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Numerical simulation of gas production potential from permafrost hydrate deposits by huff and puff method in a single horizontal well in Qilian Mountain, Qinghai province

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ABSTRACT

Based on the geological data of the Qinghai-Tibet plateau permafrost, such as the permafrost ground temperature, the thermal gradient within and below the frozen layer, we numerically investigate the gas production potential from hydrates at the DK-3 drilling site of the Qilian Mountain permafrost, which is located in the north of the Qinghai-Tibet plateau. We employ the huff and puff method using a single horizontal well in the middle of the Hydrate-Bearing Layer (HBL). The simulation results indicate that desirable gas-to-water ratio and energy efficiency can be obtained under suitable injection and production conditions in the huff and puff process. However, the absolute gas production rate remains low during the whole production process. The sensitivity analysis indicates that the gas production performance is strongly dependent on the intrinsic permeability of the hydrate deposits, the sediment porosity, the injection and production rates, the temperature of the injected water, the irreducible water saturation and P_{01}. The relative permeability exponents appear to have limited effect on the gas production behavior using the huff and puff method. The sensitivity analysis also indicates that the production potential of the natural gas hydrate deposit will be better than that of pure methane hydrate in this simulation.

1. Introduction

1.1. Background

Natural gas hydrates (NGH) are solid, nonstoichiometric compounds formed by host water molecules with small guest molecules, such as CH_4, C_2H_6, C_3H_8, CO_2, H_2S, etc. [1]. As a kind of new and potential energy resource, the estimated amount of natural gases that are trapped in gas hydrates is huge and it is thought to be the most applicable and challenging energy to replace the known conventional fossil fuel resources in the future [2]. Up to now, they have been found to exist widely in marine sediments and permafrost areas where the necessary conditions of low temperature and high pressure exist for hydrate stability [1].

There are three major dissociation methods for gas production from hydrate deposit: (1) depressurization [3–5], in which the pressure of the deposit is reduced below the dissociation pressure at the prevailing temperature; (2) thermal stimulation [6–8], in which the temperature of the deposit is raised above the dissociation temperature at the prevailing pressure with hot water or steam injection; (3) thermodynamic inhibitors injection [9,10], in which chemicals, such as salts and alcohols, are injected into the deposit to shift the hydrate pressure–temperature equilibrium and make it unstable. It usually involves the combination of these methods in actual hydrate exploitation [11]. For example, the huff and puff method, which was accidentally discovered by Shell Oil Company in 1960 and is widely used in oil industry [12,13], is the combination of depressurization and thermal stimulation if it is used in gas production from hydrates [14–17].

As an effective approach in predicting the dynamic properties of gas hydrate dissociation, numerical simulation has been developing quickly in recent years, resulting in various numerical codes that can model nonisothermal hydration reactions in multi-phase multi-component systems. One of the most typical and representative codes is the TOUGH+HYDRATE simulator that is developed from TOUGH2 family of codes at the Lawrence Berkeley National Laboratory. It is exclusively used in the simulation of hydrate formation and decomposition under conditions typical of common natural CH_4-hydrate deposits (i.e., in the permafrost and in deep ocean sediments) in complex geological media at any scale (from

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laboratory to reservoir) [18]. Li et al. used this code to evaluate the gas production potential from marine hydrate deposits in the Shenhu Area of South China Sea using a single horizontal well [5,15], and concluded that the hydrate deposit at site SH7 in the Shenhu Area was not suitable for commercial production either by depressurization or by huff and puff method.

In recent years, breakthroughs in permafrost gas hydrate exploration have already been made and the gas hydrate potentials show a good perspective of exploitation. For example, the former Soviet discovered its permafrost gas hydrate in the course of developing the Messoyakha gas field in the western Siberia in 1965 and subsequently successfully exploited gases from gas hydrate [19,20]. Grover et al. developed a range of single well 2D cross-sectional models and compared the simulation results with various field observations from the Messoyakha field [21]. In the Mackenzie delta permafrost, a series of gas hydrate research wells such as Mallik L-38, 2L-38, 3L-38, 4L-38, 5L-38 were drilled and production of gas hydrate was also tested [22]. Moridis et al. carried out the analysis of various gas production scenarios from five methane hydrate-bearing zones at the Mallik site using different well design and production methods [23]. The discovery of the permafrost gas hydrate in the North Slope of Alaska was further confirmed by drilling stratigraphic test wells [24]. The Mount Elbert Gas Hydrate Stratigraphic Test Well was drilled within the Alaska North Slope (ANS) Milne Point Unit (MPU) from February 3 to 19, 2007, and high quality well logs and core data were acquired [24,25]. Recent simulation results from Mount Elbert gas hydrate test well indicate that vertical wells operating at a constant bottomhole pressure would produce at very low rates for a very long period, while the horizontal wells could increase gas production by almost two orders of magnitude [3].

1.2. The Qilian Mountain permafrost

Recent studies have documented the occurrence of significant gas hydrate deposits in the Qilian Mountain permafrost of Qinghai province, northwest of China. The permafrost distribution of the Qinghai-Tibet plateau permafrost (QTPP) is shown in Fig. 1 [26]. Permafrost accounts for about 52% of the total area of the Qinghai-Tibet plateau, which is about 1.4×10^6 km^2 [26], and because of the abundant gas and water resources from subsurface sediment, it has favorable material and geology conditions for gas hydrate formation and stability [27]. The Qilian Mountain is located in the north of the QTPP with the permafrost area of about 1.0×10^5 km^2. It is considered to be one of the most feasible areas in the QTPP for the existence of the gas hydrate.

1.3. Hydrates in the Qilian Mountain permafrost

The Scientific Drilling Project of Gas Hydrate in Qilian Mountain permafrost was implemented by the China Geological Survey in 2008–2009, as shown in Fig. 2. The drilling sites are located in Juhugeng mining area of the Muri Coalfield, Tianjun County, Qinghai province. So far a total of 4 test wells have been completed. Samples of gas hydrate were obtained firstly from the drilling well of DK-1 in the depth of 133.5–135.5 m on November 5, 2008 and then from DK-2 and DK-3 in 2009. The gas hydrate-bearing cores of DK-1, DK-2, and DK-3 and their burning phenomena are shown in Fig. 3 [28]. This is the first discovery of gas hydrate in the permafrost of China and in the low and middle latitude plateau permafrost of the world [27].

Exposed strata of Muri Coalfield in Juhugeng mining area mainly contain Quaternary, Upper Jurassic, Middle Jurassic and Upper Triassic, as shown in Fig. 4 [27]. The lithology of these strata is

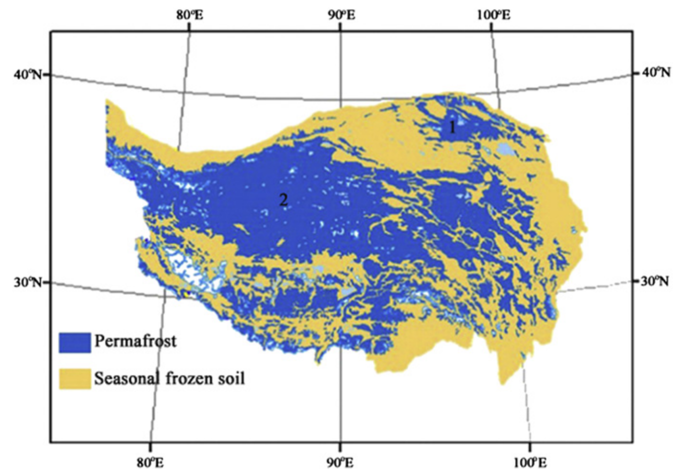

Fig. 1. The permafrost distribution in the Qinghai-Tibet plateau (1 is the Qilian Mountain permafrost, and 2 is the Qiangtang basin permafrost).

mainly sandstone, mudstone, oil shale and siltstone, of which gas hydrate is found to exist in the pores and/or in the fractures. Gas hydrate in the Qilian Mountain permafrost is characterized by a relatively thin permafrost zone, shallow buried depth, complex gas components, and coal-bed methane origin. The logging profile indicates that gas hydrates are mainly distributed at the 133–396 m intervals under the permafrost zone, and the relatively thick hydrate layers are mainly distributed in the depth of 133–300 m [27]. The annual average of the permafrost ground temperature (T_0) is around -1 to -3 °C [29]. The field measurements show that the thickness of the permafrost (H), the thermal gradient within the frozen layer (G_1) and the thermal gradient below the frozen layer (G_2) are 28–128.5 m, 0.011–0.033 °C/m and 0.028–0.051 °C/m, respectively [26,29]. These create thermodynamic conditions that favor the formation of stable gas hydrate.

There are three hydrate layers discovered in the DK-3 drilling hole in the depths of 133–156 m, 231–240 m and 392–396 m, and we investigate the first hydrate layer in this work. Comparing with the marine hydrate deposit in the Shenhu area of the South China Sea ($P = 12.38$–14.35 MPa, $T = 8.62$–16.18 °C) [5,30–33], based on the field measurements, the first hydrate layer (133–156 m) is characterized by low pressure ($P = 2.82$–3.04 MPa) and low temperature ($T = 0.79$–1.15 °C) because of its proximity to the overlying permafrost. The results of Raman spectrometry indicate that gas hydrate from the DK-3 drilling well is formed by complicated gas components, including 54%–76% CH_4, 8%–15% C_2H_6, 4%–21% C_3H_8, 1%–7% CO_2 and a little C_4H_{10} and C_5H_{12} [27]. The hydrate accumulations in the DK-3 well are characterized by the HBL without the confinement of the boundaries, which have the same permeabilities with HBL, in addition to incidence in fine-textured sediments of low permeability such as siltstones and mudstones [27,28].

1.4. Objectives

The main objective of this study is the evaluation of the gas production potential from the DK-3 gas hydrate deposit in the Qilian Mountain permafrost, as well as the factors affecting it. Based on recent simulation results that the horizontal wells would show significant advantages over vertical wells in gas production from hydrate accumulations [3,34], only horizontal wells are taken into consideration in this analysis. The sensitivity of gas production to various operation and formation parameters and conditions are also assessed.