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Analysis of depressurization mode on gas recovery from methane hydrate deposits and the concomitant ice generation☆

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HIGHLIGHTS

- Natural gas is recovered from hydrate deposits using different depressurization modes.
- The phenomenon of concomitant ice generation is observed using magnetic resonance imaging (MRI) visualization.
- The spatial-decomposition characteristic dominated by pressure drop is confirmed.
- The radial-decomposition characteristic dominated by ambient heat transfer is determined.
- The problem of ice generation is effectively eliminated by controlling the gas production pressure.

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ABSTRACT

Natural gas hydrates have garnered worldwide attention as an important potential non-conventional fossil fuel resource. When extracting natural gas from gas hydrate deposits via depressurization, problematic ice generation and hydrate reformation can occur under conditions of fast depressurizing and low production pressures, due to insufficient heat transfer in the surrounding sediments. In this work we conduct *in situ* magnetic resonance imaging (MRI) visualization and analysis of hydrate decomposition behavior for different depressurization modes; we visually determine the volumetric and spatial characteristics of the hydrate decomposition during depressurization induced gas production operation. Our results indicate that fast depressurization rate can result in a fast hydrate decomposition rate, therefore, a rapid gas production rate. In addition, the radial extension behavior of the decomposition front confirms that ambient heat transfer is a critical factor driving hydrate decomposition into free gas and liquid water. Obvious hydrate reformation and ice generation phenomenon, seen in some of the sudden depressurization experiments, can be effectively avoided using piecewise and continuous depressurization methods. The findings of this study clearly demonstrate how production pressures affect the gas production behavior from hydrate deposits and provide further insight for establishing optimal production techniques for utilizing hydrate resources in the field.

1. Introduction

Natural gas hydrates are solid crystalline compounds, wherein natural gas molecules are engaged into water cavities which are composed of hydrogen-bonded water molecules under high pressure and low temperature coexisting conditions [1,2]. Typically, the natural gas molecules include methane, ethane, propane, and carbon dioxide, they are all important contributors in the global carbon cycle [3,4]. A vast amount of natural gas hydrates with high energy density are known to be buried in permafrost regions and in sediments beneath the sea [5,6]. The total amount of natural gas trapped in these hydrate deposits could surpass the amount of available and recoverable conventional methane by two orders of magnitude [7]. Thus, natural gas hydrates have come to be regarded as an important potential global resource for natural gas recovery [8], attracting worldwide attention [9–11]. However, bringing such non-producible unconventional natural gas resource into a producible energy resource has been proven to be extremely challenging because of the severe and special existing environment of the hydrate deposits [12,13]. So far, three primary methods for gas recovery from such hydrate deposits have been proposed: (a) the depressurization

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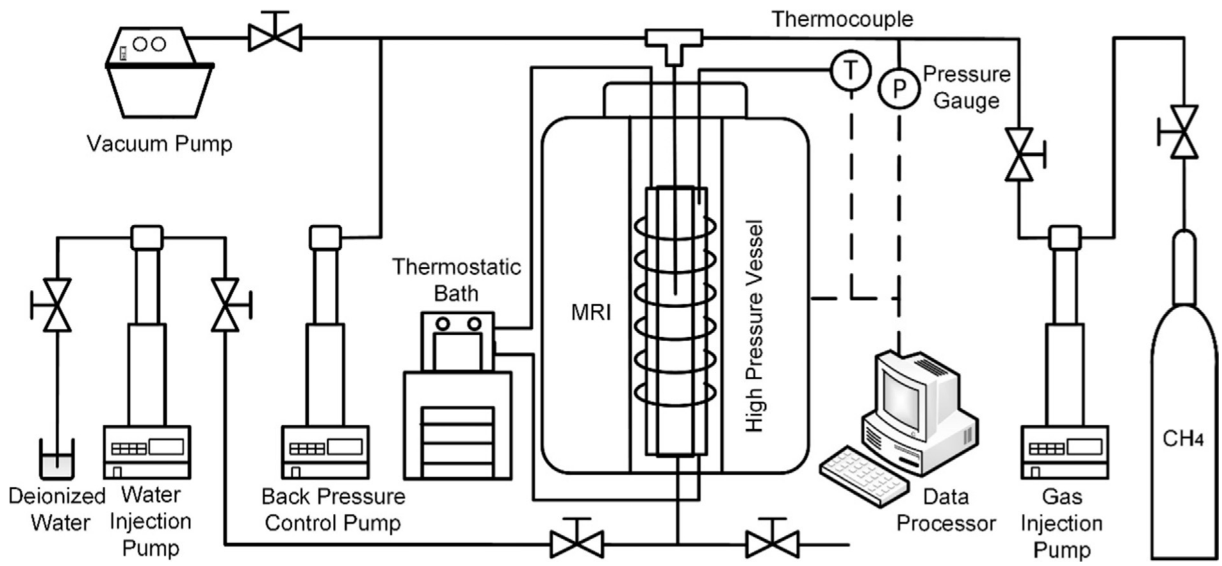

Fig. 1. Schematic diagram of the experimental apparatus.

Table 1
Experimental parameters and initial conditions.[a]

Exp. No.	P_d (MPa)	D_i (MPa)	D_r (MPa/min)	P_i (MPa)	S_{hi} (%)	S_{wi} (%)
1	2.60	–	–	3.30	28.41	10.33
2	2.40	–	–	3.24	28.28	5.41
3	2.20	–	–	3.24	27.26	9.57
4	2.00	–	–	3.28	31.93	7.23
5	2.00	0.10	–	3.28	28.73	16.11
6	2.00	0.20	–	3.28	23.03	17.13
7	2.00	–	0.01	3.24	26.05	8.12
8	2.00	–	0.012	3.21	27.57	5.35
9	2.00	–	0.015	3.18	26.52	8.50
10	2.00	–	0.02	3.29	27.66	11.08
11	2.60	–	0.03	3.36	25.66	7.73
12	1.60	–	0.03	3.35	22.08	12.13
13	0.60	–	0.03	3.32	18.74	15.83

[a] The symbols in this table are defined as follows: P_d is the designed backpressure for hydrate decomposition (MPa); D_i is the pressure drop interval (MPa) for the experiments with piecewise pressure reduction; D_r is pressure drop rate (MPa/min) for experiments with continuous pressure reduction; P_i is the initial pressure for hydrate decomposition (MPa); S_{hi} is the initial hydrate saturation before hydrate decomposition (volume fraction,%); S_{wi} is the initial water saturation before hydrate decomposition (volume fraction, %). All experiments were carried out at 274.15 K.

method, which should decrease the reservoir pressure below the local hydrate stable pressure [14,15], (b) the thermal stimulation method, which requires raising the reservoir temperature above the local hydrate stable temperature [16,17], and (c) the chemical inhibitor injection method, which should inject chemicals into the reservoir to shift the local hydrate stability boundary into a more rigorous condition (higher pressure or lower temperature) [18]. Given the feasibility of the current technological and economic constraints, depressurization is considered to be the most effective method for gas recovery from hydrate deposits [19–21].

When recovering natural gas from these gas hydrate deposits, the solid gas hydrate dissociated into liquid water and free gas which can impact the gas production efficiency, skeleton structure features and reservoir stability [22,23]. Thus, studying the hydrate decomposition characteristics can provide some guidance for designing an applicable gas recovery method from hydrate deposits [24]. The process of methane hydrate decomposition involves heat transfer, gas-water flow, and hydrate decomposition kinetics. Numerous experimental and numerical researches have been undertaken to investigate the hydrate decomposition characteristics induced by depressurization [25–27].

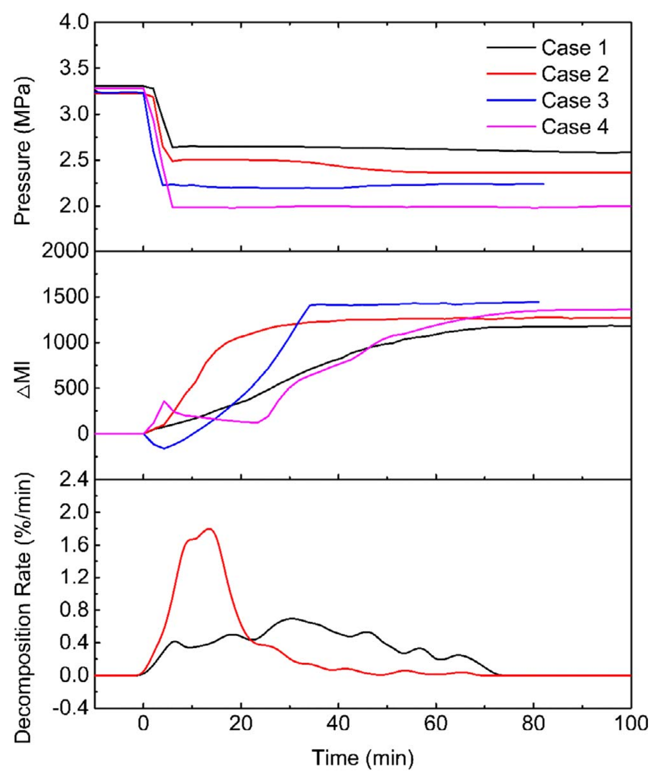

Fig. 2. Vessel pressure (top panel) and MI variation (middle panel) vs. time during the hydrate decomposition process for the sudden depressurization experiments (Cases 1–4). The bottom panel shows the decomposition rates for Cases 1 and 2 calculated using Eq. (2).

Gas recovery from hydrate deposits has been divided into three main stages: free gas liberation, a combination of free gas and hydrate dissociated gas (hydrate decomposition mainly sustained by the reservoir's sensible heat) co-production, and single hydrate dissociated gas (hydrate decomposition mainly sustained by ambient heat transfer) production [28–30]. Although a decrease in the reservoir pressure to values below the hydrate phase equilibrium pressure can cause solid hydrate to decompose into free gas and liquid water [31]. The intensive hydrate dissociation reaction will consume a significant amount of sensible heat in the reservoir when the pressure drop is large [32]. If the

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