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Methane hydrate decomposition and sediment deformation in unconfined sediment with different types of concentrated hydrate accumulations by innovative experimental system

Yi Wang[a,b,c,1], Jing-Chun Feng[d,e,1], Xiao-Sen Li[a,b,c,*], Yu Zhang[a,b,c], Han Han[a,b,c]

[a] Key Laboratory of Gas Hydrate, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, PR China
[b] Guangzhou Center for Gas Hydrate Research, Chinese Academy of Sciences, Guangzhou 510640, PR China
[c] Guangdong Province Key Laboratory of New and Renewable Energy Research and Development, Guangzhou 510640, PR China
[d] School of Enringing, Sun Yat-sen University, Guangzhou 510275, PR China
[e] Guangdong Research Center for Climate Change, Guangzhou 510275, PR China

HIGHLIGHTS

- Hydrate dissociation in different types of gas hydrate accumulations are studied.
- Influence of hydrate morphology and distribution on gas production is not obviously.
- Structure collapse of sediment is observed in the grain-displacing hydrate dissociation.
- Radial Shrinkage Effect is found and analyzed during pore-filling hydrate dissociation.

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ABSTRACT

Methane hydrates are regarded as a potential source of energy supply. Geological features of different types of concentrated gas hydrate accumulations show great variations. In this study, methane hydrate decomposition in unconfined sediment with different types of concentrated hydrate accumulations are firstly investigated by experiments, and the influence of hydrate decomposition on sediment deformation is analyzed. Two types of concentrated hydrate accumulations are selected, which are grain-displacing hydrate (nodules) and pore-filling hydrate in sediment. An innovative high pressure set-up with a quick-opening top cover is applied to investigate hydrate decomposition under the geological conditions of the hydrate reservoir in the South China Sea. Experimental results indicate that the influence of hydrate morphology and hydrate distribution on gas production is not obviously. The average heat transfer rates during grain-displacing hydrate dissociation and pore-filling hydrate dissociation are also similar. However, the sediment deformation characteristics for different types of concentrated hydrate accumulations are totally different. Structure collapse of porous media is firstly observed in the experiments within the grain-displacing hydrate, which indicates that the sediment deformation cannot be ignored during the gas recovery from grain-displacing hydrate. Meanwhile, the radial shrinkage effect of sediment is found during pore-filling hydrate dissociation, due to the cementation effect of hydrate.

1. Introduction

Methane hydrate is a kind of naturally-occurring clathrate, in which a host cage of water traps guest molecules of methane. The guest molecules do not participate in building chemically bounds to the water molecules, but are enclosed in crystalline cage [1]. Methane hydrate is similar to ice, but the physical and chemical properties of hydrate are different with those of ice. When pressure and temperature exceed those for hydrate stable, the solid crystalline cages decompose to liquid water, and the methane gas are released from host cages [2]. If decomposed at standard pressure and temperature, about 160 volumes of methane gas can be released from one volume of methane hydrate [3]. Therefore, methane hydrate is also called as “flammable ice”.

Methane hydrate has been discovered in both onshore and offshore environments all over the world [4]. Onshore hydrate reservoirs have been found in the permafrost and polar regions. Offshore hydrate

* Corresponding author at: Key Laboratory of Gas Hydrate, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, PR China.
E-mail address: lixs@ms.giec.ac.cn (X.-S. Li).
[1] These authors contributed equally to this work.

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Nomenclature

Abbreviation

HBS Hydrate Bearing Sediments
DS Depressurizing Stage
CPDS Constant-Pressure Depressurizing Stage
IMH Intermediate of Methane Hydrate

Symbols

S_G saturations of gas
S_W saturations of water
S_i saturations of ice
S_H saturations of hydrate
$n_{m,0}$ mole quantity of the total injected methane gas [mol]
$n_{m,G}$ mole quantity of free methane gas [mol]
$n_{m,W}$ mole quantity of methane dissolved in water [mol]
v_m gas molar volume [mL/mol]
V_{pore} total pore volume of the sediments [mL]
N_H the hydration number of methane hydrate
$M_{W/I}$ molar mass of water [g/mol]
M_H molar mass of methane hydrate [g/mol]
$\rho_{W/I}$ densities of water/ice [g/cm^3]
ρ_H density of hydrate [g/cm^3]
s_{H0} initial saturation of hydrate before hydrate decomposition
$s_{W0.}$ initial saturation of water
n_{m01} initial amount of the methane gas before hydrate dissociation [mol]
v_{mp} gas molar volume under the conditions during hydrate decomposition [mL/mol]
k dissociation ratio of hydrate
V_p accumulative volume of gas production [L]
m_W accumulative amount of the water production [g]
n_H molar quantity of the remaining hydrate [mol]

reservoirs mainly have been found in the continental margins [5]. It is due to the fact that the pressure and temperature conditions in these regions are suitable to form and sustain hydrate, and methane and water are present in these natural settings. The volume of methane store in methane hydrate all over the world is huge. The common perception of the total carbon content in gas hydrate is more than that of all of the conventional fossil fuels [6]. With researchers obtain new information about the location and concentration of methane hydrate, the estimation of natural gas hydrate is continually refined and improved. Therefore, methane hydrate is considered as a potential source of methane for energy supply [7,8].

In order to observe hydrate dissociation in the real environment and assess the feasibility of exploitation technologies for commercial production, depressurization [9,10], thermal stimulation [11,12], inhibitor injection [13], carbon dioxide replacement [14], and the combined application [15] have been applied and investigated for hydrate destabilization [16]. The models of hydrate dissociation using different methods have been reported [17,18]. Over past few decades, a series of field tests on gas production from hydrate deposits were carried out. The field test in the Mallik region of Canada in 2008 proved that gas production from hydrate accumulations was technically feasible from a sand-dominated reservoir, which promotes the potential of hydrates to be considered as an important recoverable energy resource [19]. During the field test in the Prudhoe Bay area (On the north slope of Alaska/USA) in 2012, the methane exchange by CO_2 injection into a methane hydrate reservoir has been tested for the first time [20]. Not only hydrate field test on hydrate deposits in the permafrost regions, but also the marine hydrate field tests were successfully conducted in the Nankai Trough by Japan in 2013 [21] and in the Shenhu area of South China Sea by China in 2017 [22]. In both of these marine hydrate field tests, the depressurization is applied for gas recovery.

On the other hand, gas hydrate has been related to a serial of issues on geohazards. The hazards generally are due to the destabilizing effects of methane hydrate dissociation and the rapidly fluids (gas/water) releasing into unconsolidated geological systems. Gas hydrate geohazards may occur due to natural processes or industrial activities. Primary researches mainly focus on designing different field programs to evaluate natural geohazard process that may occur in both marine and arctic deposits [23,24]. Furthermore, the geohazards during gas production from hydrate reservoir will become a bottleneck for the exploitation techniques of gas hydrate.

Because methane hydrate generally occurs in unconsolidated sediments, the hydrate decomposition leads to the decrease of sediment strength and significant sediment deformation [25]. Recently, some researches have been reported to investigate the change of mechanical properties and the deformation mechanism of the hydrate bearing sediments (HBS) during hydrate decomposition. Sultan et al. [26,27] reported that hydrate destabilization could increase the pore pressure and reduce the sediment strength. Kono et al. [28] carried out hydrate decomposition experiments by depressurization, and found that the rate of hydrate decomposition was related to sediments properties. Haligva et al. [29] investigated the influence of sediment volume on the gas production from hydrate dissociation. Serials of gas hydrate decomposition experiments were performed by Jung et al. [30]. In these experiment, the sediments are made of different particle sizes. The fine particle migration with multi-phase flow in pore and the fracture structure formed in sediment during hydrate decomposition are found and reported. A theory of critical fines fraction is proposed to explain these phenomena. On the other hand, to investigate the change of the sediment mechanical properties during hydrate decomposition, a serial of mechanical properties were tested by triaxial shear experiment [31] and centrifuge experiment [32]. Meanwhile, models for the change of mechanical properties in HBS also have been presented [33]. However, pervious researches mainly focused on the influence of sediment on the mechanical properties and deformation mechanism. Few literatures were reported about the influence of hydrate distribution on the sediment deformation mechanism of the HBS and the production behaviors during hydrate decomposition until now.

According to the different types of concentrated gas hydrate in sediment, hydrate reservoirs can be divided into three categories, which are grain-displacing hydrate (veins, nodules, and fracture-fills), pore-filling hydrate in sediment, and seafloor hydrate mounds [34]. Seafloor hydrate mounds are solid masses of gas hydrate which can be directly observed on the seafloor. Although seafloor hydrate mounds are easy for exploitation, the value for commercial exploitation can be ignore due to the small reserves and widely distribution. Therefore, gas production from this kind of occurrence is not being actively considered until now, which also will not be investigated in this work. Grain-displacing hydrate can be defined that the solid hydrate participates in constituting the structure of the HBS in the form of veins, nodules, and fracture-fills. Hydrate concentrations of grain-displacing hydrate are normally ranged from 10% to 30%. Because sediment for the grain-displacing hydrate generally is mud, which lacks of matrix permeability and mechanical stability, sand production and sediment deformation issues may be occurred during gas production from the grain-displacing hydrate. Recently, the pore-filling hydrate in sandy sediment is considered as the most potential category of gas hydrate deposit for commercial production in future. This potential has been reported both in field test and in numerical simulation. The typically pore-filling hydrates within sand reservoirs are found to have hydrate saturation in