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A method to recover natural gas hydrates with geothermal energy conveyed by CO_2

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ABSTRACT

A geothermal-assisted CO_2 replacement method (GACR) was proposed, in which ambient-temperature CO_2 is injected from the well head of a heat exchange well to the wellbore in geothermal reservoir for heating, and the heated CO_2 then flows upward into the hydrate bearing layer (HBL) to accelerate the natural gas hydrate (NGH) dissociation. The GACR method, which is low-carbon and environment-friendly, requires no surface heating, recovers NGHs by means of combined thermal stimulation and CO_2 replacement, and meanwhile achieves CO_2 storage. Then a numerical simulation model was developed to investigate the heat exchange performance of the heat exchange well, the development performance of HBL, the CO_2 storage performance and factors affecting such a development process. Calculations indicate that the temperature of the returned CO_2 heated by the geothermal reservoir at the entry of HBL can be up to 68.9 °C, far beyond the temperature of HBL. Hence, GACR can fulfill the NGH recovery combining thermal stimulation and CO_2 replacement. Compared with the depressurization method and the case with no geothermal reservoir, the cumulative CH_4 production after 20 years of development can increase by 305% and 51.9% respectively, with a CO_2 storage volume of 2.11×10^7 m^3 and a storage factor of 14.5%.

1. Introduction

With the rapid industrialization and urbanization, the global energy consumption has doubled in the past thirty years [1]. A relatively small amount of high energy consumption countries consume 60% of the total energy, and the average annual growth rates of energy consumption in these countries are as high as 2.5% [2]. Although fossil fuels are still to be dominant in the energy consumption structure in the future, their proportion will drop from 88.16% in 2010 to 86.40% in 2035, and the utilization of clean energy has been receiving more and more attention [1,3,4]. Guided by the Kyoto Protocol, many countries are actively engaged in the development and utilization of new energy technologies to reduce greenhouse gas emissions, and vigorously develop the CO_2 re-use technology to achieve sustainable economic development [5].

As one of the most important new energy sources in the 21st century, natural gas hydrates (NGHs) are widely distributed in deepwater sediments and continental permafrost, of which the reserve exceeds that of conventional natural gas resources by three orders of magnitudes [6]. Studies on efficient development methods of hydrate bearing layer (HBL) can provide scientific and technical support to the future large-scale commercial production. Presently, NGHs are mainly recovered by disturbing the phase equilibrium condition and dissociating water and natural gas from NGHs [7]. The primary methods include depressurization, thermal stimulation and CO_2 replacement, etc., which have been demonstrated to be feasible valid by the field tests in Messoyakha gas field, Mallik Delta, and the northern slope of Alaska, etc [8–10]. Moreover, physical experiments and numerical simulations have been conducted by many researchers to investigate the mechanism and production performance of various methods, as shown in Tables 1 and 2 respectively. Among the above four methods, the depressurization and thermal stimulation methods are relatively more mature, and therefore they are the most widely investigated in the previous works. The results of the researches demonstrated that the depressurization method is the most economical way of

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Table 1
Research on the development methods of HBLs – Physical experiment.

Development method	Author (s)	Study
Depressurization	Sung et al. [11]	The flowing characteristics of the dissociated gas and water were investigated by coreflooding experiments.
	Li et al. [12]	The dissociation of CH_4 hydrate and the variation laws of pressure and cumulative gas production etc. were analyzed by a 3D model.
Thermal stimulation	Wang et al. [13]	The development performance of hot water flooding in a five-spot well system was investigated.
	Feng et al. [14]	The optimal injection temperature range of hot water flooding was determined through a three dimensional model.
	Li et al. [15]	The energy efficiency of hot brine injection was analyzed by a two dimensional reactor.
CO_2 replacement	Lee et al. [16]	The kinetics and CH_4 recovery of the CO_2 replacement method were investigated according to the NMR measurement.
	Ota et al. [17,18]	The methane clathrate dissociation process was analyzed using the in-situ Raman spectroscopy.
	Castellani et al. [19]	The performance of the thermal-assisted CH_4–CO_2 replacement in a reactor was investigated.
	Zhang et al. [20]	The CH_4 recovery and CO_2 storage of the CO_2 replacement combined with thermal stimulation were analyzed.

Table 2
Research on the development methods of HBLs – Numerical simulation.

Development method	Author (s)	Study
Depressurization	Hong et al. [21]	A 2D cylindrical reservoir simulator was presented and the potential of depressurization for a HBL with an underlying gas layer was evaluated.
	Moridis et al. [22]	The performance of two kinds of Class 1 HBL (the HBL with an underlying layer saturated by gas and water) was analyzed.
	Ahmadi et al. [23]	The variation law of gas production rate at different well pressures and temperatures were investigated by an axisymmetric model.
	Ruan et al. [24]	The influences of depressurizing range and rate on the gas production were analyzed.
Thermal stimulation	Moridis et al. [25]	Several models were built based on the parameters of the HBLs at the Mallik site, and the performance of hot water circulation was investigated.
	Li et al. [26]	Based on the acquired data of the investigation carried out by the China Geological Survey, the production potential of HBL in the Shenhu area with respect to the warm water circulating method was assessed.
	Callarotti et al. [27]	The development performance and energy efficiency of electrical heating were analyzed.
	Su et al. [28]	The efficiency of the consumed heat and produced gas energy in thermal recovery of HBL in the Shenhu area were investigated.
	Hou et al. [29]	The recovery of a heterogeneous HBL by means of hot water huff and puff in a multi-segment horizontal well was simulated, and the parameters were optimized using the particle swam optimization.
CO_2 replacement	White et al. [30]	A five-spot well system was constructed and the development performance of CO_2 injection after depressurization was simulated.
	Uddin et al. [31,32]	A kinetic model of CO_2 replacement was proposed and dissociation and formation of CH_4 and CO_2 hydrates were analyzed.
	Bai et al. [33]	The replacement process of CH_4 hydrate by CO_2 was simulated by molecular simulation method.

development at present. However, NGH dissociation is an endothermic process, and therefore the NGH dissociation rate drastically declines as the decrease of reservoir temperature and pressure referring to the depressurization method. Moreover, the temperature decrease also results in high possibility of the re-formation of NGH and ice blockage, and consequently poor sustainability and low development efficiency [8,34,35]. Owing to the additional energy supply, thermal stimulation, promoting NGH dissociation by injecting steam, hot water or other hot fluids directly into HBL, can significantly raise the gas production. Although the studies listed in Tables 1 and 2 demonstrate that the thermal stimulation can lead to relatively high gas production rates, it is also widely found that the thermal stimulation method suffers from huge heat loss and inferior economy [14,28].

Geothermal energy, derived from the Earth, is a clean renewable energy source. It is also widely distributed with enormous quantities. According to WGC (World Geothermal Congress) 2015 Country Updates, the installed capacity of America is up to 3450 MW and that of China has reached to 27 MW [36]. Reservoir temperature is the primary indicator of required technology and specific use in the geothermal energy development [37]. Generally, low-temperature geothermal energy is directly used for heating, planting or health care; the most common medium-temperature geothermal energy is used in binary cycle geothermal plants; and high-temperature geothermal energy or hot dry rock is usually used for commercial power generation by steam [37,38]. Upon arrival of the 21st century, the CO_2-assisted geothermal recovery has gradually drawn people's attention. In 2000, Brown [39] first proposed the CO_2-hot dry rock enhanced thermal system, in which supercritical CO_2 is used as the fluid for heat extraction. Then Pruess et al. [40–42] more thoroughly studied the heat exchange and chemical reaction between CO_2 and hot dry rock. Later, Randolph et al. [43] extended the CO_2-assisted geothermal recovery to the development in the reservoir with low- and medium-temperature geothermal energy, by injecting CO_2 into deep saline aquifers or abandoned oil reservoirs and then using the returned heated CO_2 for power generation. Recently, Zhang et al. [44] evaluated the potentials of the abandoned high temperature gas reservoirs with cyclic injection of CO_2 as well as the underground CO_2 storage.

To sum up, thermal stimulation can result in relatively high gas production rates in the development of HBL compared with the depressurization method, and yet injecting hot fluids from the ground consumes massive fossil fuel, which leads to inferior economy and environmental-friendliness. However, the formations beneath HBL still have normal geothermal gradients. For instance, in HBL of the Shenhu area, the South China Sea, China, the geothermal gradient is 4.3 °C/100 m [29], while in the L-Pad area, the Prudhoe Bay, it is 3 °C/100 m, and 3.6 °C/100, in the Mt Elbert area [45]. Thus, it is possible to use the geothermal energy to enhance the development performance of HBLs, and meanwhile achieve a lower cost compared with the conventional thermal stimulation method. Though the robustness of CO_2 injection based geothermal energy development has been proved, the utilizations of geothermal energy are still limited to power generation, direct heating, etc., and the feasibility and characteristic of the NGHs recovery with geothermal energy have not been fully studied.