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Communication

Using Submarine Heat Pumps for Efficient Gas Production from Seabed Hydrate Reservoirs

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Abstract: This article reports our novel idea about the thermal stimulation of seabed hydrate reservoirs for the purpose of natural gas production. Our idea is to use submarine heat pumps, which are to be placed near the hydrate reservoir and work to recover thermal energy from the surrounding seawater and supply it into the reservoir. Although the heat pumps need an electricity supply from the sea surface level, they can provide thermal energy which is several times that of the consumed electricity in quantity. As a consequence, the use of submarine heat pumps has a distinct thermodynamic advantage over other thermal stimulation techniques already proposed in the literature.

Keywords: gas hydrate; methane hydrate; heat pump; energy; fuel

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1. Introduction

Because of the huge amount of natural gas fixed in offshore hydrate reservoirs mainly distributed over continental margins, extensive efforts have been devoted to exploring technical scenarios for recovering natural gas from such reservoirs. This article presents a new technical idea about the thermal stimulation of these reservoirs, which potentially enables continuous gas production from each reservoir at the cost of a lower energy consumption rate than other already proposed thermal-stimulation methods.

Depressurizing the wells drilled into a reservoir is now considered to be the most economical means for dissociating the hydrates in the reservoir and thereby collecting the released natural gas. Many simulation studies have been reported on the gas production by means of depressurization (see, for example, [1–5]). Thermal stimulation of the reservoir by injecting hot water or steam into the wells, which may or may not be combined with the depressurization, is also expected to be effective for promoting the hydrate dissociation and gas production, while preventing the reservoir from being overly cooled and partially frozen [4,6–12]. However, there has been little discussion in the literature about how hot water or steam can be conveyed to the depth of a hydrate reservoir typically 500–1200 m below sea level. Pumping hot water from an FPSO (Floating Production, Storage and Offloading system) to the reservoir [13] is not practical; a substantial proportion of the thermal energy initially given to the water by gas-fired boilers installed on the FPSO will be lost during its flow to the depth of the reservoir.

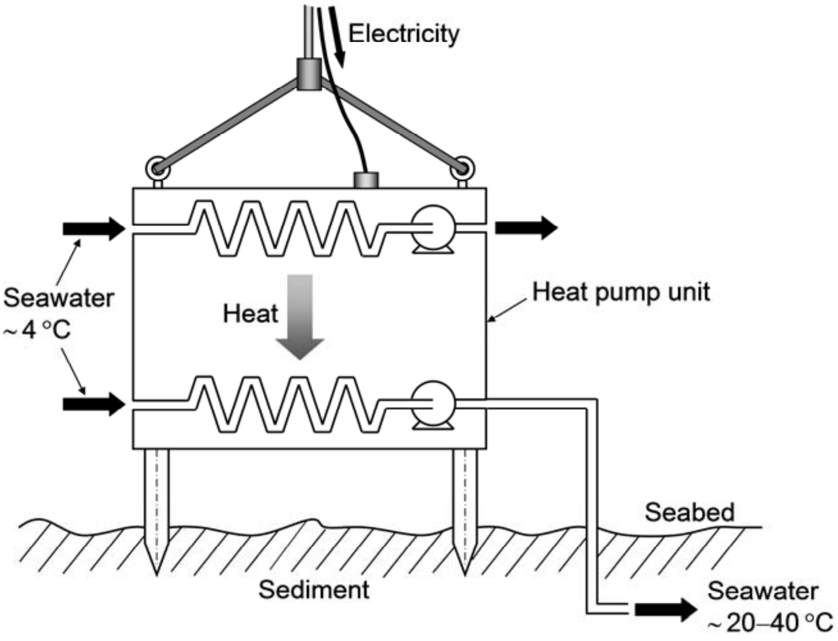
Basniev and Nifantov [14] proposed constructing a closed water circulation loop connecting a hydrate reservoir and a deeper layer in the seabed sediments such that water geothermally heated in the deeper layer may continuously be pumped to the hydrate reservoir, resulting in the dissociation of the hydrates. Almost the same idea was proposed in a simulation study by Phirani *et al*. [15]. However, it is not clear if the construction of such a water-circulation loop below the seabed close to the hydrate reservoir is technically feasible.

Thermal stimulation techniques other than the hot-water or steam injection ones have been proposed in the literature; they are, for example, *in-situ* natural-gas combustion in a horizontal borehole drilled within hydrate-bearing sand [16], microwave heating [17–20] and chemical laser heating [21]. These alternative thermal-stimulation techniques are advantageous as compared to the hot-water or steam injection technique since they can generate thermal energy at the location of hydrate dissociation without suffering from the problem of heat loss from the long energy transmission line that extends from the sea surface to the seabed. We should note, however, that all of these techniques are thermodynamically inefficient in that they inevitably consume high-quality (high-exergy) energy (thermal energy at a temperature of ~2000 K generated by natural-gas combustion or electricity) only for compensating the loss of thermal energy in the hydrate reservoirs due to hydrate dissociation, which is equivalent in quantity but much lower in quality (exergy) compared to the energy that is supplied to the reservoirs. In other words, hydrate dissociation systems based on any of the alternative thermal-stimulation techniques proposed so far must inevitably be of very low exergetic efficiencies.

2. Conceptual Description of Submarine Heat-Pump Technique

In this communication, we propose to utilize submarine heat pumps to recover thermal energy from the seawater around the reservoir and to release the energy to the seawater being injected into each well drilled into the reservoir (see Figure 1). The heat pumps may be of a conventional vapor-compression type or of a novel hydrate-formation/dissociation type [22] in which a mixture of a hydrate-guest gas, a hydrate-guest liquid and water serves as the working medium. This idea of using heat pumps came from our understanding that the critical dissociation temperature of methane hydrates at pressures corresponding to the 500–1200 m depth is no more than ~6–15 °C and hence the hydrates should easily be dissociated by contact with water at temperatures of around 20 °C. In other words, what we need to convey to the reservoir for gas production is not a high-quality thermal energy, but a huge amount of low-quality thermal energy. The heat pumps may be suspended from an FPSO to a depth a few meters above the seabed, or they may be mounted on scaffolds standing on the seabed.

Figure 1. Schematic illustration of a submarine heat pump placed on the seabed above a hydrate reservoir.



3. Discussion and Summary

Although any vapor-compression-type or hydrate-formation/dissociation-type heat pump requires electricity for driving a compressor, which must be transmitted from the FPSO via a submarine cable, the rate of energy supply to the reservoir could be multiplied by several times the consumed electric power. The factor of energy multiplication, *i.e.*, the coefficient of performance (COP) of the heat pump, ε, is dependent on two temperatures—T_1, the temperature of the surrounding seawater from which heat is taken into the heat pump, and T_2, the temperature at which the heat pump discharges heat to the seawater being pumped to a well drilled into the hydrate reservoir. Assuming T_1 to be 4 °C, we illustrate the dependence of ε on T_2 in Figure 2, in which ζ, the second-law heat-pump efficiency defined as the ratio of ε to the COP of a Carnot heat pump [$= T_2/(T_2 - T_1)$] (see, for example, [23]), is specified as a parameter. Currently, ζ available with advanced large-capacity heat pumps of the vapor-compression type achieves 0.5–0.7 [24]. Therefore, we can expect ε to be 9.2–12.9 when $T_2 = 20$ °C, and 4.3–6.1 when $T_2 = 40$ °C.

The electricity for driving the heat pumps may be generated using gas-engine-driven generators installed on the FPSO. Advanced medium-sized (3.6–5.8 MW class) Miller-cycle gas engines recently developed for use in co-generation systems can provide η_e, the electric-power generation efficiency, that exceeds 0.4 [25,26]. Taking a slight loss of electricity during its transmission to the submarine heat pumps into account, it is reasonable to assume η_e*, the power generation efficiency evaluated at the heat pumps, to be 0.4. Based on this assumption, we can estimate the overall energy-conversion efficiency η_{ov}, *i.e.*, the ratio of the rate of thermal-energy output from the heat pumps to the rate of heat release by fuel-gas combustion in the gas engines on the FPSO, as the product of η_e* and ε, which is 3.7–5.1 when T_2 = 20 °C and 1.7–2.4 when T_2 = 40 °C (see Figure 3). In contrast, η_{ov} available with the direct hydraulic supply of hot water (or steam) generated on the FPSO to the hydrate reservoir never exceeds unity, even if the 500–1200-m-long water-supply pipe is perfectly insulated, and is very likely much less than unity in practice due to the heat loss from the pipe. The magnitude of η_{ov} available with the microwave or chemical-laser heating technique is inevitably limited by η_e, the electric-power generation efficiency of the gas-engine- or diesel-engine-driven generators on the FPSO, and may not be higher than 0.4.

Figure 2. COP of a heat pump extracting heat at T_1 = 4 °C and releasing heat at T_2. ζ denotes the ratio of ε, the COP of an actual heat pump, to the COP of an idealized Carnot heat pump.

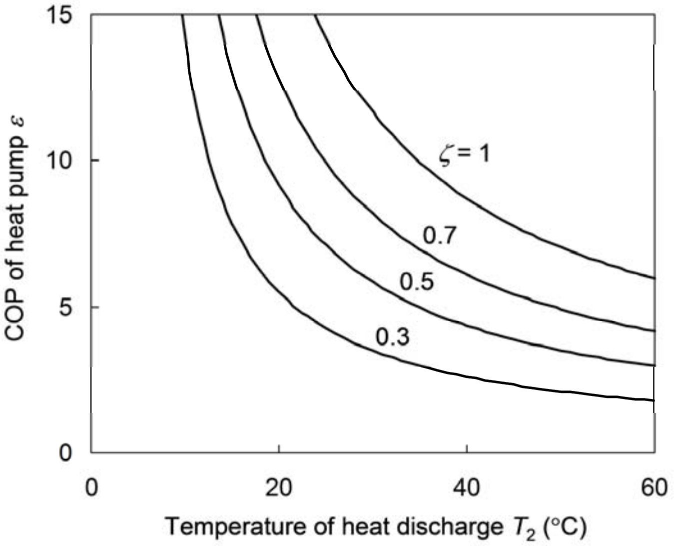
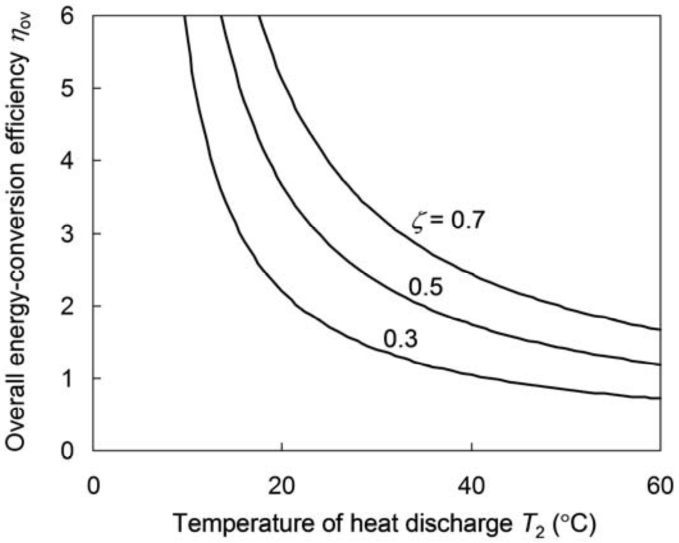


Figure 3. Dependence on the temperature of heat release from the submarine heat pumps, T_2, of the overall energy-conversion efficiency η_{ov}, *i.e.*, the ratio of the heat-release rate from the heat pumps to the rate of heat release by fuel-gas combustion in the gas engines for electric-power generation.



From the viewpoint of classical thermodynamics (particularly, the second law of thermodynamics) and heat-transfer engineering, we cannot be positive about any of the hydrate-reservoir thermal-stimulation techniques proposed so far. Obviously, the submarine heat-pump technique presented in this communication has a thermodynamic advantage over the other rival techniques. Thus, we can conclude that the submarine heat-pump technique should be seriously considered for the purpose of establishing an actual effective technology for gas production from seabed hydrate reservoirs.

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