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Original article

An analysis of the key safety technologies for natural gas hydrate exploitation

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Abstract: Natural Gas Hydrate (NGH) is a high combustion efficiency clean energy and its reserve is twice as that of natural gas and petroleum, so NGH is the potential resource which could overcome the increasing energy assumption. One of the essential aspects during the exploitation of NGH is to avoid risk, and here in this work, we summarized the relevant management experience to study the critical safety risk in the exploitation of natural gas hydrate. The problems that must be resolved during NGH exploitation were identified through the research on the comparison of the characteristics of conventional gas hydrate mining methods and potential drilling engineering risks and stratum damages in the processes of exploitation. Combined with typical case analysis of gas hydrate mining, it is concluded that the key for safe NGH exploitation is the changes of stratum stress caused by hydrate decomposition; and all safety management experiences should be based on steady drilling and reasonable exploitation to prevent environment, equipment, persons and other aspects damages from layering and stress changes.

Keywords: Natural gas hydrate, exploitation, stratum damage, CO_2 emulsion replacement.

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1. Introduction

Sediment of NGH are widely distributed in the environment of terrestrial frozen soil and deep water formation environment, such as ocean, lake and so on, which contains 80% $\sim$ 99.9% methane. The reserve of NGH is more than two times of the current known fossil fuels (Collett, 2002), whats more, NGH is much cleaner compared with conventional fossil fuels in term of combustion efficiency. The conventional NGH development methods included the thermal decomposition methods, the pressure reduction method and the chemical treatment method, and currently most of the researches on hydrate exploitation are still limited in laboratory experiments (Dai et al., 2005; Wood and Mokhatab, 2008; Mimachi et al., 2015). However, the thermal decomposition method needs consume a large amount of heat and ensure continuous and fine heat supply; depressurization always needs monitor and control the complex pressure changes in the pit, which is closely related with heat supply (Turton and Barreto, 2006). Every method is complex and has many uncontrollable factors. In geology, the submarine slope, irregular strata, faults and unstable sedimentary deposits are the conditions of the disaster (Yang et al., 2007; Chong et al., 2016).

Currently, the only representative field test is the Marek 2L-38 well project in northern Canada, which began in 1998, which showed that: the underground conditions of the hydrate exploitation are complex and the safety risk is high. It is necessary to sum up safety management experience, improve exploitation technology, improve production safety, and propose the natural gas hydrate exploitation scheme with the characteristics of well factory (Englezos, 2005; Li et al., 2008; Che et al., 2010).

2. Gas hydrate reservoir characterization

NGH is an organic genetic gas, and its accumulation depends on temperature, pressure, gas composition, saturation and pore water composition and other factors (Long et al., 2009; Xiao and Tan, 2011). Theoretically, the formation of hydrate deposits should be controlled by high pressure and low temperature, abundant gas source, migration channel and water source and so on (Li et al., 2012). As is shown in Figure

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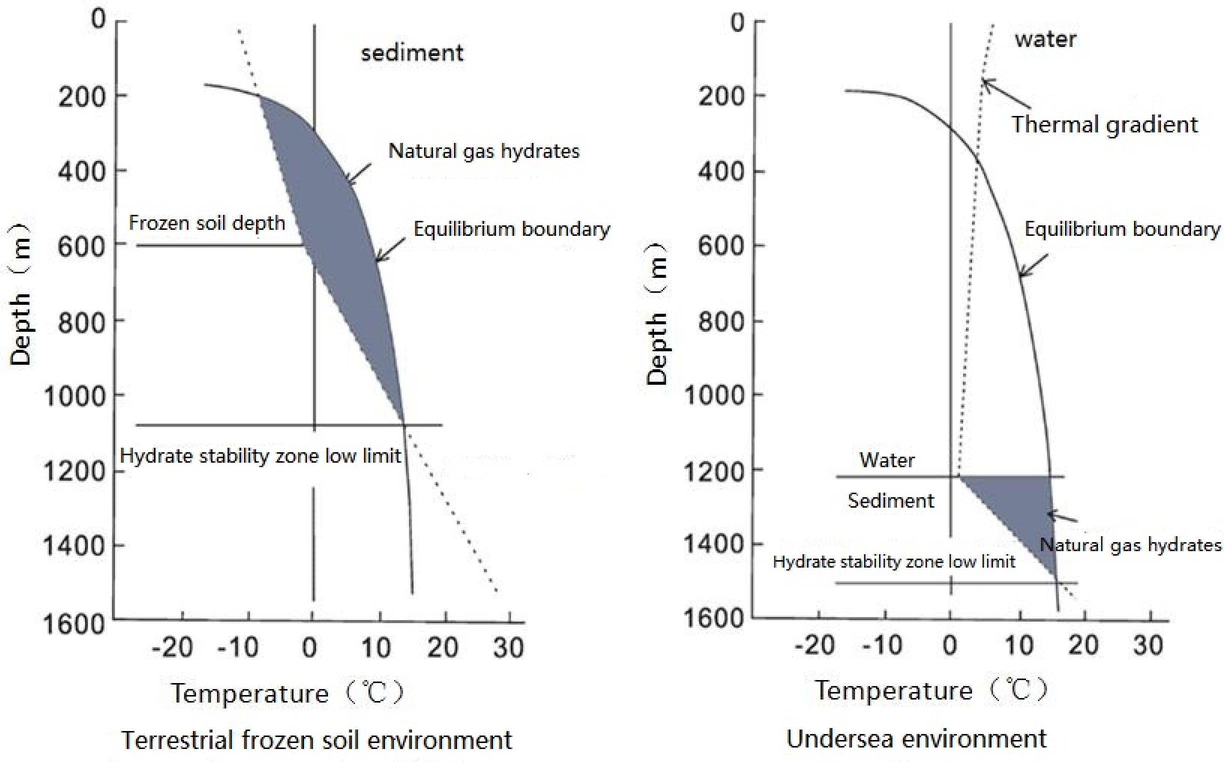

Fig. 1. Phase diagram of gas hydrate (Li et al., 2012).

Table 1. Formation types of gas hydrate.

Type	Structure	Characteristic	Proportion (%)
1	strata containing gas hydrate, strata gas bearing and cover impermeable coating	In the critical phase equilibrium state at the bottom of the formation of hydrate is easy to decompose, commercial exploitation value	14
2	strata containing gas hydrate, aquifer water-bearing stratum and cover impermeable coating	With high hydrate layer permeability and hydrate space scattered distribution	5
3	strata containing gas hydrate and cover impermeable coating	With high hydrate layer permeability and the hydrate saturation is higher	6
4	strata containing gas hydrate and cover impermeable coating	With low hydrate layer permeability and hydrate space scattered distribution, saturation is lower than 10%	75

1, hydrate stability zone were.

Geological structure and sedimentation have significant impact on the formation and preservation of natural gas hydrate. In different geological history, multiple kinetic responses may happen (Li, 2010; Johnston, 2012; Max and Johnson, 2014). Climate change, new tectonic movement, deposition, geothermal gradient, sea level change and other factors could alternate the conditions of gas hydrate reservoirs, which can also affect the stability of natural gas hydrate system. So most of the NGH reservoirs are not continuous distributed in neither vertical nor horizontal direction, and thus being obstacles for exploration and development (Cao and Bluth, 2013; Hk et al., 2010).

Based on the content of gas hydrates, stratigraphic trap, sediment type structure and other properties of the hydrate formation, the NGH reservoirs could be divided into four categories (see table 1).

3. Traditional mining methods

Change the external conditions and destroy the phase equilibrium in the reservoir, natural gas hydrate will dissociate. Exploration methods (see table 2) of conventional gas hydrate are based on the presence of hydrate in a particular phase equilibrium condition (Bouffaron and Perrigault, 2013; Feng et al., 2014).

4. Project risk−the deep water drilling

Natural gas hydrate exists in 200 ∼1500 m deep water sediments, existing in pore filling or sediment grain cementation. It is easy to form overpressure formation and increase engi-

Table 2. Natural gas hydrate exploitation methods.

Method	principle	Technology	Advantages	Shortcomings
Heating	Temperature more than balance, gas hydrates decomposition	Injection of hot fluid, fire, flooding, downhole electromagnetic, and microwave, etc.	Can recycling, fast effect	Efficiency is low, only local heating
Depressuring methods	Reduce the pressure to the critical value of gas hydrate decomposition	With low density drilling decompression	Don't need a continuous trigger, low cost, suitable for large-scale mining	Temperature limitations, located in the pressure balance boundary
Inhibitors	Injection of chemicals, such as salt water, methanol, ethanol, etc., destroy the balance, gas hydrates decomposition	To establish drug injection station, intermittent injection	Can reduce the initial energy input	Cost is expensive, slow, pollute the environment

Table 3. Hydrate drilling project risks.

Accident	Consequence	Cause
Block pipeline, kill line	Pipeline pressure-out affect production	Gather temperature-pressure field changes in hydrate
Block subsea blowout preventer	Well control problems	Gather temperature-pressure field changes in hydrate
Destroy the guide base and subsea production equipment	Drilling rig equipment damage	cold work
Deep thermal fluid into the shallow hydrate formation	Decomposition to kick or lost circulation	Drilling interzone
Decomposition result in borehole wall instability	Hole enlargement, casing deformation, flattening, wellhead wellhead settlement, even wall collapsed	The drilling result in hydrate decomposition is out of control
Hydrate change drilling fluid wall-building properties	Cause blowout and sidewall instability	Reduce annulus pressure decomposition

neering risk. The formation temperature and pressure changes or changes in the external environment caused by the drilling process will greatly influence the hydrate decomposition and increase the engineering risk (Jackson, 2014; Dong, 2015). A list of risks during drilling are listed in table 3.

5. Geological risk−formation damage

Layered destruction of formation caused by thermal decomposition of hydrate is a relevant new finding, which is now in the test and demonstration stage. Conventional gas hydrate extraction takes the hydrate into the ground after its decomposition (Steele and Heinzel, 2001). And a great deal of water from decomposition will reduce the degree of particle cementation and loosen the stratum of the mining area. The situation will become even more complicated if the formation is water sensitive. Thermal decomposition at the same time causes liberation of gas in the formation and increases the controllability (Johansen et al., 2003; He, 2004). Pore static pressure of formation will also increase (Kumar, 2006), eventually leading to the strength reduction of hydrate layer, which can cause different types of formation damage: large deformation of hydrate formation and overlying strata, the sinking of the well, the destruction of the structure (platform, wellbore and pipeline) in the overlying strata, landslide and collapse and so on (Tan and Cao, 2006; Hua and Xiong, 2007; Balat, 2010). In thermal decomposition mining, thermal expansion increases the damage effects. According to records, the Norwegian continental shelf margin due to hydrate decomposition occurred submarine landslide, lost 2500∼3200 cubic kilometers of sediment, which was found to be the largest submarine landslide (Sorensen and Terneus, 2008; Odumugbo, 2010).

According to research by Yun et al. (2012), the pressure of the gas produced by the decomposition can be released faster if the permeability of formation layer is larger. But with the development of the decomposition, the cohesive force of the stratum decreases, and it is prone to subsidence and even collapse. When the permeability of the local layer is lower, the decomposition will result in a high pressure zone. When the decomposition proceeds to a certain extent, the fluid in the hydrate formation approaches liquefaction and even gasification (Ma et al., 2012). Stratification occurs when the gas pressure is equal to the overlying layer gravity. When the gas pressure exceeds all the resistance, it can occur the eruption, cracking and other destruction phenomena of formation, especially in the bedding, sediment disturbance (Jiang, 2008; Wang et al., 2014). Therefore, the stability of stratum is the precondition of successful mining.

6. Mining advice − CO_2 emulsion displacement

Replacement of CH_4 in hydrate with CO_2 is one of possible ways to resolve the current climate change resulted from CO_2. The key is to increase the replacement rate and strengthen the replacement power. The exchange of reaction molecules and the change of energy are:

$$CO_2 + CH_4 * nH_2O = CH_4 + CO_2 * nH_2O + Q$$

where $n \geq 5.75$, and heat Q is 3.49 KJ/mol, which is an exothermic reaction process.

According to Zhou and Fan (Li and Xia, 2013), the reactions of two regions of A and B were studied respectively. As is shown in Figure 3, CO_2 hydrate is stable and CH_4 hydrate is unstable in region A. The replacement rate of hydrate CH_4 with liquid CO_2 by 24 96 hours is only 8.1% 18.6%. The 90:10, 70:30, 50:50 (WCO_2/ WH_2O) CO_2 emulsions were replaced at the same time, and the replacement rates respectively were 13.1%~27.1%, 14.1%~25.5% and 14.6%~24.3%. Under the same conditions, the replacement rate of CO_2 emulsions was higher (Fig. 4). CO_2 emulsions are highly effective and feasible. The higher the contents of CO_2 emulsion are, the higher the CH_4 is.

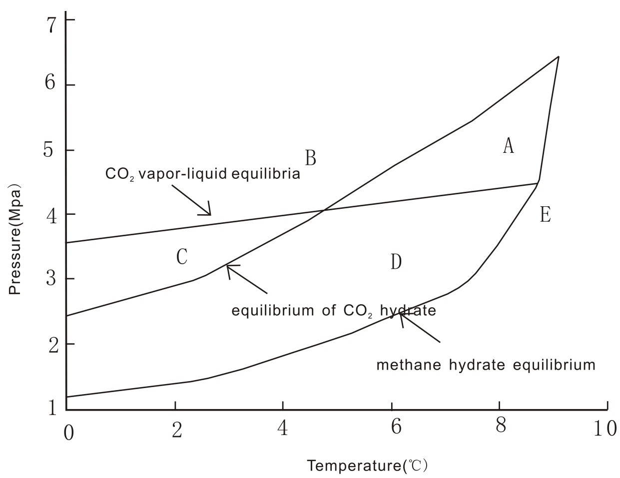

Fig. 2. Temperature and pressure curves of CO_2 emulsion with CH_4 (Li and Xia, 2013).

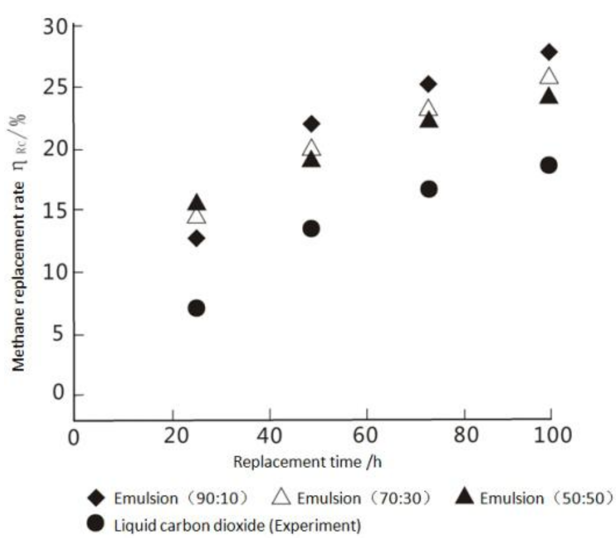

Fig. 3. The relationship between the CH_4 substitution rate and the replacement time of four kinds of CO_2 forms (Li and Xia, 2013).

CO_2 emulsion displacement technology not only produce heat itself, economically and environmental friendly (Menon, 2014), but also prevent formation damage effectively and induce hydrate orderly decomposition in a controlled manner. So the project is low risk and high feasibility.

7. Conclusions

It is of great risk to develop NGH, which is the potential resource to overcome the energy supply in the future. In this work, we summarized existing risks in the exploitation of NGH, and based on our review, the detailed conclusions are:

- Any conventional gas hydrate extraction scheme has its own disadvantages, for example, its recovery ratio is too low and the risks of safety control are high. The use of depressurization will cause cooling and lead to auto-lock of hydrate decomposition. Thermal decomposition exploitation may lead to transition or deficiency of hydrate decomposition due to non-uniform heating, low thermal efficiency, or excessive heat dissipation, which will cause blowout in severe cases. The costs of chemical injection are high, the environmental pollutions are great, and may result in amount of follow-up problems.
- The key safety management of natural gas hydrate exploitation lies in the combination of engineering and geology. Engineering, mainly prevent blowout, well collapse from stress changes and equipment damages and casualties caused by freezing plug. Geological aspects, mainly prevent the landslide, collapse from formation damage.
- The most feasible safety management of gas hydrate exploitation is the use of CO_2 emulsion replacement and combined with mature mining technology to completely solve problems of low heat efficiency, heat dissipation and so on. At the same time, it can supply formation energy and prevent formation damage from exploitation.

Acknowledgments

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