paper. Therefore, the gas entry pressure

has no obvious effect on gas production. Figure 17 shows the evolution of total water production rate Q_W and total water production V_W in three different cases with different gas entry pressure P_0 . The gas entry pressure has little effect on the water production, which is because the gas entry pressure has little effect on the water relative permeability in this study.

Figures 18 and 19 show the evolution of gas relative permeability K_{rG} , water relative permeability K_{rW} , and capillary pressure P_{cap} distribution in different S_{irG} cases on the 3650th day. It could be clearly seen that P_0 reduces gas relative permeability on the 3650th day. However, the change of P_0 does not change the effective space for fluid flow as irreducible water or gas saturation, so it has little effect on gas production. Meanwhile, as shown in Figures 18(d)–18(f), P_0 has little effect on the relative permeability of water on the 3650th day, which is the main reason that the gas entry pressure has no effect on the water production. However, the increase in gas entry pressure will significantly increase the capillary pressure in hydrate-bearing sediments, causing the amount of gas production to slightly decline.

4. Conclusions

The effects of hydrogeological parameters such as irreducible water saturation, irreducible gas saturation, and gas entry

FIGURE 19: Comparison of capillary pressure P_{cap} distribution in three different cases with different gas entry pressure P_0 on the 3650th day.

pressure on gas hydrate production were studied in this paper. The main conclusions could be drawn as follows.

- (1) When the irreducible water saturation decreases from 0.10 to 0.50, the cumulative gas production decreases from 1668799 m³ to 1536262 m³, and the total water production drops from 620304 m³ to 564797 m³, respectively. The increase in the irreducible water saturation could occupy the pore space, so it will reduce the relative permeability of gas and water. At the same time, it will make the effective pore throat diameter smaller and increase the capillary pressure, so it will reduce the gas production and water production
- (2) When the S_{irG} decreases from 0.05 to 0.01, the total gas production in 3650 days increases from 1622121 m³ to 1812522 m³, increasing by about 11.74%. When the S_{irG} decreases from 0.05 to 0.01, the total water production in 3650 days increases from 600617 m³ to 672088 m³, increasing by about 11.90%. When the irreducible gas saturation increases, a large number of gas will be trapped in the pores, and the increase in irreducible gas saturation will also affect the relative permeability of the gas, so the gas production would decrease with the increase in irreducible gas saturation. The increase in the irreducible gas saturation will reduce the effective pore space and the effective permeability of the reservoir, so the water production will decrease
- (3) The change of gas entry pressure has a slight effect on gas production and has no effect on water production. The increase in gas entry pressure has no effect on the relative permeability of water and gas, so its effect on water and gas production is not obvious. However, the gas entry pressure will change the capillary pressure distribution in the reservoir, which has a slight impact on the gas production in this paper

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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