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Evaluation on the gas production potential of different lithological hydrate accumulations in marine environment

Li Huang [a, b], Zheng Su [a], Neng-You Wu [a, c, *]

[a] Key Laboratory of Gas Hydrate, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Qingdao Instiute of Marine Geology, China Geological Survey, Qingdao 266071, China

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ABSTRACT

In this work, the marine hydrate deposits were classified into CHR (clay reservoir), SIHR (siltstone reservoir) and SHR (sandstone reservoir) according to the grain sizes of the sediments. Based on field measurements and proper estimations in Shenhu area, the gas production potentials of these different lithological hydrate reservoirs were numerically studied through Tough + Hydrate. The simulation results reveal that SHR can provide the most desirable gas production potential with the following superior features: (a) a burst gas release at initial stage of the production; (b) the highest average gas release rate 1.7×10^3 ST (standard temperature) m^3/d; (c) the highest total release gas volume 1.7×10^7 ST m^3, (d) the highest *gas-to-water* volume ratio with an average value of 9.04. However, the evolution of the spatial distributions of the characteristic parameters indicates that the gas production in SHR has met some challengeable problems in both technology and environment aspects. On the other hand, compared with CHR, SIHR shows a higher gas release rate and cumulative volume but a worse *gas-to-water* volume ratio during the entire production period. In addition, the evolution of the salinity spatial distribution indicates an unsatisfactory impact on the environment in the later stage of production for SIHR.

1. Introduction

Gas hydrate, as one of the most promising alternative energy sources in 21 century, is clathrate, ice-like compounds in which the gas molecules occupy the cage structure composed of hydrogen-bonded water molecules [1–3]. In nature, the gas hydrate only occurs in sediments of slopes at the outer continental margins and beneath the arctic permafrost as these places feature the low temperature and high pressure that favor the formation of gas hydrate [4,5]. As a research hot spot, the marine gas hydrate is attracting more and more attention, not only because of the substantial gases it contains (the amount of methane in oceanic hydrates is approximately two orders of magnitude greater than that in permafrost [6]), but also because it may cause submarine geohazards and global climate change under improper operations [7].

However, the key utilization factor for this new energy resource lies in the technical and economic feasibility of gas production from the deposits. Nowadays, the prevailing production methods includes: (I) depressurization in which the reservoir pressure is decreased to below the hydration pressure under the given reservoir temperature [8,9]; (II) thermal stimulation in which the reservoir temperature is raised above the hydration temperature under the given reservoir pressure [10,11]; (III) inhibitor injection which shifts the pressure-temperature equilibrium conditions to make the hydrates unstable [12]; and (IV) the exchange of methane molecules in the hydrate structure for carbon dioxide molecules [13–15]. Among them, depressurization is accepted as the most promising method for gas production in Class 2 hydrate deposits [16,17]. Although the application of additional thermal stimulation can enhance the gas production, the effect is limited [11].

Significant hydrate deposits are confirmed to exist in Shenhu area, SCS (South China Sea), but the proliferation studies on the gas production potential mainly focus on the production designs, while few studies pay attention to the effects of the geological characteristics in the deposits [18–22]. In fact, preliminary studies have verified that the geological accumulation settings play an important role in the formation and the dissociation of the hydrate in a given area [23–25]. Moreover, Boswell et al. proposed that the most promising and accessible hydrate is the sand-dominated reservoir

* Corresponding author. No.62, Fuzhou Rd, Qingdao, Shandong, China. Tel.: +86 13922774239.
E-mail address: wuny@ms.giec.ac.cn (N.-Y. Wu).

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Nomenclature

C	specific heat (J/kg/K)
CHR	clay hydrate reservoir
I	production potential
K	intrinsic permeability (m^2)
k_Θ	composite thermal conductivity (W/m/K)
$k_{\Theta RD}$	"dry" thermal conductivity (W/m/K)
$k_{\Theta RW}$	"wet" thermal conductivity (W/m/K)
M_w	cumulative volume of water produced from the well (m^3)
P	pressure (Pa)
Q_r	volumetric rate of CH_4 released from of dissociation (ST m^3/s)
R_{GW}	gas-to-water ratio (ST m^3 of gas per kg water)
r, z	cylindrical coordinates (m)
r_w	well radius (m)
r_{max}	maximum radius of the simulation domain (m)
S	phase saturation
SHR	sandstone hydrate reservoir
SIHR	siltstone hydrate reservoir
t	time (days)
T	temperature (°C)
V_r	cumulative volume of CH_4 released from dissociation (ST m^3/s)
X	mass fraction (kg/kg)
Δz	discretization along the z-axis (m)
ρ_R	grain density (kg/m^3)

Greek symbols

λ	van Genuchten exponent
Φ	porosity

Subscripts and superscripts

0	denotes initial state
A	aqueous phase
B	HBL base
cap	capillary
G	gas phase
i	salinity
irA	irreducible aqueous phase
irG	irreducible gas
n	permeability reduction exponent
n_G	gas permeability reduction exponent
w	well

in the "Hydrate Energy Pyramid" theory [26,27]. However, they didn't provide any numerical evidence for the details.

In this paper, the gas production potentials for different lithological hydrate reservoirs in Shenhu area were investigated by means of numerical simulations. The code we employed is Tough + Hydrate, which is developed by the Lawrence Berkeley National Laboratory [28]. By using an equilibrium and kinetic hydrate formation and dissociation model, the code can simulate the non-isothermal gas release, phase behavior as well as fluid and heat flow under conditions typical for natural CH_4 hydrate deposits in complex geological media [28]. Through the comparison of simulation results, the numerical evidences for the demonstration of "Hydrate Energy Pyramid" as well as the reasons for the selection of the exploitation targets in South China Sea can be provided.

2. Hydrates in research area

2.1. Depositional setting

The South China Sea is bordered to the west by Vietnam, to the north by the southeastern mainland and Taiwan of China, to the east by the Philippines and to the south by Malaysia and Indonesia. Its northern slope consists of three oil and gas bearing basins: Southeast Hainan Basin, Pearl River Mouth Basin and Southwest Taiwan Basin (Fig. 1(a)) [29].

Shenhu area, as a most promising location where the hydrate forms, is tectonically located in the Pearl River Mouth Basin [30]. The Pearl River Mouth Basin is in the tectonic subsidence process since the middle of Miocene, which is conducive for the formation of gas hydrate along with the high sedimentation rate [31]. During the GMGS-1 drilling expedition in 2007, the hydrate samples were detected at SH_2, SH_3 and SH_7 within 200 m below the seafloor at a water depth of up to 1500 m, as shown in Fig. 1(b) [32,33]. The hydrate-containing sediment layers were 10–25 m thick with a maximum saturation value of 48% [32]. The laboratory analysis of the core samples reveals that the types of hydrate bearing sediments are distinctive. For instance, the sediments in SH_2 are predominantly silts with sand content less than 12% of the sample. The sediments in SH_7 are coarser and dominated by sand [34]. The differences of the grain size distributions are clearly shown in Fig. 2 [34].

2.2. Classification of gas hydrate reservoirs

In the petroleum industry, the reservoirs are normally divided into 4 classes according to the grain sizes of the sediments, namely the clay reservoir, siltstone reservoir, sandstone reservoir and conglomerate reservoir. Their respective harmonic mean grain sizes are shown in Table 1. As a result of long-distance transport and weathering, however, the sediments in marine are generally fine particles, this phenomena is also confirmed in Shenhu area [34]. Therefore, only three types of hydrate deposits are developed in that area, which are CHR (clay hydrate reservoir), SIHR (siltstone hydrate reservoir) and SHR (sandstone hydrate reservoir).

2.3. Permeabilities of the hydrate reservoirs

2.3.1. The estimations of permeability: type 1

On the basis of the closely graded ball filling theory, the sediments in a hydrate reservoir are simplified to be composed of uniform spherical particles. Then the permeability of the system can be estimated by the empirical Kozeny–Carman equation [35]:

$$K_1 = \frac{k\Phi^3}{\tau S^2} \tag{1}$$

where k is the Kozeny constant related to the shape of capillary cross-section, τ is the ratio of the trace length of fluid flow to the length of rock, normally the ratio of the Kozeny constant to τ is 0.23. And Φ represents the porosity of the reservoir, S is the specific surface whose datum is referenced from the rock volume.

For the random accumulation of the sediment particles, there are [35].