SHORT COMMUNICATION

Potential applications of distributed optical fiber sensor in hydrate-induced sedimentary deformation research

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Abstract
Natural gas hydrate is regarded as a potential clean energy source. However, hydrate phase transition during gas production leads to significant hydrate-bearing sedimentary layer deformation, which is one of the main obstacles for safe hydrate exploitation. In this study, distributed optical fiber sensors were used to examine the porous medium deformation induced by phase change and verify its feasibility for application in hydrate research. Experiments on ice formation in a porous medium were conducted to mimic the hydrate formation in sediments. Optical fiber sensors were used to record and analyze the strain characteristics caused by the deformation of porous medium during the phase change process. The frequency shift during the cooling process shows that the fiber segment sensitivity is influenced by its initial length and tightness. In experiments with porous medium, the strain caused by the phase change exhibited a linear trend. In a comparative experiment using pure water, the strain caused by the phase change showed a nonlinear trend. The results indicate that the porous medium deformation induced by phase change can be accurately evaluated using strain data from distributed optical fiber sensors. The strain results also reflect the rate of the phase change. This study proves that the distributed optical fiber sensor has the potential to clarify the deformation characteristics of porous medium caused by hydrate phase change.

KEYWORDS
distributed fiber sensor, gas hydrate, strain
1 | INTRODUCTION

Gas hydrates are insertion compounds formed when water and light hydrocarbons interact. With their ice-like structure, methane hydrate consists of methane trapped within a cage structure composed of water molecules under low temperature and relatively high-pressure conditions. Methane hydrate, which is mostly found in the seabed or permafrost, is the main components of natural gas hydrates. It is considered as a potentially good source of clean energy. The total amount of carbon in hydrates is estimated to be twice that of all conventional resources, including coal, oil, and natural gas. The most common methods used to decompose hydrates into water and free gas include thermal stimulation, depressurization, inhibitor injection, and CO\textsubscript{2}-CH\textsubscript{4} replacement. Natural gas hydrate exists in the pore spaces and can be located within the sediment structure as a cement, coating, or interstitial occupant. Hydrate dissociation can weaken the sediments and decrease the layer strength, which can endanger seafloor infrastructure by triggering submarine slumps or slides (Figure 1). Because methane is also a greenhouse gas, the instability of the natural gas hydrate reservoir structure may induce large-scale methane gas leakage, which may contribute to global climate change. Therefore, prior to the commercial exploitation of gas hydrate, comprehensive research must be conducted on the strength and deformation characteristics of natural gas hydrate deposits. Researchers must have a comprehensive understanding of the mechanisms and circumstances that cause reservoir formation instability to ensure the safety of workers during mining and to avoid the environmental impacts of gas hydrate decomposition.

Most hydrate studies have focused on measuring the relevant mechanical parameters, such as the elastic modulus of natural gas hydrate sediments, using indirect acoustic measurement experiments. Others have used triaxial laboratory experiments to empirically determine both the strength and deformation characteristics of gas hydrate-bearing sediments, as well as the geotechnical implications of gas hydrate production. While this technique frequently yields valuable data, conducting triaxial experiments is both time consuming and costly. In Section 2, we introduce the theory and an experimental method for measuring deformation with an optical fiber sensor. In Section 3 we describe two experiments where we apply this technique to record and analyze the deformation of a porous medium, which serves as a proxy for hydrate-bearing sediments. In Section 4, we present a preliminary design to improve and refine our methodology for future research.

2 | MATERIALS AND METHODS

2.1 | Theory of optical frequency-domain reflectometry (OFDR)

Optical fibers have the advantages of high sensitivity, good flexibility, antielectromagnetic interference, light weight, small size, etc., and are widely used in applied science, engineering, and other fields. Several technologies have been successfully applied to distributed optical fiber sensors, such as Brillouin, Raman, and Rayleigh scattering. Optical frequency-domain reflectometry (OFDR) is based on Rayleigh scattering, which is used for distributed monitoring of deformation and temperature.
along with the fiber.\textsuperscript{31,32} OFDR has received widespread attention owing to its high spatial resolution and large dynamic range.\textsuperscript{33}

A typical experimental setup of the OFDR is shown in Figure 2. It is comprised of a tunable laser source to generate a continuous laser whose optical frequency is tuned linearly over time, an interferometer with a measurement path and a reference path, and a polarization-sensitive receiver. The receiver includes a polarization beam splitter, three wide-band photodiodes, a high-speed analog-to-digital converter, and a computer.

The light from the tunable laser source was split into the reference light and measurement light. The measurement light was transferred through the measurement path into the fiber, which returned Rayleigh backscattering. The backscattering light coming from the measurement path was recombined with the reference light from the reference path, and beat interference occurred in the photodiode. The beat frequencies were obtained by performing a Fourier transform on the combined interference signal.

To better understand the principle of OFDR, we will examine the mathematics behind OFDR in more detail. The interference between the two light signals originates from two different paths. One signal, described by an electric field intensity \( E_r(t) \), is the backscattering light in the fiber along the measurement path, and the other light signal, described by the electric field intensity \( E_m(t) \), comes from the reference path. For the laser source having a linear optical frequency tuning rate \( \gamma \), the reference light signal \( E_r(t) \) can be given as\textsuperscript{34}

\[
E_r(t) = E_0 \exp \left\{ j \left[ 2\pi f_0 t + \pi \gamma t^2 + e(t) \right] \right\} \tag{1}
\]

where \( f_0 \) is the initial optical frequency, and \( e(t) \) is the phase noise or nonlinear phase.

The signal of backscattering light \( E_r(t) \) can be given as\textsuperscript{35}

\[
E_r(t) = \sqrt{R(\tau)} E_0 \exp \left\{ j \left[ 2\pi f_0 (t - \tau) + \pi \gamma (t - \tau)^2 + e(t - \tau) \right] \right\} \tag{2}
\]

where \( R(\tau) \) is the reflectivity of fiber related to the time delay \( \tau \).

The intensity of the beat signal can be given as

\[
I(t) = 2\sqrt{R(\tau)} E_0^2 \cos \left\{ 2\pi \left[ f_0 \tau + \gamma \tau t + \frac{1}{2} \gamma \tau^2 + e(t) - e(t - \tau) \right] \right\} \tag{3}
\]

where the beat frequency \( f_0 = \gamma \tau \), which is proportional to the length of the fiber. The last term, \( e(t) - e(t - \tau) \), is the phase noise or nonlinear phase in the beat signals. By deriving and analyzing different frequency segments of the beat signal, signals from different locations of the fiber can be interrogate separately.

When the sensor experiences strain or temperature changes, Rayleigh scattered light is continuously generated in both the backward and forward directions. We record the backward-scattered Rayleigh light, which has a reflection spectrum with a frequency shift of \( \Delta \nu \textsuperscript{36,37} \)

\[
\frac{\Delta \lambda}{\lambda} = - \frac{\Delta \nu}{\nu} = K_T \Delta T + K_\varepsilon \tag{4}
\]

where \( \lambda \) is the wavelength, \( \Delta T \) is the temperature change, and \( \varepsilon \) represents the microstrain (unitless). The coefficient \( K_T \) is a strain constant, and \( K_\varepsilon \) is a temperature calibration constant that relates spectral shift to a strain or change in temperature values. Figure 3 shows a schematic of the signal process procedure. More information about the OFDR technology and analytical techniques can be found in previous studies.\textsuperscript{38,39}

### 2.2 Experimental apparatus and material

Ice is an ideal analog for methane hydrate for two reasons: (a) it is stable at ambient pressure conditions, and (b) the ice formation and melting processes in a porous medium are similar to those of methane hydrate.\textsuperscript{40,41} The experimental setup is shown in Figure 4. A water bath (GDH-2015, Ningbo Scientz Biotechnology Co., Ltd, China, measuring error \( \pm 0.02 \) K), which was filled with a solution of 50% ethylene glycol by volume, was used to keep the reaction vessel and the methane injection pump at the required temperatures.

In this work, a commercially available measurement system, Optical Distributed Sensor Interrogator B (ODISI-6100, Luna Innovations Inc.)\textsuperscript{42,43} was used for strain measurement. Luna ODISI-6100 uses the OFDR to evaluate the Rayleigh backscatter profile. These backscattering profiles are produced using a Mach-Zehnder interferometer to remove nonlinear wavelength tuning induced by laser gain dynamics. The distributed optical fiber sensor (HD6S05LC220P-strain, Luna Innovations Inc.), which had a polyimide coating, a metal connector, and an antireflection coating at the end of the sensor, was 2 m long and had a diameter of 155 \( \mu \)m. The distributed optical fiber sensor was attached to an acrylic frame (Figure 4) that was placed within a plastic reaction vessel containing ultrapure water and a porous medium made of glass beads (80–120 mesh, Macklin, Shanghai Macklin Biochemical Co., Ltd, China).

### 2.3 Experimental procedures

The optical fiber sensor was glued to an acrylic frame. The adhesive used was Master Bond EP30-4. The two-part
epoxy resin was thoroughly mixed in advance and dipped in a foam swab to coat the fiber and fixed with the frame. The epoxy used was sufficient to cover the fiber sensor and ensure as much as possible that the efficiency of the strain transfer was not affected by excessive adhesive. The setup (glass beads, ultrapure water, and optical fiber) is shown in Figure 5. The experimental procedure was as follows: (a) the optical fiber cross-section was wiped with acetone to remove dust (which could impact the flow of data), and then, the optical fiber sensor was connected to the data acquisition system; (b) the distributed optical fiber sensor was vertically centered in the plastic reaction vessel; (c) the plastic vessel was filled with either glass beads and ultrapure water (first experiment) or ultrapure water (second experiment); (d) the water bath was set to a temperature of 1°C; (e) after the temperature stabilized, the plastic reaction vessel was placed in the water bath; and (f) the water bath was initially set to −7°C to induce
ice formation. Cooling was stopped and the temperature maintained once ice started to form. We began collecting the frequency shift data of the fiber as the bath started cooling. In the second experiment, we filled the container vessel with water up to the top red line (Figure 5).

The experiment was divided into two stages: a cooling stage and a constant-temperature stage. During the cooling stage, there was no ice formation under the subcooling condition owing to the small disturbance of the system. The experimental temperature was controlled by the water bath, and the effect of phase transformation on the temperature was negligible owing to the small amount of sample and slow process of ice formation.

3 | RESULTS AND DISCUSSION

The frequency shift during the cooling stage is shown in Figure 6. The x-axis, which represents the fiber length, was divided into nine fiber segments. Each fiber segment is an independent sensor (S1–S9), as shown in Figure 5. The length of S1 to S9 are 0.1051 m, 0.1098 m, 0.1066 m, 0.1112 m, 0.1040 m, 0.1046 m, 0.1112 m, 0.1059 m, and 0.1020 m, respectively. In addition to length, the initial tightness of the nine fiber segments was also different. Before cooling, the frequency shift was calibrated to 0 GHz. Owing to the different initial lengths and tightness of the fiber segments, the frequency shift value can only be compared with the fiber segment itself on its own time scale. The value of the frequency shift cannot be compared for different fiber segments. The frequency shift changes of each fiber segment can only reflect the trend of temperature changes at its own location. In this stage, the frequency shift change only results from the temperature decrease, and there is no phase change. As shown in Figure 6, the frequency shift increased with decreasing temperature, between that there was a linear relationship. Although all fiber segments are under the same cooling process, the increase in frequency shift is not the same because of the different initial lengths and tightness of each fiber segment. Because the performance of the optical fiber sensor usually depends on the fiber geometrical parameters, each fiber segment has a slightly different sensitivity. During cooling stage, the fiber segment fiber with high sensitivity generates wider range of spectra, while spectra are in smaller range represent data from fiber segments with lower sensitivities.

Because the initial frequency shift at the cooling stage was used as a reference, the frequency shift change caused by cooling was deducted at the beginning of the constant-temperature stage. Accordingly, to clarify the results, we omitted the frequency shift results from the temperature effect.

In the constant-temperature stage, the frequency shift signal of the optical fiber changes only with the liquid–solid phase transition process. The strain calculation is as follows

\[
\epsilon = -\frac{\bar{\lambda}}{cK_s} \Delta \nu
\]

where \(\bar{\lambda}\) is the central wavelength of the scan, \(c\) is the light velocity, \(\Delta \nu\) is the reflection spectrum frequency shift, and \(K_s\) is the strain constant of the fiber.

Figure 7 shows the strain changes of the liquid–solid phase transition process under constant temperature. Although the radius of the acrylic frame is uniform, the force of manually winding the optical fiber is difficult to accurately control. Because of the edge effects, the measurement points of each segment at the two ends are imprecise. Future work will include defining a technique that ensures uniform winding of the fiber.

In the first experiment, the strain curve direction of the adjacent fiber segment was different. The winding of the fiber causes the prior fiber segment tail to connect with the head of the last fiber segment. Compared with the second experiment, the presence of porous medium at the bottom makes the strain values of the fiber relatively higher than those of the water and air parts. The initial strain value of the second experiment was relatively flat, except for the bonded-to-unbonded transition regions at the two ends. As the phase transition progressed, both experiments demonstrated similar behavior, and the measured strain value increased.

We also calculated the average strain over time for each fiber segment, as shown in Figure 8, in which the strain trend was more obvious. In the first experiment, the strain trend of all the fiber segments increased linearly with time. However, it was not linear in the second experiment, which was quite different from that in the first experiment. This was caused by the distribution of water and the porous medium in the two experiments. A diagram of the water freezing process with a porous medium was used to explain this process, as shown in Figure 9. Owing to the presence of a porous medium, ice crystal nuclei are generated in large quantities and uniformly distributed in the pores, and the phase change proceeded slowly over time because of the space constraints in the pores of the porous medium. As the phase change in the first experiment commenced, ice began to squeeze the porous medium simultaneously. Meanwhile, because the phase change process was slow and continuous, the squeezing effect of ice on the porous medium occurred concurrently. The continuous structural change of porous medium caused the strain measured by the optical fiber to increase almost linearly. However, phase change occurred rapidly in the second
experiment because of the pure water and undisturbed environment. Therefore, a large number of crystals formed quickly in the early stage of the phase transition, and the generation rate slows down later. This is consistent with the strain trend measured using the optical fiber. When the crystal formed rapidly, the squeezing effect of the crystal solid on the fiber segments was enhanced and the strain was greater. When the crystal growth rate slowed, the changes in strain also decreased.

To investigate the effects of the porous medium on the strain changes observed during ice formation, we calculated the strain increment recorded in the three sections of each fiber segment (i.e. the upper section (US), middle section (MS), and bottom section (BS)) (Figure 10). Overall, the strain changes were of a similar magnitude in the three sections of each fiber segment. In the six fiber segments (S3, S4, S5, S6, S7, and S8), the strain in the BS was the largest recorded within the total fiber segment; the overall strain was mainly caused by the strain experienced by the BS. Based on this analysis, we demonstrated that the optical fiber is sensitive to the liquid–solid phase transition process. In future, we hope to apply this methodology to investigate the deformation in hydrate formation sediments.

4 | CONCLUSIONS

This study evaluated the feasibility of quantifying deformation in a porous medium using a distributed optical fiber sensor. This method could be useful for assessing the stability of the overlying sedimentary layers in gas hydrate
We used optical fibers to gather strain data in two experiments. In the first experiment, ice formation in a porous medium was used to simulate the hydrate formation in sediments. In the second experiment, ice formation in pure water was examined as a control. In the cooling stage without phase change of the system, the frequency shift change trend during the cooling process shows that the fiber segment sensitivity was influenced by its initial
length and tightness. Fiber segments with high sensitivity generated a wider range of spectra. In experiments with porous medium, the strain caused by the phase change exhibited a linear trend. In the comparative experiment of pure water, the strain caused by the phase change showed a nonlinear trend. The results indicate that the porous medium deformation induced by phase change can be accurately evaluated using strain data from distributed optical fiber sensors. The strain results also reflect the phase change rate. The results of our experiments show that porous medium deformation induced by phase changes can be evaluated using strain data collected with a distributed optical fiber sensor. In future, we hope to expand these experiments to measure the strain in hydrate samples under high-pressure conditions.

5 | PROSPECTS

The previous experiments proved the feasibility of using a distributed optical fiber sensor for evaluating deformations in porous media. The next stage of the research will evaluate fiber optic sensors for measuring the deformation in porous medium during hydrate formation and dissociation. We developed a preliminary design for an experimental system that can study the effect of hydrate formation or dissociation on porous medium deformation (Figure 11). This experimental system will use fiber strain data to refine our understanding of the influence of hydrates on porous medium structure. Furthermore, an identical optical fiber in the same environment will be installed, to eliminate the influence of temperature on strain measurement and measure the temperature. Notably, a distributed optical fiber sensor can measure temperature values at a much finer resolution than thermocouples or other similar data loggers. This system design could provide vital information regarding the strain variation and temperature distribution in porous medium. Lastly, adding imaging technology (such as X-ray CT or MRI) to this optical fiber system would provide valuable insights in the field of hydrate research.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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