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Kinetics of methane hydrate formation and dissociation in sand sediment

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Abstract
Methane hydrate is being considered as a potential future energy source but may at the same time constitute a considerable geo-hazard. In the present study, methane hydrate bearing sand sediment was created by pressurizing methane gas into previously moistened, then chilled, packed sand specimen (excess gas method). The excess gas was then replaced by water at high pressure. Afterward, a heating/cooling cycle was applied under undrained conditions, in order to completely dissociate gas hydrates and then recreate them inside the specimen. Finally, the pore pressure was reduced to the atmospheric pressure to dissociate gas hydrates. The whole process was performed in a magnetic resonance imaging (MRI) system, allowing the determination of water and/or gas and hydrate quantity (and spatial distribution) at various times. The MRI signal was finally analyzed to interpret various processes in sand sediment: initial hydrate formation, heating-induced hydrate dissociation, cooling-induced hydrate re-formation, and depressurizing-induced hydrate dissociation.

Keyword: gas hydrate bearing sand sediment, dissociation/formation, kinetics, magnetic resonance imaging.
1. Introduction

Natural gas hydrates (primarily methane hydrates forming naturally at high pressures and low temperatures) are nowadays considered as a potential alternative energy source [1]. Among the existing methods of gas recovery from hydrates, depressurization method is considered as the most economically promising method [2]. This method, conducted by lowering the pressure in overlying sediments, may be hampered by the formation of ice and/or the reformation of gas hydrates (GH), because of the endothermic cooling nature of GH. Fundamental understandings of hydrate dissociation kinetics models are essential to predict hydrate reservoir dissociation process. The objective is to select appropriate hydrate bearing zones and estimating gas production behavior, prior to executing any field tests. Some kinetics models were developed to simulate the production process, based on heat/mass transfer and/or intrinsic kinetics of hydrate decomposition and/or gas-water flow [3,4]. Even if different assumptions were made, their applicability to reservoir level studies is valid only case by case. Various GH reservoir simulators (i.e. computational tools, taking into account the complex highly-coupled transport equations, the reaction kinetics, the phase transition and the physical/chemical properties of hydrate bearing sediment) are being developed [5,6]. The accuracy of reservoir model needs, however, to be improved and the availability of long-term field production test data is of great important. Two successful offshore field tests - together with two onshore field tests in Mount Elbert – Alaska and Malik in 2007 [7]-, until now, used the depressurization method. The first offshore methane hydrate production test was conducted by Japan Oil, Gas, and Metals National Corporation (JOGMEC) in the eastern Nankai Trough. Approximately 120,000 m³ of methane gas (20,000 m³/day) were produced by lowering pressure from 13.5 MPa to 4.5 MPa. The
production was interrupted due to an unexpected increase in sand production [8].

Recently in 2017, the China Geological Survey extracted 300,000 m³ of gas (for 60 days) from natural GH deposits in the Shenhu area with a methane concentration of 99.5 percent [9]. As production costs are still high, an economically feasible way to exploit GH on a large scale should be found to commercialize the production of the natural GH. As it is challenging to get intact cores of methane hydrate-bearing sediments, most the experimental works concern laboratory tests on synthetic specimens to investigate hydrate dissociation rate, pressure-temperature evolution [10–14]. The experimental reactor scale is a crucial factor; a larger reactor better mimics actual field conditions but it would be more difficult to ensure the homogeneity of synthesized specimens [15].

In order to create synthetic methane hydrates in sandy sediments, several methods were proposed and evaluated: dissolved gas [16], partial water saturation [17], excess water [18] or ice-seeding [19]. Among them, dissolved gas and water excess method may allow forming non-cementing hydrate habit in sandy sediments. However, dissolved gas is a time-consuming method, especially at high hydrate saturation, due to the low solubility of methane gas in water [16]. In addition, methane hydrate is observed to form heterogeneously inside the sample by using water excess method, after X-Ray Micro-Tomography [20] and measures of pressure at different positions in the sample [21]. Recently, Choi et al. [22] proposed an efficient method combining the partial water saturation, saline water injection at restricted conditions and a temperature cycle. However, compressional wave velocity measured after the heating process was quite high while sample was not saturated. The hydrate dissociation was perhaps not finished before the hydrate reformation.
Besides elastic wave velocity measurement [19,23–25] and synchrotron X-ray computed tomographic microscopy [26,27], which are used to study the kinetics and mechanisms of hydrate formation and dissociation, $^1$H Nuclear magnetic resonance spectroscopy (NMR), in particular Magnetic Resonance Imaging (MRI) (at macroscopic scale of NMR) is well-suited to follow these kinetics. In most MRI studied cases, glass beads were used to simulate the porous media to investigate the tetrahydrofuran (THF), carbon dioxide (CO$_2$) hydrate formation and dissociation [28,29]. Methane hydrate formation (obtained by dissolved gas or partially water saturation methods) was observed via Mean Intensity ($MI$) evolution and 2D images [30,31]. Effects of different sizes of glass beads on hydrate growth stage were investigated in these works. The results show that, in general, hydrate growth rate increased when the size of the porous media decreased. In addition, three growth stages were observed: the initial growth, the rapid growth and the steady stage. In sandstone media, methane hydrate formation and spontaneous conversion of methane to CO$_2$ hydrate were studied using $MI$ and 3D images [32,33]. As a significant duration was needed to take 3D images, spatial distribution of specimen during the hydrate formation was not measured regularly. Methane hydrates formation in unconsolidated bed of silica, with different size ranges, was investigated by following the $MI$ evolution, measured on vertical and horizontal slices [34]. The formation was non-uniform and occurred at different times and positions. In addition, by using different water saturations, hydrate formation was found to be faster for lower water content. The methane hydrate formation, dissociation and reformation in partially water saturated Ottawa sand at different water saturations were studied by combining measurements of $MI$ and elastic velocities [35]. $MI$ profiles along the
specimen axis after these three procedures (hydrate formation, dissociation and reformation) showed an almost homogenous distribution of GH. Actually, consolidating unsaturated sand would have made water distribution more homogenous, before GH formation. The effect of depressurizing range and rate on methane hydrate dissociation, and in particular the hydrate reformation and ice generation due to fast depressurizing rate, were observed [36,37].

In the study, methane hydrate formation based on the method proposed by Choi et al. [22] is used. Nevertheless, it was modified to improve the heating-cooling process and adapt with the existing facilities. It is investigated to follow the specimen homogenity during the whole GH formation phase. In addition, GH dissociation after depressurization method is observed. Methodological efforts were made to perform fast measurements and follow the kinetics of GH formation/dissociation during transitory steps.

2. Experimental method

2.1. Materials

The soil used in this study is Fontainebleau silica sand (NE34). It consists of poor-graded sub-rounded grains, having diameter ranging from 100 to 300 microns (see the grain size distribution curve in Figure 1 obtained by laser diffraction analysis). The physical characteristics of this material are detailed in Table 1. Tap water and methane gas with 99.995% of purity were used in the tests. In this study, as the conditions used to create GH (in terms of temperature and pressure) are far enough from the equilibrium phase, the electrolyte concentrations of tap water were supposed to not affect the GH creation/dissociation.
2.2. Experimental setup

The schematic views of experimental setup are presented in Figure 2. The sand specimen (1), 38 mm in diameter and 76 mm in height, is covered with a neoprene membrane (2). The confining pressure is applied to the specimen by a volume/pressure controller (7) using a perfluorinated oil (Galden®) as confining fluid (3). This fluid was chosen due to its low signal intensity in MRI measurements. Methane gas is then injected via the bottom inlet (5) by a pressure controller connected to a gas flowmeter (10). The top inlet (6) was closed in this study. A second volume/pressure controller (12) is used to control the water pore pressure. The specimen temperature is controlled by circulating a perfluorinated oil (Galden®), which is connected to a cryostat (8), around the cell (4). The cell is installed in a nuclear magnetic resonance imaging system (13) for observations.

Proton (¹H) NMR/MRI measurements are performed at a Bruker 24/80 DBX spectrometer operating at 0.5T (21MHz proton frequency) equipped with:

- A birdcage RF coil, 200 mm in diameter and height, where the whole pressure cell can fit
- A BGA-26 gradient system delivering a maximum gradient strength of 50mT/m with a rising time of 500µs.

Measurement protocols used in this work rely on well-established methodology. They consist of:

- A pulse acquisition sequence, where the overall NMR signal owing to hydrogen is measured after a dead time of 40µs following the exciting RF pulse. This signal is referred to as ‘FID INTENSITY’ signal hereafter.
A 1D profile imaging based on spin-echo acquisition with a read-out gradient orientated in the vertical direction and an echo time of 4.2ms, which provides profile measurements with 200 pixels covering a field of view of 20cm. This is sufficient to avoid image aliasing. It also provides a space-resolved view of the contribution.

In both kinds of measurement, the signal intensity is expected to be proportional to the amount of hydrogen atoms owing to either liquid (water) or gas (methane) phases. It is underlined that due to the Curie-law for spin polarization, the signal intensity is also inversely proportional to the absolute temperature in °K of the sample. The dead-time and the echo time are regarded as short enough to neglect bias owing to spin-spin relaxation. On the contrary, the gas-hydrate phase, and ice phase are negligible due to its short spin-spin relaxation time. Let us emphasize that FID intensities do not correspond directly to profile intensities, since the MRI parameters used for these two measurements are different from each other. Related data are then presented on independent scales.

If any, the related data processing relied on home-made routines under Scilab.

### 2.3. Test procedure

Methane hydrate bearing sediment (MHBS) specimens were prepared by the following procedure:

- Step 1 - Compaction: moist sand (having known moisture content) is tamped in layers to obtain a specimen with a void ratio of 0.63 inside the neoprene membrane before the assembly of the experimental setup as shown in Figure 2. The void ratio is calculated from the dry mass of sand and the volume of the specimen.
- Step 2 - Consolidation: the confining pressure is increased to 25 MPa then decreased to 10 MPa.

- Step 3 – Hydrate creation: the temperature of the cell is decreased to 2 °C. Vacuum is then applied to eliminate pore air in the specimen prior to the injection of methane gas at 7 MPa of pressure.

- Step 4 – Water saturation: the valve $V_2$ is opened to atmosphere during a short period to let all the excess methane gas (initially under a pressure of 7 MPa) escape from the specimen (pore pressure decreases to zero). This valve is immediately closed when the pore pressure reaches zero to limit GH dissociation. Afterward, the valve $V_1$ is opened, the bottom inlet is connected to the volume/pressure controller (12) to inject tap water (at ambient temperature) fixed at 7 MPa of pressure to the sample. This procedure is used to replace the excess gas in the specimen by water while minimizing the disturbance of methane hydrates that already exist inside the specimen. Skempton’s coefficient is measured at the end of this step to make sure that the sample is fully saturated.

- Step 5 – Heating-induced hydrate dissociation: from this step on, the confining pressure is imposed to be 3 MPa higher than the pore pressure. The pore pressure is first decreased from 7 MPa to 4 MPa. The drainage valve ($V_1$) ($V_2$ is always closed) is then closed and the temperature of the cell is increased up to higher than 25 °C. This is done to heat the specimen under undrained condition to dissociate the existing GH progressively. Note that the pore pressure at the end of this step can vary from between one test and the other, depending on hydrate saturation [38]. In the present study, pore pressure is
increased to 19 MPa at the end of this step, to ensure that the parameters
used in the subsequent tests are identical.

- Step 6 – Cooling-induced hydrate re-formation: the cell temperature is
decreased to 2 °C while the pore pressure is maintained constant at 19 MPa
by injecting water from the volume/pressure controller (12) into the sample.
This allows GH to be reformed faster and providing also the same final
pressure - temperature conditions for GH in the end for all tests.

- Step 7 – Depressurization-induced hydrate dissociation: The confining
pressure is maintained at 22 MPa while the valve V2 is opened to decrease
the pore pressure. The volume of methane dissociated from the specimen is
measured by the system (9) which is composed of a gas/water separator and
a gas collection system.

The steps 3 – 7 are performed in the MRI system and the data are logged
automatically during these steps.

2.4. Calibration tests

Calibration tests were performed at 2°C on the compacted specimen of the first test,
which density was also very similar to that of the second one, saturated with pure
phases of various fluids: (a) vacuum; (b) methane gas at 7 MPa of pressure; (c)
water at 7 MPa of pressure; (d) and water at 19 MPa of pressure. In Figure 3, $FID$
$INTENSITY$ obtained for the whole system in each case is plotted. The values
corresponding to methane gas at 7 MPa of pressure, water at 7 MPa of pressure,
and water at 19 MPa of pressure were then calculated by subtracting that
corresponding to the system containing vacuum, in order to remove the spurious
signal owing to the pressure cell and the imperfectly perfluorinated oil. In the working
conditions of the present study, and as far as the temperature is not modified, the
corrected signal is directly proportional to the total amount of hydrogen atoms contained in the fluid molecules. The corrected values of \( FID\ INTENSITY \) are also plotted in the Figure 3. Note that the signal for pure methane is significantly smaller than that for water due to the different density and chemical composition. In the subsequent sections, the corrected values of \( FID\ INTENSITY \), i.e. \( FID\ INTENSITY_{\text{measured}} - FID\ INTENSITY_{\text{obtained from the case (a)}} \), are shown.

2.5. Test program

Two tests were performed in this study with the same procedure and the same parameters to ensure the repeatability of the results. The water saturation obtained after compaction equals 25% (corresponding to a moisture content of 6%).

3. Experimental results and Discussions

3.1. Hydrate creation

Figure 4 (a) shows the evolution of \( FID\ INTENSITY \) during hydrate creation (step 3) for the two tests. When methane gas is injected into the specimen, \( FID\ INTENSITY \) increases slightly during the first minutes then decreases continuously; the relationship between \( FID\ INTENSITY \) and logarithm of time during the decrease phase can be correlated with a linear function. After \( t = 40 \, \text{h} \), \( FID\ INTENSITY \) remains constant. The results obtained by the two tests look similar even if during the first test, the data were not recorded during the first minutes. The increase of \( FID\ INTENSITY \) during the first minutes can be explained by the accumulation of methane gas inside the specimen when the gas pressure was increasing until it reached the target value (7 MPa), see Figure 4 (b) where gas pressure is plotted versus elapsed time for Test 2 (data for Test 1 was not available). When gas pressure exceeds the conditions required to create \( GH \) (3 MPa at 2 °C), \( GH \) starts to
be created inside the specimen. This phenomenon decreases the quantity of water and increases the quantity of GH. This explains why GH formation decreases the total FID INTENSITY. Note that the intensity related to GH is negligible [32].

The following equation is used to estimate hydrate saturation ($S_h$):

Where $I_o$ is the initial FID INTENSITY of the moist sand specimen and $S_{wo}$ is the initial water saturation ($S_{wo} = 25\%$). The remaining void (about 75\% of total void) contains methane gas (at 7 MPa of pressure when this pressure is reached). For this reason, $I_m$ - the FID INTENSITY of methane gas (at 7 MPa of pressure) in the specimen before the hydrate formation - equals to 75\% of the value obtained from the calibration test (case (b)): $I_m = 0.75 \times 1000 = 750$. This equation is applicable only when the gas pressure equals 7 MPa. The underlying assumption for this equation is that water reacts locally to form hydrates, and that gas can go in and out of the sample to occupy the remaining space between hydrates and remaining water, owing to the 10\% of volume increase when water is converted to hydrate. As a result, during the hydrate formation, the remaining void containing methane gas is $(100 - S_{wo} - S_h)\%$ of total void.

Figure 4 (c) shows the estimated hydrate saturation evolution for Test 2. Hydrate starts to be created immediately when the gas pressure is higher than 3 MPa. As mentioned above, hydrate saturation is only calculated when pore pressure reaches 7MPa (at $t = 0.06$ h, hydrate saturation is 0.3\%). Hydrate saturation increases then linearly with the logarithm of time and reaches its maximal value after 40 h. Note that, after 40 h, $S_h = 27\%$ means all water in the specimen has been transformed into
hydrate, and the remaining NMR signal at the end of the process corresponds to the methane gas phase.

Figure 5 shows the signal (i.e. owing to water and methane gas) versus altitude ($Z = 0$ approximatively corresponds to the bottom of the specimen) for various times. It can be noted that the signal is generally homogenous along the specimen elevation. At the beginning ($t = 0$), the specimen contains only water and air in the pore space. Slight signal fluctuation along the Z-axis should indicate compaction process (moisture sand tamped by layers of 10 - 20 mm), which induces slight heterogeneity of porosity and water distribution in the specimen. When methane gas is injected into the specimen, GH is formed and the water content decreases progressively. This explains why the signal decreases progressively with time and the profile becomes more homogenous.

Bagherzadeh et al. [34] found that hydrate formation occurs faster in a bed with lower initial water saturation and as opposed to the higher water saturation case, hydrate formed homogenously at 25% of initial water saturation. This agrees with homogenous Z profiles during GH formation in gas saturated media in this study.

Rydzy [35] investigated the kinetics of methane hydrate formation in unsaturated Ottawa sand via the combination of wave velocity measurements and MRI (Mean Intensity, $MI$). The results showed that at low initial water saturation, $MI$ decreased quickly few hours after gas injection, indicating that hydrate saturation increased quickly. In addition, velocities (compressional and shear velocities) increased quickly during hydrate saturation, then slowed down and became stable when hydrate
formation was almost finished. This could be explained by cementation model
illustrating hydrate growth in capillary water at sand grains contacts \[39,40\] which
supposed that films of hydrates are first formed quickly at water-gas interfaces, the
subsequent hydrate formation (from the films toward the centers of grain contacts) is
slower depending on methane molecule diffusion through the hydrate film and water.
This can be also used to explain the linear relationship between \textit{FID INTENSITY} and
logarithm of time observed in the present study during the hydrate formation.
However, in the work of Rydzy \[35\], 5\% to 12\% of pore water remained unconverted
to hydrate at the end of their experiments, while in the present study, almost 100\% of
water becomes hydrates. Actually, in the work of Rydzy \[35\], the signal of methane
gas was not considered and that would induce errors in water content estimation in
the specimen.

\section*{3.2. Water Saturation}

Figure 6 shows \textit{FID INTENSITY} during the water saturation (Step 4). $t = 0$
corresponds to the opening of the valve $V_2$. That induces a quick decrease of \textit{FID
INTENSITY} to 0. Afterward, when water is injected to the specimen ($t = 0.06$ h) \textit{FID
INTENSITY} increases quickly and reaches the maximal value when water pressure
reaches 7 MPa. Note that water injection in Test 1 was stopped between $t = 0.1 - 0.4$
h because the volume/pressure controller (12) has reached its limit in volume (no
more water available in its reservoir). Injection was restarted from $t = 0.4$ h after filling
the controller with water.

The signal versus elevation is plotted at various times for the Test 2 in Figure 7.
Profile at 60s ($t = 0.047$ h) was measured when methane gas was decreased to the
atmospheric pressure. When water is injected with a pressure of 7 MPa from the
bottom inlet, signal at the bottom starts to increase first ($t = 0.063 \text{ h}$). The specimen
can be expected to be fully saturated with water at $t = 55 \text{ h}$ (methane gas should not
exist in this conditions). At this state, higher signal can be observed in the zone close
to the bottom of the specimen while it is lower in the zone close to the top.

Figure 8 plots the signal versus elevation for both two tests at the end of the water
saturation step. The results of the Test 1 show also a higher signal close to the
bottom but the signal at the top is similar to the remaining part of the specimen. The
heterogeneity of water distribution at the end of this step can be explained by the
saturation procedure. Actually, methane gas evacuation and water injection were
performed both from the bottom. Methane gas evacuation, even if it was performed
quickly, less than one minute, would induce hydrate dissociation at the zone close to
the bottom. That explains why in the end, hydrate saturation at the bottom was lower
(higher signal) than the other parts of the specimen. In the work of Choi et al. [22],
the pressure of sediment was maintained at 6.89 MPa during water saturation stage,
which prevented mass dissociation of hydrates. Therefore, the phase distribution
derived from this work may be significantly different from what would have been in
the work of Choi et al. [22]. However, more complex experimental setup would be
required in the present work to apply similar procedure.

Hydrate saturation is estimated 20.5% and 27.5% respectively for two tests based on
the intensity of water saturated sample at 7 MPa. It should be noted that, during the
Step 4 “Water saturation”, decreasing gas pressure to atmospheric pressure would
induce GH dissociation. Hydrates dissociation close to the bottom eventually
decrease hydrate saturation. However, for Test 2, GH measured at the end Step 4 is identical to that estimated at the end of Step 3 “Hydrate creation” (25% of water saturation corresponds to 27% of hydrate saturation). Actually, when water is injected from the bottom, the remaining gas could cumulate close to the top of the specimen, thus impeding total water saturation. At the end of water saturation phase, remaining gas would be transformed to GH, hydrate saturation increased as a result. That is why the hydrate saturation in this zone seems higher than in the other parts (lower signal) in Figure 8.

3.3. GH Dissociation-Reformation

As mentioned above, a temperature cycle was performed after the water saturation phase. Figure 9 shows the pore pressure (a), the cryostat temperature (b) and FID INTENSITY (c) versus elapsed time for Test 1. It should be noted that specimen temperature could not be measured during these tests in the MRI system. However, preliminary tests performed outside the MRI system showed a characteristic time of 20 min for the temperature exchange between the cryostat and the specimen. At the beginning of the tests, the pore pressure is first decreased to 4 MPa. Afterward, the cryostat temperature is increased from 2 °C to 25 °C with a constant rate. As heating is performed under undrained conditions (the valves V₁ and V₂ were closed), pore pressure increases according to heating and stabilizes at 14 MPa when the temperature reaches 25 °C. Heating-induced pore pressure increase is mainly due to thermal dilation of water and hydrate dissociation [38]. Following this step, the valve V₁ is opened to connect the cell to the pressure/volume controller (No. 12 in Figure 2) in order to impose a pore pressure of 19 MPa. This pressure is maintained until the end of the cooling-induced hydrate re-formation phase (Step 6). At t = 7.5 h, the cell temperature is decreased quickly to 2 °C to re-create GH. Note that the system was
designed for a maximal pore pressure of 19 MPa. Heating the specimen under undrained conditions without decreasing a priori the pore pressure from 7 MPa to 4 MPa would generate pore pressure higher than that limit. For the sake of security, in the present work, the pore pressure was reduced to 4 MPa before dissociation. However, during the GH reformation step, the pore pressure was maintained at 19 MPa to ensure that all methane gas has been converted into GH.

Figure 9 (c) shows FID INTENSITY versus elapsed time during these steps. The data from the beginning to $t = 1.6$ h was unfortunately not available. From $t = 1.6$ h, FID INTENSITY decreases as the specimen temperature increases. Note that owing to Curie law for spin polarization in the MRI magnet, FID INTENSITY is considered to be also influenced by temperature, being inversely proportional to its absolute value in Kelvin. For a given fluid content, it then increases when temperature decreases and vice versa. At $t = 2.8$ h, FID INTENSITY starts to increase when the signal of water creation (from dissociated GH) was higher than that induced by temperature increase. In the present study, no direct temperature measurement was available inside the specimen, and no temperature correction of FID INTENSITY was made. At $t = 3.6$ h, FID INTENSITY decreases when GH has been completely dissociated (pore pressure reached 14 MPa) but the specimen temperature continues to increase to reach the imposed temperature in cryostat. At $t = 4.4$ h, increasing pore pressure from 14 MPa to 19 MPa induces an increase of FID INTENSITY. When the cryostat temperature is decreased quickly ($t = 7.5$ h), the temperature of the specimen decreases progressively inducing an increase of FID INTENSITY. At $t = 8.2$ h, GH starts to be re-created progressively inducing decrease of FID INTENSITY. When the GH re-creation is completed, FID INTENSITY stabilizes.
The results of the Test 2 are shown in Figure 10. After reducing the pore pressure from 7 MPa to 4 MPa, the cryostat temperature is increased quickly from 2 °C to 20 °C (t = 0.1 h) and then to 25 °C (t = 2.1 h). It is decreased to 2 °C at t = 22 h. Heating under undrained conditions induces an increase of pore pressure from 4 MPa to 15 MPa. The subsequent heating (from 20 °C to 25 °C) does not influence the pore pressure. From t = 4.1 h, the pore pressure is maintained at 19 MPa as the case of the Test 1. The results on FID INTENSITY show phenomena similar to those observed in Test 1: t = 0 – 0.6 h, FID INTENSITY decreases due to heating; t = 0.6 – 1.9 h, FID INTENSITY increases due to GH dissociation; t = 1.9 – 4 h, FID INTENSITY decreases due to heating; from t = 4 h, FID INTENSITY increases due to increase of pore pressure (from 14 MPa to 19 MPa); and t = 22 h FID INTENSITY increases first due to cooling then decreases due to GH re-formation. More regular FID INTENSITY acquisitions between t = 2-5 h are not available to better reflect the GH dissociation – reformation.

Figure 11 shows the signal versus elevation for the two tests at the end of the water saturation, GH dissociation, and GH reformation phases. The results show a slight redistribution of water after the GH dissociation/reformation cycle. At the end of this cycle, water seems distributed more homogeneously. Actually, for the test T1, the peak to average signal ratio reduces from 1.30 at the end of the water saturation phase to 1.10 at the end of the GH reformation phase. For the test T2, this value reduces from 1.32 to 1.26 between these two phases.
3.4. Depressurization-induced hydrate dissociation

To observe the depressurization-induced GH dissociation, pore pressure is first decreased from 19 MPa to 5 MPa while specimen temperature is maintained at 2 °C. Note that, these conditions are inside the GH stabilization zone. The valve $V_2$ is then connected to the system (9) while the valve $V_1$ is closed. That reduces pore pressure directly to atmospheric pressure. The quantity of dissociated methane gas measured by the system (9) is used to estimate the hydrate saturation $S_h$ remaining in the specimen. MRI data are disregarded for such purpose because ice is likely to appear in the specimen at this step and impede the direct interpretation of signal intensity.

Figure 12 shows hydrate saturation and FID INTENSITY versus elapsed time during the GH dissociation for Test 1 (a) and Test 2 (b). The results of Test 1 show a quick decrease of $S_h$ from 21% at the beginning to 0 almost after 0.2 h. During this period, FID INTENSITY decreases quickly. Once the hydrate dissociation is finished, FID INTENSITY increases slowly during the next hour. The results of Test 2 show similar trends but FID INTENSITY decreased more slowly at the beginning. In fact, in the objective of decelerating the GH dissociation, for Test 2, valve $V_2$ was opened partly at the beginning ($t = 0 - 0.067$ h). However, hydrate dissociation was stopped as created gas and water were blocked in the sample. Valve $V_2$ was then opened completely, FID INTENSITY decreased fast afterward. The decrease of FID INTENSITY during the hydrate dissociation phase can be explained by the expellee of water from the specimen by the created methane gas. At the same time, as hydrate dissociation is an endothermic process, ice would be formed during this phase. That induces decrease of FID INTENSITY even when GH has been almost
dissociated. In the subsequent phase, ice melting increases the quantity of liquid water in the specimen, which explains the increase of FID INTENSITY.

The signal versus elevation is plotted for various times during this step in Figure 13. These results confirm the statement above. Ice formation takes place only in the zone where hydrate is present (that means along the specimen except the zone close to the bottom). For this reason, signal at this zone increases at the end of the dissociation phase (which corresponds to ice melting) while the signal at the zone close to the bottom remains constant. Actually, rapid dissociation by depressurizing the sediments below the quadruple point of methane hydrate drops the temperature below the freezing point of water causing ice formation [10,11]. The energy released by hydrate dissociation is 450 Jg⁻¹ [41] while it is -342Jg⁻¹ for the transformation of water at 2 °C to ice. Depending on heat transfer in the temperature control system to compensate the temperature decrease due to GH dissociation, GH reformation and ice formation ratio varies depending also on the kinetics of GH dissociation. Thus, pore pressure is reduced from 19 MPa to 5 MPa before finally set up at atmospheric pressure to better observe the GH dissociation. Fan et al. 2017 [36] investigated the methane hydrate dissociation in glass beads by depressurization method. Ice formation was also observed by a rapid reduction of MI and water distribution variation with time in the case where pore pressure was reduced below the quadruple point of methane hydrates.

To exploit natural GH after the depressurization method, the pressure in a bottom hole is first lowered by a submersible pump. During the GH dissociation, GH saturation decreases, low pressure is transferred to a distant region from well due to
dramatic increase of permeability. GH dissociation stops when reservoir temperature is lower or identical to the corresponding GH equilibrium due to an endothermic reaction [15]. GH reformation and/or ice formation during GH dissociation is a common problem to overcome to increase the potential of hydrate production after the depressurization method. Some reservoir simulators (Hydrosim, MH 21, STOMP-HYD, CMG-STARS, TOUGH + HYDRATE) have been developed and are commonly used [15]. However, field scale production tests are needed to improve the accuracy of numerical predictions. In this study, due to the limited laboratory specimen size, the high production pressure and the fast depressurizing rate, the dissociation and ice formation are observed almost homogenous along the elevation. Experimental scale is then one of the important factors needed to be paid attention for future laboratory GH dissociation studies.

**Conclusion**

MHBS is firstly created by pressurizing methane gas (at 7 MPa) into already chilled, moistened and packed sand specimen (after excess gas method). Following the hydrate formation, water is injected into the specimen and the remaining gas is bled out simultaneously. A subsequent heating/cooling cycle is applied in order to completely dissociate GH and then recreate them inside the specimen. Methane hydrate dissociation after the depressurization method is also investigated after the whole GH formation process. From MRI measurements, the following conclusions can be drawn:

- Pressurizing methane gas into already chilled, moistened and packed sand specimen creates GH homogenously in the specimen. The formation is fast at the beginning, slows down after some hours and then stabilizes after some ten hours.
- Subsequent water saturation redistributes GH in the specimen. $S_h$ at the water inlet is smaller than the other part (due to GH dissociation) while $S_h$ at the opposite end could be higher (due to additional GH formation).

- Undrained heating/cooling cycle makes the GH distribution more homogenous in the specimen.

- The ice formation due to depressurization-induced GH dissociation below the quadruple point of methane hydrate is observed.

The findings of the present work could be helpful for future laboratory studies on MHBS. The temperature cycle is considered as an essential step to reproduce natural MHBS homogenously in the specimen. MRI is a good mean to investigate the hydrate dissociation.

**Acknowledgement**

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**References**


[37] Zhang L, Zhao J, Dong H, Zhao Y, Liu Y, Zhang Y. Magnetic resonance


Table 1. Characteristics of Fontainebleau sand [42]

<table>
<thead>
<tr>
<th>Material</th>
<th>$d_{50}$ (mm)</th>
<th>$d_{10}$ (mm)</th>
<th>$e_{\min}$</th>
<th>$e_{\max}$</th>
<th>Angularity</th>
<th>$\rho_s$ (Mg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fontainebleau sand</td>
<td>0.206</td>
<td>0.150</td>
<td>0.56</td>
<td>0.88</td>
<td>Sub-rounded</td>
<td>2.65</td>
</tr>
</tbody>
</table>

$d_{10}$, $d_{50}$: grain sizes corresponding to 10, 50% passing respectively; $e_{\min}$, $e_{\max}$: minimum and maximum void ratio respectively; $\rho_s$: grain mass density.
Figure 1. Particle size distribution (modified from [37])

Figure 2. Schematic diagram of the experimental setup
Figure 3. Reference signal
Figure 4. (a) FID Intensity evolution of the two tests during GH Formation in gas saturated media; (b) Pore Pressure and (c) Estimated gas hydrate saturation evolution of Test 2.
Figure 5. Signal versus elevation for the two tests during GH formation in gas saturated media

Figure 6. FID Intensity evolution of the two tests during the water saturation process
Figure 7. Signal versus elevation for Test 2 during the water saturation process

Figure 8. Signal versus elevation for the two tests at the end of the water saturation phase
Figure 9. (a) Pressure evolution; (b) Temperature evolution; (c) FID Intensity evolution during GH dissociation-reformation of Test 1
Figure 10. (a) Pressure evolution; (b) Temperature evolution; (c) FID Intensity evolution during GH dissociation-reformation of Test 2
Figure 11. Signal versus elevation at the end of the water saturation, GH dissociation, and GH reformation phases: (a) Test 1; (b) Test 2.
Figure 12. FID Intensity and Remaining GH evolution during GH dissociation for (a) Test 1 and (b) Test 2.
Figure 13. Signal versus elevation for the two tests during GH dissociation