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Numerical Investigation into the Production Characteristics and Methane Leakage from the Hydrate Reservoir with Underlying Free Gas in Horizontal Well System#

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ABSTRACT

This study established a Class I gas hydrate reservoir model (namely, a double-layer reservoir consisting of an upper hydrate-bearing layer and its underlying free gas-water mixing layer) based on the hydrate exploration data from the Site GMGS4-SC_W02 in Shenhu area of South China Sea. Then a numerical simulation of hydrate extraction using the TOUGH+HYDRATE simulator was carried out. The gas-liquid production characteristics during hydrate exploitation using horizontal wells under different production schemes were analyzed. The production potential and the risk of methane leakage were evaluated. The results showed that the depressurization method is the optimal way for the low permeability Class I reservoirs exploitation in the view of long-term production. In addition, depressurization combined with thermal stimulation (in-situ wellbore heating) production did not show significant synergistic effects on increasing production and efficiency for Class I reservoirs. Instead, the pure thermal stimulation method can make a large amount of methane leak from the reservoir to the overburden layer, with the underlying free gas being the main source of methane leakage.

Keywords: natural gas hydrate exploitation, horizontal well, methane leakage, free gas, numerical simulation

NONMENCLATURE

Abbreviations	
NGH	Natural gas hydrate
T+H	TOUGH+HYDRATE
HBL	Hydrate-bearing layer
FGL	Free gas layer
OB	Overburden
UB	Underburden
bsf	Below the seafloor

1. INTRODUCTION

Natural gas hydrate (NGH) is one of the most potential alternative energies in the 21st century [1]. It is increasingly urgent to realize the commercial exploitation of hydrate resource at present. However, the resource utilization prospects for different types of hydrate deposits differ greatly [2]. In addition, the risk of methane leakage and the characteristics of leaking methane migration and transformation are still poorly understood during the long-term production [3]. Therefore, adequate study on the dynamic aggregation and dispersion process of methane within the sediments during the NGH development and exploring the safe, efficient, green, and stable production schemes are of great significance for the future commercialized hydrate exploitation. Equally, this will also contribute to revealing the fate of leaking methane and its impact on global carbon budget.

NGH reservoirs can be divided into four categories based on geological conditions, which are Class I、II、III and IV, respectively. Thereinto, the Class I reservoir charactered by free gas lying beneath the hydrate layer is considered to be the most favorable reservoir type for exploitation at present [4]. Hence, a Class I reservoir model was established to investigate the long-term production characteristics and the methane leakage

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mechanism using numerical simulation method in this study. The main research contents were as follows:

(1) The long-term production performance of Class I reservoir exploitation using horizontal well system under pure depressurization, thermal stimulation and depressurization combined with heat injection was carried out.

(2) The implicit factors of methane leakage during the NGH exploitation were identified. Then, the migration and transformation characteristics of leaking methane were further analyzed and discussed.

This study aims to provide a scientific and valuable reference to the green and safe exploitation strategy for NGH.

2. NUMERICAL CODE AND SIMULATION METHOD

2.1 Numerical simulation code

In this study, the parallel version of the numerical code TOUGH+HYDRATE (T+H) developed by Lawrence Berkeley Laboratory was employed for numerical simulation. T+H consists an equilibrium and a kinetic model, whose validities have been verified by Moridis et al.[5] and Li et al.[6] using the experimental data. The equilibrium model is generally considered to act with better performance during predicting the physical and chemical features of various hydrate-associated processes based on the comparisons of the two models [7]. Therefore, the decomposition behaviors of gas hydrate were described by the equilibrium model in this numerical study.

2.2 Geometric features and system description

The Class I reservoir physical model was established referring to the physical features of the hydrate deposit chosen from the drilling location of GMGS4-SC_W02 at Shenhu area, South China Sea. Based on the field measurement data and some published literatures [8, 9], a 28-meter-thick and highly saturated hydrate-bearing layer (HBL) ranging from 144 to 172 m below the seafloor (bsf) exists at a water depth of 1285 m. The underlying free gas layer (FGL) is mainly distributed in 172-186 mbsf. The main physical property of the reservoir and the simulation parameters used in this study were summarized in Table 1.

Table. 1 Physical features and simulation parameters of the hydrate reservoir at the Site SC-W02.

Parameter	Value
Thickness of HBL, FGL, OB, and UB [m]	28, 14, 35.5, 21.5
Hydrate and gas saturation [%]	30.9, 19.4 (average)
Intrinsic permeabilities of OB and UB [K_x=K_y=K_z, m^2]	1.16×10^{-15}
Intrinsic permeabilities of HBL and FGL [K_x=K_y=K_z, m^2]	5.50×10^{-15}, 2.00×10^{-15}
Porosity [%]	66 (OB&UB), 42 (HBL), 58.4 (FGL)
Seawater salinity	3.5%
Gas components	100% CH_4
Seafloor temperature [℃]	4.95
Initial pressure (at base of HBL) [MPa]	14.69
Initial temperature (at base of HBL) [℃]	16.15
Relative permeability model	$K_{rA}=[(S_A-S_{irA})/(1-S_{irA})]^n$, $K_{rG}=[(S_G-S_{irG})/(1-S_{irG})]^{n_G}$
Capillary pressure model	$P_c=-p_0[(S^*)^{-1/\lambda}-1]^{1-\lambda}$, $S^*=(S_A-S_{irA})/(S_{mxA}-S_{irA})$
S_{irA}, S_{irG}	0.2, 0.01
S_{mxA}	1
n, n_G	3.5, 2.5
λ	0.45
p_0 [Pa]	10^4

The well configuration of single horizontal well and lateral dual horizontal wells was considered in this study. Fig. 1a-b showed the sketch of the simulation systems. The wells were placed at the locations of z=0 m, which corresponded to the middle of the HBL. Additionally, the thickness of the overburden (OB) and underburden (UB) was set as 35.5 m and 21.5 m, respectively, which had enough for the heat and mass exchange with the HBL. The simulation interval in the x direction was from 0 to 45 m. The locations at x=0 and x=45 m were set as no exchange of heat and mass due to symmetry, which represented a well spacing of 90 m. A unit of Δy=1 m was simulated, based on the assumption of the uniform properties along the length of the horizontal well.

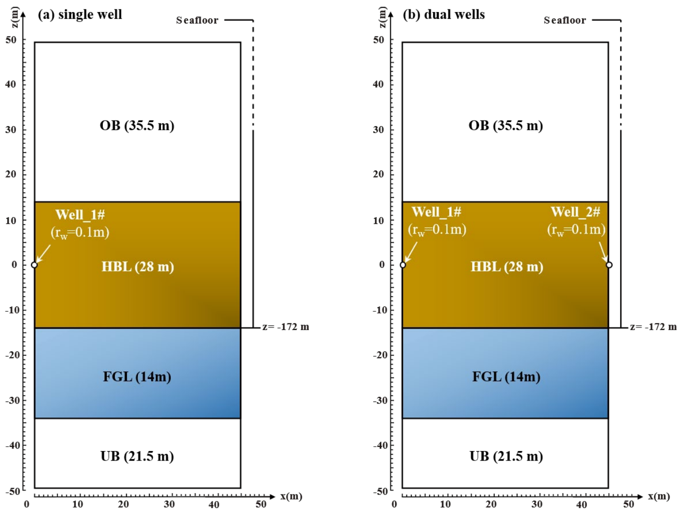

Fig. 1 Sketch of the Class I hydrate reservoir with (a) single horizontal well and (b) lateral dual horizontal wells configuration at the Site SC_W02

2.3 Domain discretization and initial conditions

The corresponding grid divisions of the Class I reservoir model were shown in Fig. 2a-b. Here the single well model was only described due to the dual wells model was similar to the single well model.

The entire simulation area was discretized into a total of 9292 grids. The topmost part of the OB and the lowermost part of the UB were set as reservoir boundaries with a total of 142 grids. These boundary grids were regarded as inactive grids, in which the temperatures and pressures were kept constant during the simulation process. All grids were 1 m thick in the y-direction. Along the x-direction, the grids were divided non-uniformly. 84 grids were divided within 45 m, and the grids around the well were the densest, with a minimum of 0.1 m. Meanwhile, due to the significant heat and mass transfer of the HBL and the FGL during the production process, the grids in these two areas were also finely divided along the z-direction (Δz= 0.1-0.667 m). The grid size of the OB and UB gradually increases with depth (Δz>0.667 m). The size of the uppermost and lowermost parts was set to thinner (Δz=0.5 m) to ensure that the simulation can obtain a realistic boundary behavior.

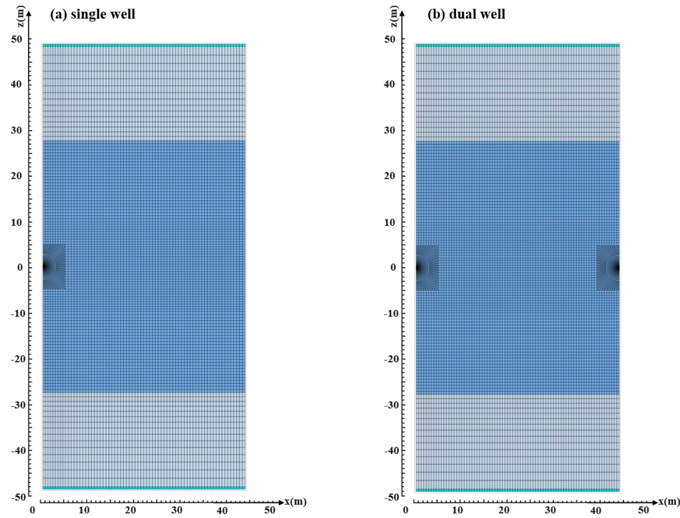

Fig. 2 Sketch of the domain discretization for (a) single horizontal well and (b) lateral dual horizontal wells

The initialization for Class I reservoir model referred to the method proposed by Moridis et al., which have been described in detail in his previous research work [4]. The initial conditions of the NGH reservoir at the Site SC_W02 were shown in Fig. 3.

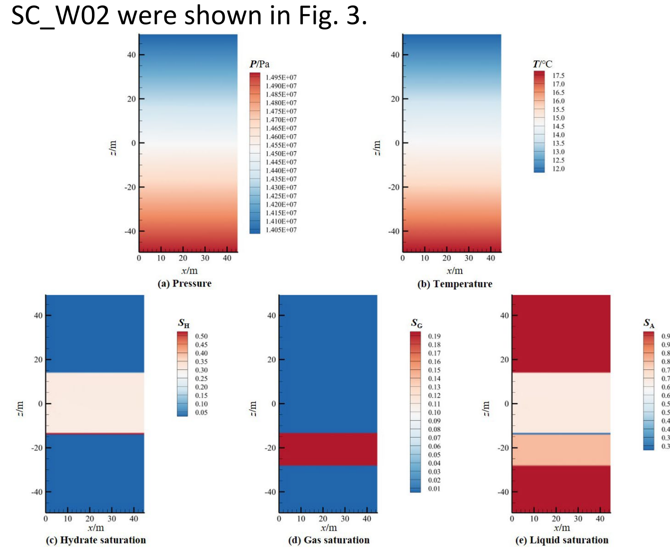

Fig. 3 Initial conditions of the NGH reservoir at the Site SC_W02

3. RESULTS AND DISCUSSION

3.1 Gas production

Fig. 4a-c showed the evolution of the gas recovery rate (Q_P) and the total volume of the obtained methane (V_P) under different production methods in horizontal wells within 30 years. Fig. 4a showed that the depressurization production with dual horizontal wells (Case4) can significantly improve the production efficiency of Class I gas hydrate reservoirs. The combination of depressurization and thermal stimulation (Case3 and Case5) did not show significant

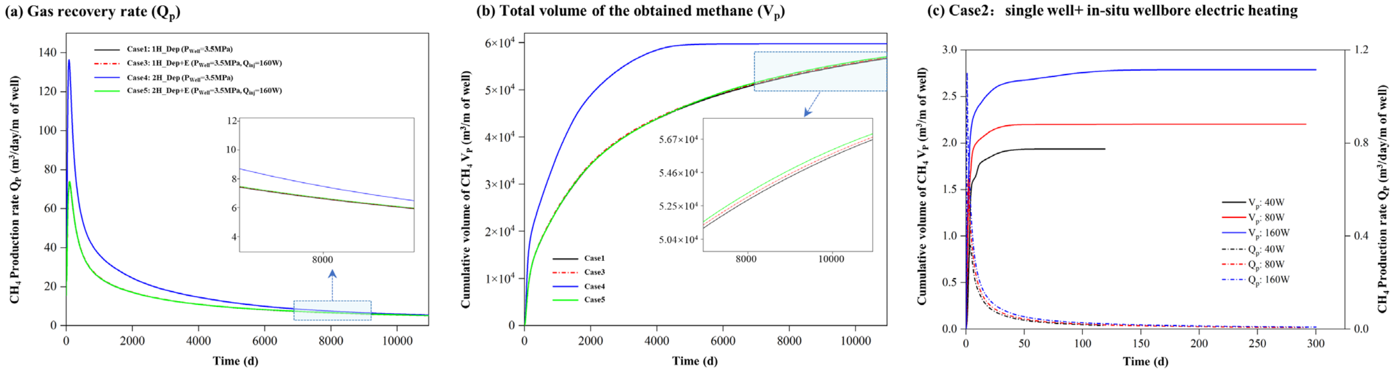

Fig. 4 Change profiles of the gas recovery rate (Q_p) and the total volume of the obtained methane (V_P) under the different production models

synergistic effect in improving productivity. This phenomenon may be attributed to the rate of hydrate decomposition was lower than the rate of the underlying free gas invading upward into the HBL, meanwhile, the free gas entering the HBL and hydrate dissociated gas were strongly limited by the low reservoir permeability and accumulated in a large area of the reservoir, thus inhibiting the heat transfer efficiency. The average gas production rate per unit well length was 28.8 m^3/d, which was about twice that of other production cases. As shown in Fig. 4b, the maximum total methane gas production per unit well length during the whole production can reach 5.98×10^4 m^3. The gas production contribution of different production schemes was successively as follows: depressurization with dual wells (Case4) > depressurization combined heat injection with dual wells (Case5) > depressurization combined heat injection with single well (Case3) > depressurization with single well (Case1). In contrast, the optimal gas production rate of pure thermal stimulation method was much lower than that of depressurization method, only about 1.5%. Total methane gas production per unit well length was only 1.9 to 2.8 m^3 (Fig. 4c). This was mainly caused by a large amount of methane leaking from the FGL, which will be further analyzed and discussed in Section 3.2.

3.2 Methane leakage and transformation characteristics under thermal stimulation

Fig. 5 showed the temporal and spatial evolution of the key physical parameters of the reservoir during the thermal stimulation exploitation (in-situ wellbore heating). It can be visually seen from Fig. 5o-p that the pure thermal stimulation can make a large amount of methane leak from the NGH reservoir during the long-term production. Shang et al.[3] have also confirmed the environmental risk of methane leakage in the NGH exploitation process with heat injection method in their recent study. Compared with the conventional Class III hydrate reservoirs charactered by only one single hydrate layer, Class I gas hydrate reservoirs may face a greater degree of methane leakage risk and a wider range of leakage. The reason is that there is an amount of free gas in the lower part of the hydrate layer of Class I reservoir. In the process of thermal stimulation, local pressure rise of the reservoir cannot be avoided and sufficient pressure drop driving force cannot be generated to make the gas flow into the production well in a timely and effective manner (Fig. 5a-d). Therefore, the underlying free gas will eventually leak upward under the action of buoyancy and become the main methane leakage source. However, it's worth mentioning that the transport ability of leaking methane was limited due to the low permeability of the OB. The leaking methane will be reconverted to hydrate under suitable temperature and pressure conditions (Fig. 5k-l).

In order to further quantify the methane leakage process under thermal stimulation, the fluid fluxes at the interface between the HBL and OB were monitored in this study. The results were shown in Fig. 6a-b. In Fig. 6a, the aqueous flux (F_A) at the interface was negative, indicating that the water flowed from the HBL into the OB during the production process. As shown in Fig. 6b, methane gas did not flow through the interface during 1-year production. By 5-year production, methane leakage occurred, but the leakage was concentrated in the area of 0 m⩽x⩽15 m. The leakage flux near the wellbore (x ⩽1 m) was the largest. In the middle and late stages of production, large amounts of methane invading into the OB was detected throughout the interface.

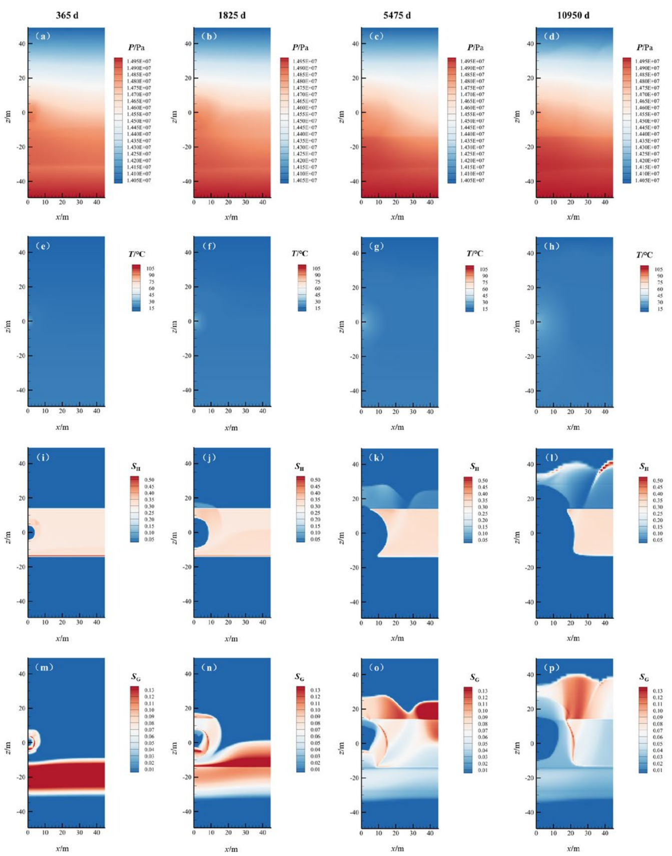

Fig. 5 Spatiotemporal evolution of the key physical parameters of reservoir under thermal stimulation

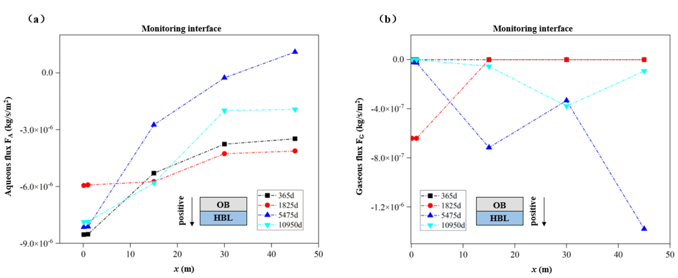

Fig. 6 Change profiles of the aqueous and methane fluxes at the HBL-OB interface under thermal stimulation

4. CONCLUSIONS

A numerical simulation for the exploitation of the hydrate reservoir with underlying free gas (that is, Class I reservoir) was carried out in this study based on the field measurement data in the Shenhu area, South China Sea. The main conclusions were as follows:

(1) Depressurization method was the most cost-effective and environmentally friendly production method for the long-term exploitation of the low-permeability Class I hydrate reservoir. The average gas production rate for dual horizontal wells during a 30-year depressurization production was 28.8 m^3/d per unit well length, which was about twice as much as that of other production strategies.

(2) Depressurization combined with thermal stimulation did not show significant synergistic effects in improving the productivity efficiency of Class I hydrate reservoir. Pure thermal stimulation will lead to a large amount of methane leaking from the reservoir, and underlying free gas was the main source of methane leakage. The intrusion of large amounts of methane into the overburden mainly occurred in the middle and late stages of production (15-30 years).

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