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Effect of vertical wellbore incorporation on energy recovery from aqueous rich hydrate sediments

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HIGHLIGHTS

- Vertical wellbore was incorporated within water saturated hydrate sediment.
- Hydrate accumulation around wellbore reduced gas production and dissociation rate.
- Cumulative gas production enhanced by up to 8% through vertical wellbore.
- Simultaneously, water production was reduced by up to 43% at 4.5 MPa.

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ABSTRACT

Natural gas hydrates, an abundant source of natural gas in nature, have the potential of supplying energy for the future. However, due to the complexity of physical processes that occur simultaneously during the dissociation of hydrates within porous media, further understanding on the dynamic behavior of hydrates dissociation (e.g. heat transfer associated with phase transition, permeability changes, and simultaneous gas/water production) is required to elucidate the process of gas recovery from hydrates. In this work, we investigate the effect of a single vertical wellbore incorporation on the production behavior from hydrates formed in sandy sediments (0.1–0.5 mm). Depressurization approach (3.5, 4.0 and 4.5 MPa) was applied to dissociate the hydrate-bearing sand at a constant surrounding temperature of 281.5 K. Through the incorporation of a vertical wellbore, the gas production rate decreased with increasing bottom hole pressure, and continuous production of gas was observed at 4.5 MPa even after 10 h of dissociation. For water production, a majority of water was produced within the first 2 h, beyond which only a small amount of water was recovered. It was also observed that the incorporation of a vertical wellbore in the current design and apparatus impeded hydrate dissociation, which was attributed to a stronger flow resistance for fluids to exit through the vertical wellbore. Cumulatively, the incorporation of vertical wellbore enhanced gas production by up to 8% and reduced water production by up to 42%. In the future, innovative production schemes, such as heated wellbore and hydraulic fracturing can be applied to further optimize gas production from hydrate-bearing sediments.

1. Introduction

Gas hydrates are solid, ice-like inclusion compound formed by the encapsulation of suitably sized guest molecules within the crystalline lattices created by water molecules [1,2]. In nature, a substantial amount of natural gas (with methane as the major constituent) is trapped in solid hydrates in both offshore and terrestrial permafrost regions, where the hydrate stability conditions of relatively low temperature and high pressure are met [3]. It is estimated that the amount of methane stored in global hydrate resource is on a scale of $3 \times 10^{15}\,m^3$ (equivalent to 1500 GtC) [4], comprising about a third of mobile organic carbon on the earth and representing an attractive unconventional energy resource for the future [5,6]. The methods proposed to harness methane from hydrate deposits include

Abbreviations: BHP, bottom hole pressure; DAQ, data acquisition system; GLS, gas-liquid separator; GR, gas receiver; HBS, hydrate-bearing sediments; MH, methane hydrates; OD, outer diameter; S_H, hydrate saturation; SL, standard liter (at standard conditions of 100 kPa and 273.15 K); VW, vertical wellbore

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depressurization [7], thermal stimulation [8,9], inhibitor injection [10,11], gas exchange [12,13], and a combination of the above approaches [14,15]. These approaches have been tested in the laboratory scale as well as in the field-scale production testing. From 2002, several field-scale production tests have been carried out in onshore hydrate reservoirs in Canada [16], Alaska [17] and China [18]. In recent years, offshore field production tests were conducted in China [19] and Japan [20,21], both of which successfully unleashed natural gas from hydrate reservoirs below the seafloor. While field testing affirmed the potential of energy recovery from hydrate deposits, these field tests also shed light on the challenges to overcome for the successful extraction of natural gas from hydrates, including sand intrusion [20] and slow gas recovery accompanied with water breakthrough [21,22]. These findings also revealed that the multiphase production behavior from hydrate reservoir needs to be further elucidated, as it imposes a significant effect on the reservoir productivity, heat transfer across the sediment and the geomechanical stability of hydrate fields [23].

The properties of natural hydrate reservoirs are characterized through advanced tools, such as geophysical logging and pressure coring [24,25]. However due to the high cost of hydrate expedition projects, limited pressure core availability and inevitable perturbation to the retrieved hydrate cores, it is essential to elucidate the dynamic behavior of hydrates during phase transition from synthetic hydrate-bearing sediments (HBS) formed in the laboratory. The techniques to form synthetic HBSs in the laboratory include ice seeding [26], excess gas [27], excess water [28], and dissolved methane approach [29,30]. Excess gas approach was reported to form hydrates cementing grain contacts, whereas excess water approach was reported to form frame supporting morphology at a hydrate saturation (S_H) below 40% [28]. On the other hand, dissolved methane approach which mimics the natural hydrate formation process from microbial origin has the capacity to produce highly saturated HBS ($S_H \sim 95\%$) [30]. Despite various advantages offered by dissolved methane approach, it requires sophisticated equipment and months of time to form hydrates [30]. Recently, it was demonstrated that the rate-limiting step of dissolved methane approach was the methane dissolution step, which can be improved through innovative process design [31].

With the capability to form synthetic HBS, the production dynamics from HBS can be elucidated in the laboratory scale research under controlled production conditions, which is difficult to achieve in the field-scale tests and can be applied to validate numerical simulators [32]. Amongst these investigations, physical wellbores have been incorporated in some studies to realistically mimic the production scenario from HBS. In general, the wellbore designs applied in the hydrate production studies include liner design [15,33] and perforated design [34,35]. The incorporation of wellbores within hydrate sediment is typically experimented in medium scale (~1 L) [36] to large scale (> 100 L) [37,38] facilities. These miniature wellbores were incorporated in both vertical [33] and horizontal orientations [39,40], either in a single well [40] or multiple well [41,42] configurations to acquire the specific production dynamics.

The simplest well configuration was the *single vertical wellbore* configuration, whereby the wellbore is typically installed at the center of the hydrate reservoir. This configuration has been applied in the field production tests (e.g. Mallik site [16], Alaska North Slope [17] and Nankai Trough [21]). It is also considered in the numerical studies to evaluate the recovery potential of a particular hydrate reservoir (e.g. in South China Sea [43], Alaska North Slope [44,45] and Black Sea [46]) employing the specific properties of the reservoir. In the experimental setting, the production dynamics from HBS through a single vertical wellbore were elucidated in HBSs of various scales [35,47], ranging from 210 L [37] to 0.73 L [36]. In the simplest case, the single vertical wellbore served as the "production wellbore" through which pressure drawdown was achieved with the production of gas/water [48]. In a recent study, Nair et al. demonstrated the recovery of gas from clayey hydrate reservoir through depressurization from a single production wellbore in the free gas layer [49]. Falser et al. experimented with the coupling of a heating element to the single production wellbore [35], through which an enhancement in cumulative gas recovery by 3.6 times was reported. The single wellbore has also been applied as the "injection wellbore" in some other studies, delivering inhibitors [11] or warm water [15] into the sediment on top of their role as the production wellbore. Recently, Feng et al. [50] employed single well huff and puff approach (HP) to dissociate water saturated HBS in 117.8 L hydrate simulator. The authors demonstrated that HP cycle above equilibrium condition was unsuitable for hydrate production due to rapid hydrate reformation, highlighting the need for depressurization during gas production from hydrates.

In a multiple wellbore configuration, wellbores are incorporated within the HBS for various purposes, including the production of gas/water, warm water injection [34,48], inhibitor injection [10,51], and wellbore heating [52]. The configurations which have been experimented on the hydrate recovery studies include dual wellbore [9,42] and five-spot configuration [41,53]. A consensus of these study is that the energy efficiency and gas productivity can be enhanced through the segregation of production wellbore and heating wellbore (either through hot fluid injection or electrical heating), due to the resultant forced convection which can enhance heat transfer towards the production wellbore [41,52]. Recently, Wang et al. analyzed the effect of well spacing during thermally stimulated hydrate dissociation in a 5.8 L cubic hydrate simulator at 6.5 MPa [9]. Through the evaluation of gas production rate, heat consumption per unit of gas harnessed and the hydrate dissociation ratio, the authors reported that a larger well spacing and higher water injection rate is favorable for the particular system, and an optimal well spacing can be found according to the rate of hot water injection.

To enable the successful production of gas from natural hydrate reservoir, it is essential to develop an in-depth understanding on the mechanism of hydrate dissociation within porous media through the coupling of experimental observation, numerical modelling, and field production data [54]. From a fundamental point of view, it is clear that the production behavior from HBS is dependent on a variety of reservoir properties (e.g. types of hosting sediments, saturation of hydrates etc.) as well as the production configurations (e.g. production intervals [45], wellbore orientation [39] and well spacing [9]). As reviewed above, we found that while wellbores of various design/configurations have been experimented in the laboratory scale research, limited attention has been given to investigate how the incorporation of wellbore would affect the production behavior from HBS. Our previous study [55] has demonstrated an enhancement in gas recovery and simultaneous reduction in water recovery through the incorporation of a horizontal wellbore. In this study, we further investigate the effect of vertical wellbore (VW) within a cylindrical hydrate sediment (1 L scale) on the production behavior from HBS under 3 bottom hole pressures (BHP) of 3.5, 4.0 and 4.5 MPa. Simultaneous water and gas production, temperature distribution across the sediment and the hydrate dissociation kinetics were evaluated during depressurization to provide experimental evidence on the effect of vertical wellbore incorporation on the macroscopic production behavior from HBS of the current scale. Finally, discussions on the effect of wellbore incorporation/orientation were made to highlight the significance of wellbore consideration in the future work.

2. Experimental section

2.1. Materials

In this study, methane gas (99.9%) supplied by Air Liquide Singapore Pte Ltd was used as the hydrate former. Unconsolidated silica sand with particle size ranging from 0.1 to 0.5 mm (W9 grade sand supplied by River Sands Pty Ltd) was applied as the host sediment. Deionized water was used to create excess water environment during