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The use of heat-assisted antigravity drainage method in the two horizontal wells in gas production from the Qilian Mountain permafrost hydrate deposits

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ABSTRACT

The occurrence of gas hydrate deposits in the Qinghai–Tibet plateau permafrost (QTPP) were confirmed during the Scientific Drilling Project of Gas Hydrate in Qilian Mountain permafrost (QMP) in 2008–2009. A total of four test wells were completed, and gas hydrate samples were obtained from the drilling wells of DK-1, DK-2, and DK-3. The objective of this study is the analysis of gas production potential from gas hydrate-bearing zone of DK-2 using dual horizontal wells based on its geological properties at this site. In this paper, production strategies of permafrost hydrate deposits with the novel Heat-Assisted Antigravity Drainage (HAAD) method are investigated numerically. Gas production is induced in a two-well system and its influence factors are evaluated. When suitable heat injection rate and depressurization driving force are applied to the lower well and the upper well, respectively, favorable gas-to-water ratio and energy ratio can be obtained during the whole HAAD process. However, the absolute gas production rate may not be economically attractive for the production method we have employed. The sensitivity analysis indicates that the hydrate deposits with higher intrinsic permeability and larger rock porosity will show better perspective for hydrate exploitation.

1. Introduction

1.1. Background

Natural gas hydrates (NGH) are solid crystalline compounds in which water and gas molecules are bounded in the ice-like crystal lattices called hosts (Sloan and Koh, 2008). The general chemical formula of gas hydrates is $G{\cdot}nH_2O$, in which the molecule number ratio n of water to gas in the lattice is called the hydration number. It is ranged from 5.77 to 7.4, with the average value of $n=6$ and the complete hydration number of $n=5.75$ (Sloan and Koh, 2008). Most of gas hydrates occurring in nature are usually formed with methane gas, and they have attracted global attention as a potential energy resource to meet the increasing energy demand. Because of the favorable geological conditions (high pressure P and low temperature T) in deep ocean sediments and in the permafrost, natural gas hydrate deposits have been found to exist widely in these areas through scientific drilling projects and field-based researches within national gas hydrate programs. Although current estimates of the amount of the methane gas trapped in natural gas hydrates vary widely, it is prevalently agreed that the size is vast and that it is worth further exploring as a kind of new and challenging energy resource in the future (Boswell and Collett, 2011). For example, abundant methane hydrate resources are proved to exist in the Shenhu area of South China Sea (Li et al., 2010; Su et al., 2012), and the volume of methane gas is estimated to be 1.38×10^{14} m^3, 1.41×10^{14} m^3 and 1.70×10^{14} m^3 for gas hydrate types I, II and H, respectively (Trung, 2012). Recently, Japan carried out an *in-situ* gas hydrate exploitation research in the seabed in Pacific waters off its central, and successfully extracted natural gas from methane hydrate. This is the first time natural gas is produced from the real oceanic hydrate formations.

Gas production from hydrate is based on the principle that hydrate dissociates when its stability conditions are broken down because of temperature increase or pressure reduction. The main techniques that have attracted the most attention and may be used for methane extraction from actual gas hydrates involve the

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Nomenclature

G_1	thermal gradient within the frozen layer (°C/m)
G_2	thermal gradient under the frozen layer (°C/m)
H	permafrost thickness (m)
k	intrinsic permeability (m^2)
k_{eff}	effective permeability (m^2)
k_{rA}	aqueous relative permeability (m^2)
k_{rG}	gas relative permeability (m^2)
$k_{\Theta C}$	thermal conductivity (W/m/K)
$k_{\Theta RD}$	thermal conductivity of dry porous medium (W/m/K)
$k_{\Theta RW}$	thermal conductivity of fully saturated porous medium (W/m/K)
$k_{\Theta I}$	thermal conductivity of ice (W/m/K)
M_W	cumulative mass of produced water (kg)
P	pressure (Pa)
P_B	initial pressure at base of HBL (Pa)
P_0	atmosphere pressure (Pa)
P_W	pressure at the well (Pa)
P_{W0}	initial pressure at the well (Pa)
Q	injected heat (J)
Q_{avg}	average gas production rate (ST m^3/day/m of well)
Q_W	average water production rate (kg/day/m of well)
Q_{inj}	heat injection rate (W/m of well)
r	radius (m)
R_{GW}	the gas to water production ratio (ST m^3 of CH$_4$/m^3 of H$_2$O)
S	phase saturation
t	time (days)
T	temperature (°C)
T_0	permafrost ground temperature (°C)
T_B	initial temperature at the base of HBL (°C)
T_T	initial temperature at the top of HBL (°C)
V_P	cumulative volume of produced CH$_4$ (ST m^3)
W	pump work (J)
x,y,z	cartesian coordinates (m)
X_S	salinity
ΔH_c	combustion enthalpy of produced methane (J)
ΔP_W	driving force of depressurization, $P_{W0}-P_W$ (Pa)
Δx	discretization along the x-axis (m)
Δy	discretization along the y-axis (m)
Δz	discretization along the z-axis (m)
ϕ	porosity
η	energy ratio
λ	van Genuchten exponent – Table 1

Subcripts and superscripts

0	denotes initial state
A	aqueous phase
B	base of HBL
cap	capillary
G	gas phase
H	solid hydrate phase
irA	irreducible aqueous phase
irG	irreducible gas
n	permeability reduction exponent – Table 1
n_G	gas permeability reduction exponent – Table 1
OB	overburden
S	salinity
UB	underburden
W	well

depressurization (G. Li et al., 2012; X.S. Li et al., 2012d), the thermal stimulation (Fitzgerald et al., 2012; X.S Li et al., 2012b), the use of inhibitors (Lee, 2010), and the combinations of them (B. Li et al., 2012; X.S. Li et al., 2012). The depressurization is usually thought to be the most promising and practical method for hydrate dissociation because of its simplicity for operation. However, the gas production is often burdened with the limited sensible heat of the hydrate deposit. The Steam-Assisted Gravity Drainage method (SAGD) is a prevalently used method in enhancing the heavy oil recovery in the oil industry. It was firstly proposed by Butler and his coworkers in the late 1970s (Al-Bahlani and Babadagli, 2009). Recent studies (Sasaki et al., 2009; G. Li et al., 2013, X.S. Li et al., 2013) have introduced a new kind of horizontal well design for gas production from various hydrate deposits with methods similar to the SAGD process. There are two parallel horizontal wells placed in the hydrate deposits. Hot water or steam is provided into the hydrate-bearing sediments through one of the wells, while the other one (positioned on the same vertical plane) performs as a producer that is operated under constant pressure condition. The Steam-Assisted Antigravity Drainage (SAAD) method (Sasaki et al., 2009; G. Li et al., 2013) is similar to the SAGD, with the only difference being that the lower well is the injection well while the upper one is the producer. Both of the SAGD and SAAD have been employed for the experimental production from hydrate-bearing sediments (G. Li et al., 2013; X.S. Li et al., 2013), and it is found that gas can be produced from the upper production well more easily during the SAAD process (G. Li et al., 2013). However, high pressure will occur at the injection well if the injected mass could not be promptly transferred outside. In such case, the Heat-Assisted Antigravity Drainage (HAAD, pure heat stimulation without mass injection) will be more preferable for gas production from low permeable reservoirs.

In recent years, great success has been made in gas hydrate exploration from permafrost in the world, such as the Messoyakha gas field in the western Siberia (Yakushev and Chuvilin, 2000), the Mackenzie delta permafrost in Canada (Dallimore and Collett, 2005), and the Mount Elbert within the Alaska North Slope (Lee et al., 2011). Corresponding numerical simulations have been fulfilled to assess the exploitation potential of these permafrost hydrate deposits using various kinds of well design and production methods (Grover et al., 2008; Moridis et al., 2011b). In 2008–2009, the existence of the significant gas hydrate deposits was confirmed in the Qilian Mountain permafrost (QMP) of the Qinghai–Tibet Plateau Permafrost (QTPP) in China through the Scientific Drilling Project of Gas Hydrate. It represents the possible energy source of gas hydrate in the permafrost of China (Zhu et al., 2010a). X.S. Li et al. (2012a, 2012c) carried out the investigations of producing gas from site DK-3 in a single horizontal well by depressurization and huff and puff methods through numerical simulation. In this study, we numerically evaluated the gas production potential of the DK-2 gas hydrate deposit in the QMP by means of HAAD method, as well as the reservoir properties affecting it.

1.2. Hydrate exploration in Qilian Mountain

The Qilian Mountain is situated in the north of the QTPP with the permafrost area of about 1.0×10^5 km^2 (Wu et al., 2010). Previous studies (Lu et al., 2009; Wu et al., 2010) estimated that the gas hydrate stability zones were amongst dozens to hundreds of meters within the QTPP. The Scientific Drilling Project in the