Methane hydrate bearing sediments: An analysis of production strategies

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Introduction

Estimates of methane gas accumulations in hydrate bearing sediments range from $3x10^{15}$ m^3 to 10^{17} m^3 at standard temperature and pressure. However, the recoverable amounts remain uncertain due to the inherent characteristics of hydrate accumulations and associated recovery limitations. Methane hydrate is stable under high pressure and low temperature. Therefore, the required PT conditions are met in sediments found at high water depths and under the permafrost. The lower bound of the stability zone is temperature-limited by the geothermal gradient. Hydrate formation favors coarse-grained sediments, where it nucleates in the pore space and fills pores. Hydrate nucleation and growth in fine-grained sediments is grain-displacive and forms nodules and lenses. Figure 1 summarizes observed hydrate morphologies as a function of the reservoir texture.

Sediment Type	**Clean coarse-grained**	**Coarse with fines**	**Fine-grained**
Mechanical Control	coarse	coarse	fine
Hydraulic control	coarse	fines	fine
Properties			
Hydrate morphology	pore filling	pore filling & chunks	nodules & lenses
*Permeability**	high	low	low
Compressibility	low	low	high
Examples	Mt Elbert Nankai Trough Mallik Gulf of Mexico	Okushiri Ridge	Ulleung Basin NGHP Blake Ridge Cascadia Margin Offshore Peru Sea of Okhotsk Atwater Valley Hydrate Ridge Shenhu Area
Production			
Possible Method	Depressurization CH_4-CO_2 replacement	Depressurization CH_4-CO_2 replacement	Thermal Shallow production
Consider reservoir characteristics	Layered – Turbidites – Homogeneous Proximity to stability boundary Depth bellow seafloor		

Note: *before destructuration **Fig. 1: Hydrate morphology and potential production methods as a function of reservoir texture**

Production techniques already explored

Potential production strategies depend on the reservoir type (Fig. 1). Three methods are often discussed: depressurization, thermal stimulation, and chemical stimulation (inhibitors and CO_2 replacement).

Depressurization. Depressurization seems to be the most viable production method for hydrate-bearing sandy sediments (Moridis et al. 2009; Reagan et al. 2015). During depressurization, the dissociation front advances from the production well until it reaches its terminal position which defines the maximum amount of recoverable methane. This terminal position of the dissociation front is a function of (1) the relative permeabilities between the hydrate free sediment, the hydrate bearing sediment, and the aquitard layers, and (2) the relative fluid pressures between the pressure at the well, at the phase boundary, and in the far field (Terzariol et al. 2017).

Alternative well-deployment strategies may significantly increase the affected volume and improve the overall economics. For example: (1) horizontal wells along the hydrate layer extend the affected volume linearly with the well length (Terzariol et al. 2017), and (2) zonal depressurization through multiple well-points can significantly increase the affected volume-per-well (Figure 2 – See experiments in Wang et al. 2015).

Thermal stimulation. Most hydrate accumulations are found in clayey reservoirs (Note: a clay content as low as 10% can render a sandy reservoir clay-dominant from a permeability point of view – Park and Santamarina, 2017).

Production from clayey reservoirs faces great challenges associated with low permeability, high gas entry pressure, and high volumetric contraction (Moridis et al., 2010; Jung et al., 2011). Thermal stimulation overcomes some of these limitations through the following sequence of events: hydrate expansion upon dissociation (2 to 4 times across the phase boundary plus succeeding gas expansion), increased gas pressure, and the creation of highly conductive open mode discontinuities (Jang and Santamarina, 2011, 2016; Shin and Santamarina, 2010).

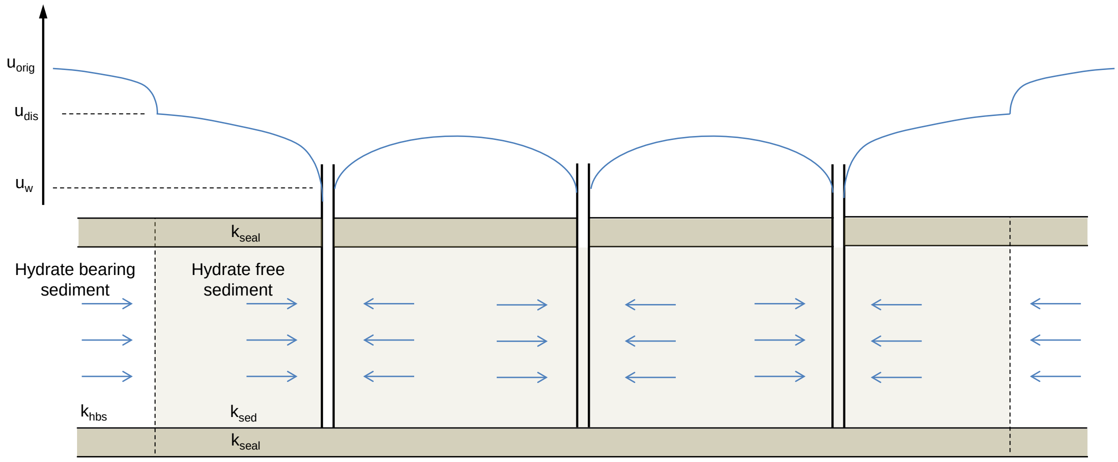

Fig. 2: Multi well production strategy - Increased production volume. The design of the production system must take into consideration the pore water pressure at the well u_w, for dissociation u_{dis} and in the far field u_{orig}, and the permeabilities of the hydrate bearing sediment k_{hbs}, the hydrate-free sediment k_{sed}, and the seal layers k_{seal}.

Nevertheles, novel implementation strategies are necessary because thermal stimualtion consumes large amounts of heat (Moridis and Sloan, 2007).

Chemical stimulation. Chemical inhibitors are used to prevent hydrate formation within the production well, and could have a role in production. The most promising chemical method is the injection of CO_2 to cause CH_4-CO_2 replacement within the reservoir, whereby CH_4-hydrate becomes CO_2-hydrate. Implications are noteworthy: CH_4 recovery, sequestration of CO_2, preservation of the hydrate mass, limited changes in effective stress, and minimal strains. Underlying processes and implications have been extensively tested in the laboratory (Ersland et al., 2009; Jung et al 2010; Espinoza and Santamarina 2011) and in the field (Schoderbek et al. 2013). The replacement is exothermic, thus the reaction favors further exchange. The field implementation must consider the reservoir permeability, viscous fingering and sweep efficiency, and premature CO_2 hydrate formation.

Other potential production methods: Shallow accumulations

The economic viability of production strategies explored above is hindered by the small volume affected by depressurization, the high cost of massive heating, and fluid flow localization in CO_2 injection. In addition, those strategies do not effectively address the fact that most hydrate accumulations are found in fine-grained sediments. In this context, shallow accumulations appear more promising, regardless of the sediment type.

Shallow seafloor accumulations experience low vertical effective stress; therefore methane gas can readily escape by bubbling through or forming gas driven openings through the overburden (Sun and Santamarina, 2018). Under these conditions, production strategies for shallow accumulations could involve (1) horizontal wells that circulate hotter water from the water column and an 'inverted umbrella' to collect the released gas (Hall and Willman 2012; Nohmura 2001), (2) dome-based depressurization and collection, or (3) shallow mining followed by dissociation (Zhang et al. 2017)

Other engineering challenges - Wells

Laboratory and field trials have highlighted the effects of loss of sediment strength, fines migration and clogging, sand production, and well failure. In particular, well analysis and design requires careful consideration. Hydrate dissociation couples with changes in effective stress (if depressurization is used) to cause pronounced volumetric and shear strains in the sediment. The sediment-well shear interaction transfers load to the well and may cause it to break in tension (above the production layer) or to collapse in compression (within the production horizon - Shin and Santamarina 2017). Slip-joints and soft-tip completions would be required to ensure a reliable well performance.

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