Review on the Gas Hydrate Development and Production as a New Energy Resource

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Abstract

Gas hydrates consist of guest gas molecules inside hydrogen-bonded water lattices. Natural gas hydrates are found in offshore and permafrost regions. The large amounts of gas hydrate reserves suggest the potential of gas hydrates as an energy resource if economically viable production methods were developed. The proper understandings of hydrate formation/dissociation are important for the drilling and oil production applications. The investigations of physical and geotechnical properties provide the in-depth understandings of the in-situ hydrate formation mechanism and the associated production technologies. The purpose of this review paper is to provide a starting kit for civil engineers who have recently started the research related to the hydrate development and production and want to have insights on the general trends of the hydrate research and the relevant knowledge needed for their research. Gas hydrate explorations include the geophysical explorations, such as the seismic survey, the borehole logging and the geological and geochemical explorations. Gas hydrate productions require the dissociation of gas hydrates, and the production technologies are categorized based on the dissociation techniques involved: depressurization method, thermal stimulation method, and inhibitor injection method. Establishing safe and efficient gas production technology requires the extensive information on the geotechnical characteristics of hydrate reservoirs. Flow assurances, the integrity of sediment formation and the well bore stability are crucial for the safe and efficient productions of gases from gas hydrates in sediments. The strength and deformation characteristics, the fluid migration characteristics, and the thermal conduction characteristics are key factors for controlling the above.

Keywords: *gas hydrate, production, geotechnical characterization, production technology, exploration, safety*

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1. Introduction

Clathrate hydrates consist of guest gas molecules inside hydrogen-bonded water lattices (Fig. 1). Gas hydrates were first reported by Davy (1811). It is first observed that hydrates clogged oil and gas pipelines (Hammerschmidt, 1934); this discovery stimulated research interests in the identification of hydrate-forming gas molecules and the thermodynamic properties of hydrates. Y. F. Makogon found gas hydrates in the Siberian permafrost region in 1965, and C. Bily and J.W.L. Dick reported the presence of hydrates in a core extracted from the MacKenzie Delta in 1974 (Bily and Dick, 1974; Sloan, 1998). The discovery of Bottom Simulating Reflectors (BSR) as potential indicators of the gas hydrate occurences led to active geophysical research for identifying the locations and the amounts of gas hydrates in oceanic and permafrost sediment formations.

Natural gas hydrates are mostly found in offshore and permafrost regions. The reported global estimations of natural gases in gas hydrates range from 10^{13} m^3 to 10^{19} m^3 STP

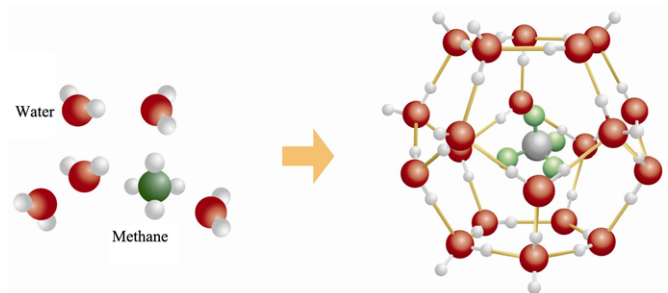
Fig. 1. Schematic Diagram of Natural Gas Hydrate Formation in Molecular Scale (Tetrahedral molecule is methane and dipole molecules are water.)

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(Trofimuk *et al*., 1977; MacDonald, 1990; Soloviev, 2002; Klauda and Sanlder, 2005; Sloan and Koh, 2008). Boswell and Collet (2006) have estimated the amount of natural gases trapped in hydrate-bearing sand layers to be 10^{13} m^3 STP out of 10^{15} m^3 STP. These large amounts of reserves suggest the potential of gas hydrates as an energy resource if economically viable production methods were developed. Furthermore, the proper understandings of hydrate formation/dissociation are important to the drilling and oil production applications (Sloan, 1998). In addition, the dissociations of hydrates within sediments due to natural changes in seawater temperature or human activities may cause massive seafloor instabilities (Sultan, 2004; Vogt and Jung, 2002). More recent research explores utilization of gas hydrate for the disposal of "green house" gases (Masuda, 1998; Park *et al*., 2008).

The purpose of this paper is to provide a starting kit for civil engineers who have recently started the research related to the hydrate development and production and who want to know the general trends of the hydrate research and the relevant knowledge needed for their research.

2. Gas Hydrates

2.1 Basic Chemistry and Occurrences

Gas hydrates consist of guest gas molecules inside hydrogen-bonded water lattices (Fig. 1). The one cubic meter of methane hydrate can hold approximately 163 m^3 of methane at Standard Temperature and Pressure (STP). Methane is the most common guest molecule, but higher order hydrocarbons, such as hydrogen sulfide, and carbon dioxide can also form gas hydrates under appropriate pressure and temperature conditions. Gas hydrates are stable at a certain temperature and pressure condition, which is called as phase equilibrium conditions (Fig. 2). Compared to ice which prevails only in permafrost regions, gas hydrates are

far more widespread, occurring in both permafrost sediments to the depths of ~1 km and deep marine sediments at the water depths of greater than ~300 m on the world's continental margins where the pressure and temperature conditions meet the gas hydrate equilibrium conditions. However, the equilibrium pressure/temperature conditions of hydrates in sediments are often shifted by the presence of electrolyte in pore fluids and curved interface between hydrates and pore fluid in infinitesimal pores (Lee, 2007; Lee *et al*., 2008). The occurrence characteristics vary according to sediment characteristics. Hydrates are generally found disseminated in sand whereas fine grained sediments often contain lenses or veins of hydrates.

2.2 Physical Properties

The investigations of physical properties provide the in-depth understandings of the in-situ hydrate formation mechanism and the associated production technologies. The several phases and compositions (e.g., hydrates in solid, pore fluid in liquid, soil grains in solid, pore gas in gas) coexist in nature, which makes it challenging to estimate the physical properties of hydrate-bearing sediments. Although saturations and spatial distributions of hydrates in pore space mainly affect physical properties of hydrate-bearing sediments, it is feasible to overview physical properties of hydrate-bearing sediments based on accumulated research efforts both in-situ and in laboratory. In this section, the properties of hydrate-bearing sediments are discussed.

2.2.1 Thermal Properties

The phase changes such as hydrate formation and dissociation processes involve heat transfers among multi-components. The thermal properties of hydrate-bearing sediments are mostly governed by the porosity, the effective stress and the degree of saturations. The simplest approach to estimation of thermal conductivity assumes that hydrate-bearing sediments consist of two-phases (*i.e.*, solid grain and pore fluid), as the thermal conductivity of methane hydrate and water differ by <10% (Waite *et al*., 2007). However, the presence of gas phase complicates the heat transfer problems among phases by forming preferential heat paths. The most important thermal properties include (1) specific heat c_p, (2) thermal conductivity λ, (3) thermal diffusivity κ, and (4) the enthalpy of reaction ΔH. The thermal diffusivity, which is a measure of the rate at which a body changes temperature when subjected to an external heat flux, is defined as:

$$\kappa = \frac{\lambda}{\rho c_p} \tag{1}$$

Although the thermal conductivity values of water and methane hydrates are alike, the thermal diffusivity of methane hydrate is twice higher than that of water, due to the low specific heat of the hydrate. This highlights that the accurate estimation of thermal properties of hydrate-bearing sediments has a significant implication in the investigation of the dissociation behavior and the relevant production technologies. The enthalpy of reaction ΔH is
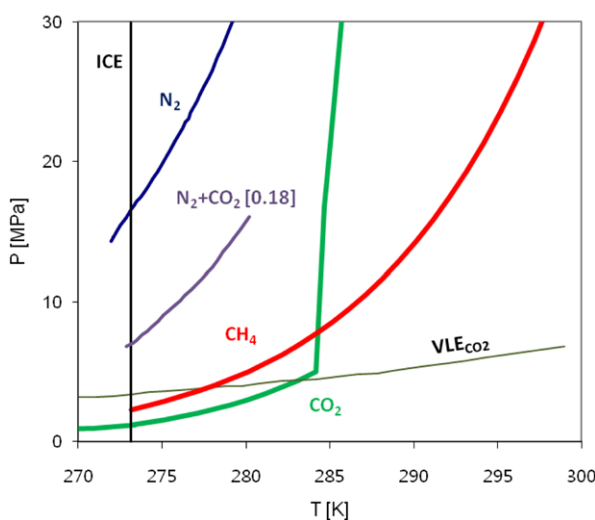

Fig. 2. Phase Equilibrium Conditions of Gas Hydrates (The VLE$_{CO2}$ is the vapor-liquid equilibrium line for CO$_2$ (Kang *et al*., 2001 and Sloan and Koh, 2008).)

defined as the energy change during phase transformation. For instance, the enthalpy of dissociation of structure I methane hydrate (from hydrate to gas and liquid water) is $\Delta H = 52.7$-56.9 kJ/mol at $T \sim 0ºC$, while ΔH increases to 68.7 kJ/mol with replacing 1% of methane in hydrates with ethane (Rydzy *et al*., 2007; Lee *et al*., 2005). Endothermic hydrate dissociation may result in the secondary hydrate or ice formation, which affects the physical properties of hydrate-bearing sediments.

2.2.2 Strength and Deformation

The strength and deformation behaviors of hydrate-bearing sediments are critical for evaluating the stability of sediments and production facilities installed in production sites (Rutqvist and Moridis, 2007). The strength of hydrate-bearing sediment has been investigated in-situ or in controlled laboratory environments so far. The evaluation of the sediment stability should be based on more complex scenarios of gas productions during hydrate dissociation, the associated generation/dissipation of gas and pore fluid pressure, fluid migrations, and temperature changes. Therefore, the coupled analyses of mechanical behavior of hydrate-bearing sediments (e.g., thermo-hydraulic-mechanical-chemical model) need to be further explored to ensure the sediment stability during the production phase.

The soil type, confining pressure, and hydrate saturation mostly determine load-deformation behaviors. In general, the shear strength of hydrate-bearing sediments is obtained from laboratory tests and is assumed to follow the Coulomb's failure criterion. The presence of methane hydrates increases stiffness and dilation effects, leading to higher strengths. For example, experimental results show that the peak strength and dilation increase as the hydrate saturation increases (Musui *et al*., 2006; Hyodo *et al*., 2007). As the evolution of the stress-strain behavior is dominated by the pore-filling nature of hydrate formation, compared with the cementation model, the following mechanisms of strength evolution are proposed depending on the degree of hydrate saturation S_h. More detailed description can be found in Yun *et al*. (2007).

- $S_h < 0.25$-0.4: particle frictional resistance and dilation driven by hydrates on grain surfaces
- $S_h > 0.5$: particle frictional resistance and hydrate cementation/ subsequent shearing of hydrates

The overall mechanical behaviors of hydrate-bearing sediments suggest that both the stiffness and the strength increase along an increase in the hydrate saturation. Also, the initial effective stress becomes irrelevant above a certain hydrate saturation, in which hydrate phase controls the strength and deformation behaviors as discussed above.

2.2.3 Volume Change due to Hydrate Formation and Dissociation

Pore volume expands when hydrate forms due to volumetric differences among phases. The growth of disseminated hydrates in pores causes no significant volume change in sediment under a drained condition and low hydrate saturation. The experimental study with THF hydrate in various types of sediments (sand, silt, and clay) suggests that hydrate formation-induced expansion occurs when the hydrate saturation is higher than about 0.7 and the effective stress is low (Lee *et al*., 2010a). The hydrate dissociation under the zero lateral strain and drained condition causes the sediment contraction regardless of effective stresses sediment types, and hydrate saturations. The volumetric strain is proportional to the compressibility C_c and the hydrate saturation (Lee *et al*., 2009; Lee *et al*., 2010a).

Also, the sediment volume change can occur due to hydrate lenses. Hydrate-induced heave is similar to the frost heave, and the formation of hydrate forces sediment grains apart (Krause, 2001).

2.2.4 Fluid Migration: Permeability

The fluid (e.g., both gas and liquid phases) flow characteristics affect the design of production technology and the corresponding behaviors of the reservoir during hydrate production. Commonly accepted models to describe the fluid flow include Darcy's law and Kozeny-Carman model, while those deal with single phase flow based on porosity. In multi-phase flow simulation, the van Genuchten capillary pressure model and Mulaem porosity distribution function are combindely used (Mulaem, 1976; van Genuchten, 1980). Variables affecting both the permeability and relative permeability in hydrate-bearing sediments include the wettability of fluid and mineral grains, the spatial distribution of hydrates, the existence of gas (e.g., unsaturated condition), the pore-size distribution, and the associated formation of preferential paths of fluid flow. In particular, pore-filling hydrates reduce the permeability more significantly than surface-coating hydrates due to the increased surface area and thus the increased surface friction (Liu and Flemings, 2007). Yet, even the small fraction of hydrates at grain contacts may block the pore throat, which causes sharp reduction in permeability. A detailed discussion on the permeability of hydrate-bearing sediment can be found in Waite *et al*. (2009).

2.2.5 Electromagnetic Properties

The electromagnetic properties of hydrate-bearing sediments are mainly governed by the vertical effective stress, porosities, hydrate saturations, fabrics, the ionic concentration of the pore fluid, and temperatures (Lee *et al*., 2008; Lee *et al.,* 2010b).

The electrical conductivity of the hydrate-bearing sediment is strongly affected by the electrical conductivity of the pore fluid, σ_f, scaled by the volumetric fraction of liquid in pores, $\phi(1 - S_h - S_g)$, where ϕ is the porosity, S_h is the hydrate saturation (the volume of hydrate / the total volume of pores), and S_g is the gas saturation. Note that surface conduction plays an important role in high specific surface sediments, such as marine sediments that generally bear hydrates in ocean environments (Lee *et al*., 2008; Lee *et al*., 2010b). Archie's semi-empirical relationship often explains the electrical conductivity of hydrate-bearing sediments

as a first approximation:

$$\sigma_{sediment} = \frac{\alpha \sigma_f \phi^{\beta}}{(1-S_h-S_g)^{\chi}} \qquad (2)$$

where α, β, and χ are empirically obtainable parameters of which the values are summarized in Waite *et al.* (2009).

The dielectric permittivity in microwave frequency is a good indicator of the free water volume fraction in sediments and is hardly affected by the ionic concentration, the pore structure and the surface conduction (Lee *et al.*, 2010b). Then, the generalization of CRIM model (Sen *et al.*, 1981) for the permittivity of hydrate-bearing sediments becomes (Lee *et al.*, 2010b):

$$\kappa_b' = [(1-\phi)\sqrt{\kappa_m'} + \phi(S_g\sqrt{\kappa_g'} + S_h\sqrt{\kappa_h'} + S_w\sqrt{\kappa_w'})]^2 \qquad (3)$$

In the microwave-frequency range, the permittivity values of the components in hydrate-bearing sediments are $\kappa_w' = 86$ for the water, $\kappa_a' \sim 1$ for the air/gas, $\kappa_{oil}' \sim 3\text{-}5$ for the oil, $\kappa_m' \sim 4\text{-}9$ for the mineral, and $\kappa_h' \sim 2.5$ for the hydrate.

Yet, the accurate estimation of the electrical conductivity in hydrate-bearing sediments, albeit it is important identifying hydrate saturation in the field during the logging, has been challenged due to the pore-scale characteristics, the nature of sediment fabric in fine-grained sediments, and the measurement scales.

2.2.6 Elastic Properties

The elastic properties of hydrate-bearing sediments have been extensively investigated using compressional waves V_p and shear waves V_s at different frequency regimes to explore the occurrences of in-situ hydrates (low frequency, lower than 1 Hz) and to evaluate the small-strain stiffness (high frequency, higher than 10^4 Hz). The wave propagation causes a directional strain with the particle motion and its velocity is controlled by the stiffness of sediments (e.g., the constrained modulus M and the shear modulus G) and the bulk density ρ.

$$V_p = \sqrt{M/\rho} \text{ and } V_s = \sqrt{G/\rho} \qquad (4)$$

The elastic properties of hydrate-bearing sediments are mostly governed by the vertical effective stress, the porosity, the hydrate saturation, the soil fabric and the hydrate formation locus in pores (Lee *et al.*, 2008). The presence of hydrates increases the skeletal stiffness and thus the shear stiffness, particularly when the hydrate saturation is higher than ~0.4. At very high hydrate saturations, the small strain shear stiffness is mostly determined by the hydrate saturation and, in lesser extent, by the effective stress (Lee *et al.*, 2010c). The P-wave velocity increases with the hydrate saturation due to an increase in both the skeletal stiffness and the bulk modulus of sediment mixtures (Lee *et al.,* 2010c).

The relationship between V_p and V_s often further enables estimating the bulk stiffness $K_{\text{sediments}}$ of hydrate-bearing sediments, using Gassmann's equation:

$$K_{sediment} = K_{sk} + \frac{\left(1 - \frac{K_{sk}}{K_m}\right)}{\phi\left(\frac{S_w}{K_w} + \frac{S_g}{K_g} + \frac{S_h}{K_h} + \frac{S_{ice}}{K_{ice}}\right) + \frac{1-\phi}{K_m} - \frac{K_{sk}}{K_m^2}} \qquad (5)$$

where the subscripts *w, g, h, ice, m* and *sk* stand for water, gas, hydrate, ice, mineral and sediment skeleton, respectively. This equation highlights that the presence of free gas reduces the bulk stiffness of sediments. Unlike the bulk stiffness, the shear stiffness is more sensitive to the sediment skeleton and the presence of hydrates in pore space. The pore-filling hydrates hardly affect the shear stiffness by $S_h \sim 0.25\text{-}0.4$ in which hydrates form the load-bearing structure in sediments. On the other hands, the cemented hydrates between grain contacts, even with very small fraction of hydrates, readily takes over the load from the effective stress. A field and laboratory data set compiled for elastic wave propagation is presented in Waite *et al.* (2009).

3. Exploration

Gas hydrate exploration includes geological and geochemical explorations as well as geophysical exploration such as seismic survey and borehole logging (Fig. 3).

3.1 Geophysical Exploration

The most widely used geophysical exploration method is seismic, which can detect regional structures and gas hydrate-bearing regions. A popular seismic indicator of hydrate occurrence is the presence of a Bottom Simulating Reflector (BSR) that is produced by high impedance mismatch between hydrate-bearing formation and free gas-bearing formation underneath the hydrate-bearing region. Gas seepage, vent or chimney structures can be another indicator of potential gas hydrate occurrences. Recently, electromagnetic surveys are also attempted in the gas hydrate explorations, using a big difference in electromagnetic properties of pore water and hydrates in pores. After the regional geophysical survey, well-logging and core analysis are accompanied, and those data are combined with regional survey data to obtain detailed hydrate occurrence characteristics, such as hydrate saturation and occurrence types.

3.2 Geological and Geochemical Exploration

Geochemical exploration is performed by analyzing actual core samples, so it is less cost-effective and more destructive than geophysical. However, geochemical exploration serves an important role in gas hydrate exploration combined with geophysical exploration. Geochemical indicators of gas hydrate occurrence include dissolved gas distribution, gas and organic compound composition in sediments, chlorinity, salinity, and alkalinity of pore fluid, and the isotope compositions of water. These indicators inform us about the origins of natural gases and gas hydrate formation mechanisms. For example, pore fluid freshening of core sample indicates hydrate dissociation and the enrichment of $\delta^{18}O$ indicates the presence of gas hydrates (Tomaru *et al.*, 2007).
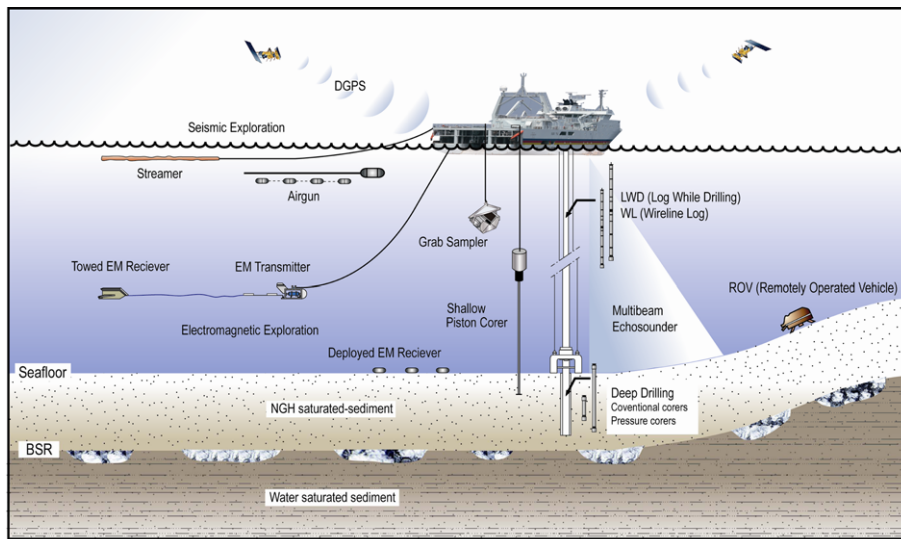
Fig. 3. Schematic Drawing of Gas Hydrate Exploration

3.3 Challenges

Research on determining resource potential involves establishing marine exploration methods to indentify good quality hydrate reservoirs and assessing hydrate recovery rates from physical properties and geological structure of the hydrate reservoir. Although a potential for characterizions of marine hydrate reservoir using seismic indicators have been reported in literatures (e.g. Hornbach *et al.*, 2003; Dai *et al.*, 2004), characterizing based only on seismic survey results is less reliable. The optimal combination of other tools such as electromagnetic survey and geochemical exploration with seismic data should be established for the valid and robust estimation of hydrate reservoir characteristics as a exploration protocol we have for conventional petroleum systems (Boswell *et al.*, 2008). A valid characterization of reservoir also leads to a valid assessment of recovery rates by comparing characterized reservoir to hydrate reservoir classification and/or by the numerical simulation of gas hydrate production in the characterized reservoir setting (Moridis and Collett, 2003).

4. Production

Gas hydrate production requires the dissociation of gas hydrates and the production technologies are categorized according to the dissociation techniques involved.

4.1 Methods

Major gas production methods from gas hydrates include depressurization, thermal stimulation, chemical injection, gas swapping method, and the combination of these (Fig. 4).

The depressurization method dissociates hydrates by lowering pressure below the hydrate equilibrium pressure. The depressurization method is currently regarded as the most promising
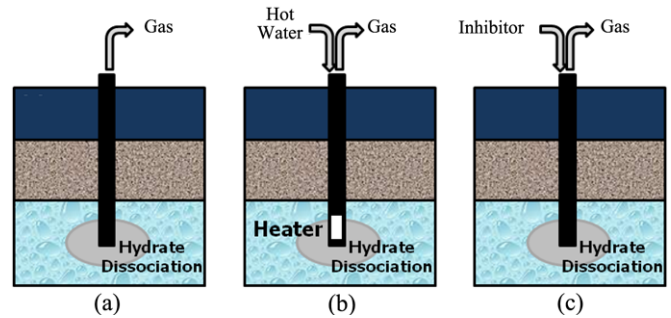

Fig. 4. Gas Hydrate Production Methods: (a) Depressurization, (b) Thermal Stimulation, (3) Inhibitor Injection or Gas Swapping

method among others, but several issues, such as subsidence during the depressurization and hydrate reformation due to endothermic depressurization event, should be solved. Such problems could be mitigated by using combined methods such as the combination of the depressurization and the gas swapping for mitigating the subsidence and the combination of the depressurization and the thermal stimulation for mitigating hydrate reformation.

The thermal stimulation method dissociates hydrates by raising temperature above the hydrate equilibrium temperature. In the thermal stimulation method, the energy that takes in the dissociation and the production should not exceed the energy we can get from produced gases to meet a simple economic principle. The energy needed for the hydrate dissociation is governed by thermal characteristics of the hydrate-bearing region.

The chemical injection method injects inhibitors of gas hydrates to dissociate hydrates in the reservoir. Typical inhibitors used are brine and methanol. The main obstacle of chemical injection method is the low permeability of hydrate-bearing regions, which hinders the diffusion of injected chemicals. Also, retardation of

injected chemicals by fluid mixing hinders the diffusion of injected chemicals.

The gas swapping method injects other guest gas molecules for hydrates into a reservoir. In the injection of guest gas molecules, injected guest gas molecules replace methane in natural gas hydrate and liberate methane to pore fluid. Carbon dioxide gas is mostly used, but sometimes gas mixtures of carbon dioxide and other compounds are injected to promote the guest gas molecule exchange. In bulk hydrates surrounded by gas phases, the swapping efficiency can become more than 60% (Park *et al*., 2008), but the efficiency tends to decrease in sediment due to the lower permeability in sediments and the multi-phase condition. The best swapping efficiency can be obtained by controlling swapping gas injection rate and soaking time. Lower gas injection rate and longer soaking time will produce higher swapping efficiency but will cause higher operation cost. Consequently, optimum combinations should be assessed with field conditions and laboratory tests. The main obstacle of the gas swapping method is also the low permeability of hydrate-bearing regions, which hinders the diffusion of injected gases. Also, additional hydrate formation between injected guest gas molecules and free water phase in pores not only reduce the permeability further but also hinders the delivery of guest gas molecules to the target area.

Gas hydrate reservoirs have been classified according to the geologic setting of the reservoir for the purpose of developing optimal production strategies for each geologic condition (Moridis and Collett, 2003; Moridis and Sloan, 2007). The four classes are depicted in Fig. 5. Class 1-3 has overburden and underburden layers in the geologic setting. Class 1 reservoir consists of a hydrate-bearing layer with underlying free gas zone, class 2 reservoir consists of a hydrate-bearing layer with underlying water zone, and class 3 reservoir consists of one hydrate-bearing layer without underlying free-fluid phase zones. Class 4 reservoir consists of single hydrate-bearing layer. The examples of class 1 reservoir are most of arctic hydrate reservoirs such as Mallik sites in Mackenzie Delta, Cancada, Eileen sites in North Slope, Alaska, USA, and Messoyakha field in West Siberia, Russia. Nankai Trough in offshore Japan and Gulf of Mexico in offshore USA have class 2 and class 3 reservoir. Ulleung Basin, East Sea, Korea is another example of class 2 hydrate reservoir. Class 4
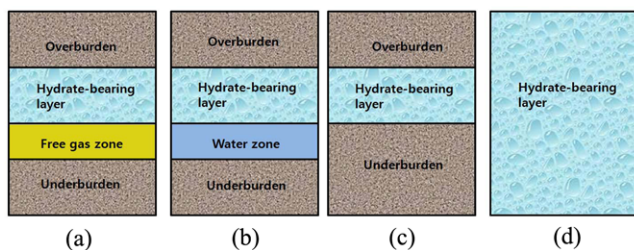

Fig. 5. Classes of Hydrate Reservoir: (a) Class 1, (b) Class 2, (c) Class 3, (d) Class 4 (Concepts from Moridis and Collett 2003 and Moridis and Sloan, 2007)

could be found some of the marine hydrate reservoir.

Class 1 reservoir is considered as the most promising reserve since the underlying free gas zone guarantees gas production and the T/P condition is close to the hydrate equilibrium condition (Moridis *et al*., 2007). In most cases, the depressurization method is the most promising method because it is the most simple and cost effective (Moridis *et al*., 2007). Class 2 is less effective in propagating depressurization front since the underlying free water zone continuously supply a large body of water (Moridis and Kowalsky, 2006). Class 3 reservoir would exhibit even slower propagation of depressurization front due to the absence of free gas or water zone that is more permeable than hydrate-bearing layers and can serve as a conduit for depressurization front (Moridis *et al*. 2007). Class 4 reservoir has been reported as the least effective in depressurization, producing very large amount of water and small amount of gas (Moridis and Sloan, 2007).

In summary, large water body or the existence of adjacent water-rich and permeable layers reduces production efficiencies due to the slower propagation of depressurization front and the large amount of water production. Hydrate reformation due to endothermic event could be mitigated using thermal stimulation locally near wellbore, as stated earlier or utilizing the deep source of thermal energy below the reservoir. Thermal stimulation in large area is less effective than depressurization since thermal diffusion is slower than pressure diffusion (Demirbas, 2010 and Moridis and Reagan, 2007). The chemical injection is not efficient in water-rich reservoir such as class 2 and class 4 because the dilution of chemicals into free water reduces the deliverability of chemicals into target zone.

4.2 Challenges

The development and the production of natural gas from hydrates may pose many critical challenges such as assessing hydrate recovery rates from physical properties and geological structure of the hydrate reservoir, securing the economic viability of produced gas from a particular resource, locating potential resources, quantifying hydrate content, keeping process safe from geomechanical impacts from hydrate dissociation, and transporting the extracted natural gas to the market.

Gas production methods from gas hydrates significantly deviate from the conventional gas production since the gas hydrate production involves phase transformations from solid phase to gas and liquid phases. These phase changes produce following uncertainties during production processes; (1) changes in stress conditions due to pore pressure changes during phase transition, (2) permeability changes due to vanishing hydrates and subsequent settlements, (3) sediment softening and volume contraction due to loss of hydrate bonding, and (4) vanishing of the segregated hydrate volume in lenses and nodules. These uncertainties are mostly related safety issues during production which should not be ignored during establishing production strategies.

5. Conclusions

In the research field of hydrate as a potential energy resource, production technology is closely related to geotechnical engineering. Thermal conduction characteristics govern 1) heat front diffusion in the thermal stimulation method; 2) the moving front of gas hydrate stability zone invoked by the any stimulation for hydrate dissociation; and 3) hydrate dissociation rate. Fluid migration characteristics govern 1) depressurization front diffusion in the depressurization method; 2) gas production rate; and 3) the dissipation of excess pore water pressures due to hydrate dissociation. Strength and deformation characteristics govern deformation behavior during gas production, such as integrity of formation and well bore stability.

Establishing safe and efficient gas production technology requires extensive information on geotechnical characteristics of a hydrate reservoir. Flow assurance, integrity of formation and well bore stability are crucial issues to be addressed for the safe and efficient production of gases from gas hydrates in sediments. Strength and deformation characteristics, fluid migration characteristics, and thermal conduction characteristics are key factors for controlling the above issues. Among these issues, the better propagation of the stimulation front and the prediction and mitigation of settlement of strata due to hydrate production are the most crucial issues. Arctic hydrate reservoirs have advantages for favorable geologic setting (mostly class 1 reservoir) and easy accessibility to developers and consumers while marine hydrate reservoirs are mostly less favorable geologic setting (mostly class 2-4), suffer from large water production and have disadvantageous accessibility to developers and consumers. Many numerical simulators (*e.g.*, CMG. Ltd., 2007; Kurihara, 2005; Moridis *et al.,* 2008; Phale *et al.*, 2006) have attempted various strategies to obtain the optimum strategies that can overcome these issues as discussed in section 4. Experimental studies have also explored these issues. However, none of them have produced very successful strategies for these issues, necessitating extensive and comprehensive further studies.

Acknowledgements

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