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An investigation of interaction of drilling fluids with gas hydrates in drilling hydrate bearing sediments

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ABSTRACT

Natural gas hydrates, preserved in deep ocean sediments, are supposed to be the future hydrocarbon source of energy. The possibility of gas production from natural gas hydrate bearing sediments (NGHBS) has been scrutinized by many researchers. Thermal stimulation, depressurization and use of thermodynamic inhibitors are three main proposed approaches to produce gas from the hydrates. When drilling through NGHBS, these mechanisms may cause wellbore instability and other drilling hazards such as severe mud gasification, low quality logging and cementing, casing collapse due to high pressure gas accumulation behind the casing, casing subsidence due to NGHBS failure and consequently instability of the ocean floor. In this study, the mechanism of thermal stimulation was studied. An experimental set up was designed and manufactured to investigate hydrate behavior when it comes in contact with warmer drilling fluids. Several muds with different additives were tested to investigate which properties are responsible for wellbore integrity maintenance. For this intention, linear temperature distribution in the hydrate was recorded for near distance from hydrate–mud contact and the hydrate dissociation rate was calculated. The purpose was to reduce the heat flux of the drilling fluid into the hydrate using relevant additives or by altering the mud circulation rate. Experimental results were validated by a hydrate dissociation model to obtain viable assessment for designing prospective exploration wells.

1. Introduction

Hydrates are crystalline compounds, in which water molecules trap small gas molecules in a cage like structure. Gas hydrates are stable at a span of low temperatures and high pressures, called the hydrate stability zone (Max et al., 2006). These condition are usually found in permafrost regions and deep-water seas (Sloan, 1998).

Hydrates are a threat to the drilling industry rather than being an energy source. During the drilling operation, heat is released to the hydrate formations, which may result in hydrate dissociation into gas and water. Drilling fluid gasification, wellbore instability (wall diffusion), casing running difficulties, widening wellbore, formation failure and casing subsidence and personnel health risks are examples of dangers which may occur during drilling operations in hydrate bearing sediments in deep waters. Another concern is the risk of hydrate dissociation during surface casing cementing. Negative effects on cement quality may result if gas bubbles flow into fresh cement. Escaped gas from dissociated hydrates may find its way to the sea floor, or to the other formations which may bring hazardous consequences to personnel and the drilling platform.

Hong et al. (2003) studied gas production from hydrates in porous media. They declared that heat transfer, as one of the three main mechanisms of hydrate production, has an important effect on hydrate safety and efficient production. Pooladi-Darvish and Hong (2004) stated that providing the necessary heat for hydrate dissociation is one of the main requirements of any production technique, which is determined by heat transfer. They showed that gas hydrate stability conditions frequently extend from the seafloor to 500 to 1700 feet below sea floor, but drilling operations disturbs hydrate stability conditions and usually result in hydrate dissociation. Iida et al. (2001) investigated Tetrahydrofuran (abbreviated as THF hereafter) hydrate formation and growth and dissociation in a one-dimensional heat transfer system under atmospheric pressure. They analyzed the heat transfer at the hydrate-solution interface across the hydrate and solution. Their experimental data are also in general agreement with that predicted by theoretical analyses of transient conduction at the hydrate-solution interface.

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Up to now, relatively little attention has been given to the problem because of the inherent complexity encountered when dealing with hydrate in contact with the drilling fluid. Due to the limited amount of experimental work on hydrate dissociation during drilling, the various parameters are not fully understood and a number of critical issues remain unresolved. In this paper, a 6 L volume reactor was used to investigate the heat transfer characteristics of hydrates in porous media during the dissociation process in a closed reactor by a thermal method. Three thermal resistance thermometers were distributed uniformly in a linear direction in the reactor. The hydrate decomposes at a different rate when it comes in contact with different drilling fluids in a closed reactor. The relation of temperature difference of the different positions in the linear direction and the hydrate dissociation rates were obtained. The characteristics of THF hydrate decomposition were also investigated.

2. Experimental design

2.1. Approach

Due to the similarity in the mechanical and thermal properties of methane hydrate and THF hydrate, different molar fractions of THF-Water solution were used in hydrate formation. When a well is drilled through a gas hydrate bearing formation, the hydrate is dissociated into gas and water and carried up by the drilling fluid. NGH dissociation occurs because drilling fluids change the temperature or pressure within the well bore affecting the NGHSZ. Also, using thermodynamic inhibitors such as salts in drilling fluids, causes hydrate dissociation. High performance drilling fluids were designed which met the simulated conditions. The temperature, rate of circulation, rheology and hydraulics of the drilling fluid were tested. The final results were validated by a theoretical model of hydrate dissociation. Table 1 shows some similarities and differences in physical properties of NGH and THF-Hydrate.

2.2. Apparatus

The experimental apparatus was constructed as to enable linear simulation of THF hydrate dissociation. Fig. 1 illustrates the test cell, the main section of the apparatus, in which aqueous THF solution mixed at a specific molar ratio with various sized sediments consolidated, and then, cooled into THF hydrate. The test cell was made of Steel and all surfaces of the test cell became stainless by phosphating. The dimensions of the test cell are: OD = 155 mm, ID = 111 mm and L = 580 mm. To record pressure and temperature values, four pressure transducers and four thermocouples can be attached to the test cell in a distance of 6 cm from distance to each other. In intent of providing an appropriate environment for hydrate formation, 16 holes were embedded in the reactor mantle for coolant fluid circulation. The drilling fluid ½ inch inlet, perforated on the upstream cap, provided a conduit for drilling fluid into the test cell. At the bottom of the test cell, a ¾ inch outlet is devised for drilling fluid circulation providing a drain for drilling fluid and washed out sediments. Schematics of the reactor and the experimental set up are illustrated in Figs. 1 and 2. Experimental set up of the hydrate evaluation test is shown in Fig. 3.

2.3. Procedure

2.3.1. Hydrate formation

Table 2 shows the main materials used in the experiment. First, the grain mixture was saturated with aqueous THF solution in a predetermined proportion. After that the mixture was discharged into the reactor and tightly packed. Then a piston was placed in the reactor and the upper cap was closed. The piston was used to press the mixture by HP N2 until the axial pressure increased to 1500 psi. After that, an antifreeze solution was circulated by a coolant circulator through holes embedded in the reactor mantle. For hydrate formation, the mixture was cooled to −10 °C by coolant circulation for 24 h. After that the hydrate temperature was kept at 0 °C for 3 h to stabilize hydrate HBS. The hydrate formation process

Table 1
Properties of methane and THF and their hydrates (Lee et al., 2007).

Property	Methane	Tetrahydrofuran (THF)
Properties of guest molecule		
Molecular formula	CH_4	C_4H_8O
Molecular size, Å	4.36	6.3
Dipole moment, D	0	1.63
Molecular polarizability, Å^3	2.6	7.9
Permittivity	1.7	7.5
Density, kg m^{-3}, at 293.5 K	N/A	888
Viscosity, cP, at 298.5 K	N/A	0.46
Surface tension, N m^{-1}, at 293.5 K	0.00676 at 140 K	0.028
Solubility in water at 293.5 K	0.04×10^{-3} [mole fraction]	Miscible
General characteristics		
Hydrate structure	I	II
Hydrate cavity diameter, Å	7.9, 8.66	7.82, 9.46
Ideal hydrate stoichiometric ratio	$CH_4 \cdot 6H_2O$	$C_4H_8O \cdot 17H_2O$
Slope of phase transformation boundary at 10 MPa, K MPa^{-1}	+0.96	−0.08
Thermal properties of the frozen state		
Heat capacity, kJ kg^{-1} K^{-1}, at 270 K	2.07	2.07
Heat of dissociation, kJ kg^{-1}, at 273 K	338.7	262.9
Thermal conductivity, W m^{-1} K^{-1}	0.5 @ 270 K	0.5 @ 270 K
Thermal diffusivity, m^2 s^{-1}	3×10^{-7} @ 270 K	2.8×10^{-7} @ 270 K
Thermal linear expansivity, K^{-1}, at 200 K	77×10^{-6}	52×10^{-6}
Mechanical properties of the frozen state		
Density, kg m^{-3}, at 273 K	910	~910
Interfacial tension, J m^{-2}	0.017 (19)–0.032	0.016–0.031
Adiabatic bulk compressibility, Pa, at 273 K	$\sim 14 \times 10^{-11}$	$\sim 14 \times 10^{-11}$
Isothermal Young's modulus, Pa, at 268 K	$\sim 8.4 \times 10^9$	$\sim 8.2 \times 10^9$
Shear wave speed V_s, m s^{-1}	1950	1890
Compressional wave speed V_p, m s^{-1}	3370 (23)~3800	3670
Strength, MPa	2–10	0.9–44

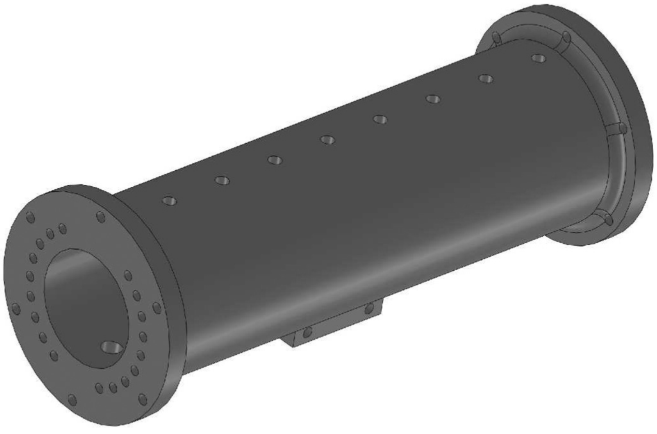

Fig. 1. Schematic of test cell.