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Short Communication

# Permeability measurements of quartz sands with methane hydrate

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## HIGHLIGHTS

- We measured water effective permeability of sands with/without hydrate.
- Shape factor in hydrate-bearing sediments was associated with hydrate saturation.
- Ratio of permeability with/without hydrate was related to the hydrate saturation.

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## ABSTRACT

The permeability of porous media is one of the critical parameters that determines gas recovery from natural gas hydrate reservoirs. We measured the permeability of quartz sands by injecting water at a certain flow rate. In hydrate-bearing sands, the larger the hydrate saturation, the smaller the shape factor in the presence of hydrate. A $k_r$ - $S_H$ relationship with the hydrate saturation both lower and higher than 10% was obtained. Based on the experimental results, the saturation exponent $n$ varied from 6.0 to 1.0.



## 1. Introduction

Considered to be a potential energy resource, Natural Gas Hydrates (NGH) formed by water and gas molecules are widely distributed in marine and permafrost sediments (Collett et al., 2015). There have been no field tests developed that are capable of indicating the commercial recovery of gas from hydrate reservoirs under reliable permeability estimation. The permeability of porous media with hydrate is one of the most critical parameters that determines the gas recovery potential from natural gas hydrate reservoirs (Li et al., 2010).

Permeability measurements in hydrate-free and/or hydrate-bearing sediments have been reported. Minagawa et al. (2008) measured the permeability of artificial sands and Mallik simulated sands with and without methane hydrates, and compared the results using Darcy's Law and the NMR spectra method. Kumar et al. (2010) measured the permeability of glass beads with and without $CO_2$ hydrates, and the permeability without hydrates was 66.9 Darcy. Sakamoto et al. (2010) measured the water permeability with methane hydrates in three types of sands, and the results indicated that the parameter was sensitive to the types of porous media, the hydrate-forming gas and the hydrate saturations.

In this study, we measured the permeability of quartz sands with and without methane hydrates by injecting deionized water. A $k_r$ - $S_H$ relationship with an $S_H$ both lower and higher than 10% was obtained.

## 2. Experiments

The complete descriptions of the apparatus and the materials have been introduced by Li et al. (2017). Table 1 shows the properties of the quartz sands. The grain size (the volume weighted mean diameter) of the quartz sands were measured using the Mastersizer 2000E (0.0001–1.0000 mm) produced by Malvern Instruments Ltd, United Kingdom. The effective permeability $k$ ($m^2$) was calculated using Darcy's Law:

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**Table 1**
Properties of the quartz sands.

| Parameter | Quartz Sands I (QS I) | Quartz Sands II (QS II) | Quartz Sands III (QS III) | Quartz Sands IV (QS IV) |
|---|---|---|---|---|
| Sieve mesh | 30–40 | 40–60 | 60–80 | 80–120 |
| Grain size (volume weight mean diameter, mm) | 0.7085 | 0.5502 | 0.3332 | 0.2316 |
| Density of quartz sands (kg/m$^3$) | 2603.0 | 2599.1 | 2593.4 | 2615.7 |
| Mass of quartz sands in the vessel (g) | 120.05 | 118.31 | 116.28 | 117.98 |
| Total pore volume (mL) | 37.52 | 39.28 | 38.59 | 41.72 |
| Porosity (%) | 45.87 | 48.02 | 47.18 | 51.00 |
| Volume weighted mean diameter (μm) | 731.9 | 572.0 | 336.1 | 226.6 |
| Specific surface area (m$^2$/g) | 0.038 | 0.053 | 0.114 | 0.087 |

$$k = \frac{\mu QL}{A\Delta P} \tag{1}$$

where μ is the dynamic viscosity of the fluid (Pa s). $Q$ is the fluid flow rate (m$^3$/s). $L$ = 0.250 m and $A$ are the inner length and the inner cross-sectional area (with the radius of 0.010 m) of the cylindrical vessel. ΔP is the differential pressure (Pa). 1 Darcy = 0.987 × 10$^{-12}$ m$^2$. The absolute permeability $k_0$ was considered to be equal to the water effective permeability $k_w$, which was measured by injecting water with a certain flow rate under stable pressure and temperature.

Table 2 shows the experimental conditions and the results of the permeability measurements in the hydrate-free sands. For $k_0$ of QS I, there was no statistical difference between Runs 1–8 and 9–16 under different system pressures. This confirmed the results of the previous study by Li et al. (2013). From the coarse sands of QS I to the fine sands of QS IV, $k_0$ decreased significantly from over 50.0 Darcy to approximately 14.0 Darcy. The main reason for this was that with the reduction of the particle size, the flow channels in the porous media became narrow and the flow resistance increased significantly.

The hydrate formation process and the calculations of the gas ($S_G$) and hydrate ($S_H$) saturations have been described by Li et al. (2017). Table 3 shows the experimental conditions and the results of the permeability measurements in the hydrate-free and hydrate-bearing sands. For the system with low gas saturation (<30%), the gas could be driven out by the injected water quickly and effectively. The permeability in hydrate-bearing sands $k(S_H)$ could be calculated using Eq. (1).

## 3. Results and discussion

### 3.1. Kozeny–Carman equation

Predicting the absolute permeability of porous media is difficult, especially for particles with widely distributed grain sizes. The Kozeny–Carman equation (Kozeny, 1927; Carman, 1937) is a widely used model. It successfully relates the permeability of porous media with the parameters that describe the properties of the pores. A simple form (Hearst et al., 2000; Kleinberg et al., 2003) of the Kozeny–Carman equation refers to the internal surface area of the pore space and the total pore volume:

$$k_0 = \frac{\phi}{v\tau(A_{pore}/V_{pore})^2} \tag{2}$$

where $k_0$ is the absolute permeability (Darcy). $\phi$ is the porosity (%). $v$ is the shape factor. $\tau$ is the tortuosity. $A_{pore}$ is the internal pore surface area (m$^2$). $V_{pore}$ is the total pore volume (m$^3$).

In a previous study by Kleinberg et al. (2003), the shape factor $v$ in the Kozeny–Carman equation was on the order of unity. However, the micro-structure of the grains and the pore spaces may

**Table 2**
Experimental conditions and results of the permeability measurements in the hydrate-free sands.

| Parameter | Runs | $P$ (MPa) | $T$ (°C) | $\mu_w$ (×10$^{-3}$ Pa s) | $\Delta P$ (kPa) | Q (×10$^{-7}$ m$^3$/s) | $k_0$ (Darcy) |
|---|---|---|---|---|---|---|---|
| QS I | 1 | 0.10 | 8.42 | 1.368 | 3.16 | 1.677 | 58.5 |
| | 2 | 0.10 | 8.55 | 1.363 | 12.43 | 4.995 | 44.2 |
| | 3 | 0.10 | 8.33 | 1.372 | 13.12 | 4.912 | 41.4 |
| | 4 | 0.10 | 14.79 | 1.144 | 5.41 | 3.328 | 56.8 |
| | 5 | 0.10 | 8.47 | 1.366 | 7.75 | 3.248 | 46.2 |
| | 6 | 0.10 | 8.46 | 1.367 | 4.54 | 2.497 | 60.6 |
| | 7 | 0.10 | 8.37 | 1.370 | 3.76 | 1.614 | 47.5 |
| | 8 | 0.10 | 14.73 | 1.146 | 3.30 | 1.603 | 44.9 |
| | 9 | 15.48 | 8.52 | 1.347 | 9.87 | 4.939 | 54.4 |
| | 10 | 15.28 | 8.39 | 1.352 | 11.18 | 4.916 | 48.0 |
| | 11 | 15.43 | 8.47 | 1.349 | 8.19 | 4.083 | 54.2 |
| | 12 | 15.56 | 8.39 | 1.352 | 6.53 | 3.280 | 54.7 |
| | 13 | 15.68 | 8.38 | 1.352 | 7.09 | 3.267 | 50.2 |
| | 14 | 15.39 | 8.39 | 1.352 | 4.77 | 2.436 | 55.7 |
| | 15 | 15.42 | 8.52 | 1.347 | 3.15 | 1.607 | 55.3 |
| | 16 | 15.45 | 8.53 | 1.346 | 3.41 | 1.448 | 46.1 |
| QS II | II-1 | 0.10 | 8.50 | 1.365 | 4.68 | 1.511 | 35.5 |
| QS III | III-1 | 0.10 | 8.34 | 1.371 | 8.78 | 1.675 | 21.1 |
| QS IV | IV-1 | 15.32 | 8.50 | 1.348 | 12.36 | 1.646 | 14.5 |
| | IV-2 | 15.35 | 8.64 | 1.342 | 6.23 | 0.832 | 14.4 |
| | IV-3 | 15.20 | 8.38 | 1.353 | 6.29 | 0.795 | 13.8 |
| | IV-4 | 15.07 | 8.57 | 1.345 | 6.19 | 0.805 | 14.1 |
| | IV-5 | 15.28 | 8.43 | 1.350 | 12.02 | 1.612 | 14.6 |
| | IV-6 | 15.31 | 8.40 | 1.352 | 12.11 | 1.575 | 14.2 |
| | IV-7 | 15.06 | 8.54 | 1.346 | 6.24 | 0.831 | 14.5 |
| | IV-8 | 15.46 | 8.53 | 1.346 | 12.19 | 1.649 | 14.7 |
| | IV-9 | 15.08 | 8.52 | 1.347 | 6.37 | 0.831 | 14.2 |