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Effect of Gas Hydrate Drilling Fluids Using Low Solid Phase Mud System in Plateau Permafrost

Chen Liyi[a]*, Wang Sheng[a], Ye Changwen[a]

[a]*State key laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China*

Abstract

Designing and optimizing suitable drilling fluids for permafrost exploration to get gas hydrates at low temperature is one of most essential and urgent demands in the current research on exploration and exploitation of gas hydrates. The issue on rheological properties and maintaining borehole stability of drilling fluids is especially important to focus on. This work studies the gas hydrates and wellbore stability conditions and designs a low solid phase mud system with chemical additives. The measured values and effect on rheological and physical properties of the drilling fluids with different type and concentration of additives are studied. Hydration expansion is tested in laboratory to estimate the hydration property of different additives. It is showed that the drilling fluids with a dose of 1 % HT have suitable rheological and physical properties at low temperature. Potassium ion performs well in preventing borehole instability and gas hydrate dissociation. According to the study, the optimized drilling fluid formula is: base mud + 10 % NaCl + 5 % KCl + 1 ‰ NaOH + 1 % HT.

Keywords :Gas Hydrate; Drilling Fluid; Permafrost; Wellbore Stability; Low Temperature

1. Introduction

Gas hydrates are crystalline compounds formed when natural gas molecules are trapped by water molecules, which form an ice-like structure around the natural gas molecule [1]. They are stabilized in conditions of low temperature (normally ≤283 K) and high pressure (≥38 bar at 277 K) [2]. Naturally on earth gas hydrates can be found in the ocean and deep lake sediments, as well as in the permafrost regions. The amount of natural gas

* Corresponding author. Tel.: +86 13658056638.
E-mail address: cly@cdut.edu.cn

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molecules potentially trapped in gas hydrate deposits is significant (probable 10^{15} to 10^{17} cubic meter), which makes them of major interest as a potential energy resource [3].

The Tibetan Plateau, also known as the Qinghai–Tibetan Plateau, encompasses a vast and elevated plateau in southwestern China covering over extensive permafrost regions (1.73×10^{6} km^2) [4]. The thermodynamic phase equilibrium relations of biogenic and thermogenic gas hydrates demonstrate that the potential resource of natural gas trapped in gas hydrates is approximate 1.2×10^{11} to 2.4×10^{14} m^3 in Tibetan Plateau [5]. Along with the rising pressure of greenhouse effect and energy supply, the exploration and exploitation of gas hydrates in Qinghai–Tibetan Plateau has become one of the most attractive research fields [6].

Permafrost exploration during last two decades indicates that huge deposits of gas hydrates exist in the permafrost regions of the Tibetan Plateau. Drilling is the most direct and essential approach to explore the gas hydrates in permafrost regions [7]. When drilling in gas hydrate bearing sediments in permafrost regions, the change in pressure and temperature can make gas hydrates unstable. The dissociation of gas hydrates may bring about a large amount of problems such as the potential for fire or explosion related to drilling in the permafrost regions [8]. In addition, when gas hydrates dissociate, the rheological and physical properties of the drilling fluids will change that could lead to the drilling hole enlargement and even wellbore collapse. Serious collapse can result in drilling string and piping to get stuck causing drilling delay and paying large resource cost [9-10].

It is important to take applicable efforts to develop novel drilling techniques and suitable drilling fluids for the special drilling condition in the permafrost regions of the Tibetan Plateau. At present, the typical water-based and oil-based drilling fluids used in gas hydrate bearing sediments have already been research on permafrost exploration. It is showed from the study that inorganic salt and organic antifreeze such as ethylene glycol as anti-low temperature additives are able to inhibit gas hydrates decomposition and maintain wellbore stability [11]. The water-based drilling fluids possess more advantage that oil-based drilling fluids in inhibiting gas hydrates decomposition. However, there remain some significant technical challenges in developing appropriate drilling fluids for permafrost exploration. At the same time, there has not any report of successful application drilling fluids for the purpose of gas hydrate drilling in permafrost regions of the Tibetan Plateau [12].

In this paper, a formulation of low solid phase drilling fluid with antifreeze and special polymer treatment agent HT designed is described for drilling in gas hydrate bearing sediments in permafrost regions. We have discussed the existence conditions and stability of gas hydrates in permafrost exploration and designed a series of laboratory experiments to investigate the rheological properties and drilling effectiveness of drilling fluids. The theoretical and experimental data related to wellbore stability have also been reported in the conditions on using the low solid phase drilling fluids at low temperature. These works will set the stage for the forthcoming geological investigation of scientific research project on permafrost exploration for exploiting the gas hydrates in the Tibetan Plateau, under the auspices of the Chinese Ministry of Science and Technology.

Nomenclature

PV	plastic viscosity
AV	apparent viscosity
k	heat conductivity
qx	local heat flux
ΔV	filtrate volume
A	cross-sectional area
e	cake thick (mm)
s	cake permeability
ρ	density (kg/m-3)
η	viscosity (mPa•s)
θ	reading (r/min)

1.1. Gas hydrates Stability Conditions

Gas hydrates are a kind of crystal lattice substance formed by water and natural gas. There exists the chemical balance relation with water phase, gas phase and crystal lattice. The thermodynamic equation of the gas hydrates can be obtained according to the thermodynamic balance theory [19]:

$$\frac{\Delta\mu_0}{RT_0} - \int_{T_0}^{T_H} \frac{\Delta H_0 + \Delta C_K (T_H - T_0)}{RT_H^2} \mathrm{d}T_H + \int_{P_0}^{P_H} \frac{\Delta V}{RT_H} \mathrm{d}P_H = \mathrm{Ln}(f_w / f_{wr}) - \sum_{i=1}^{l} M_i \mathrm{Ln}(1 - \sum_{j=1}^{L} A_{ij}) \quad (1)$$

$$\mathrm{Ln}(f_w / f_{wr}) = \mathrm{Ln} x_w \quad (2)$$

If inhibitor is added into drilling fluids:

$$\mathrm{Ln}(f_w / f_{wr}) = \mathrm{Ln}(\mathrm{y_w} x_w) \quad (3)$$

Two main factors affecting the stability of the gas hydrates are the temperature and pressure conditions determined by the geothermal gradient and gas composition [5]. Some other factors have also a little effect including the pore-fluid salinity and pore-pressure. Gas hydrates often dissociate at point in the formation when the temperature and pressure fall outside the stability phase boundary of the gas hydrates [2]. The dissociation of the gas hydrate can release natural gas and water to increase the pore pressure and break the thermodynamic equilibrium [13]. Gas hydrate stability phase diagram is showed in Fig. 1 to indicate the relationship between the affecting factors and stability of the gas hydrates [14]. In this phase diagram, the three geothermal gradients such as 1.5, 2.5 and 3.5 °C/100m are used to show the sub-permafrost temperature profiles. The two gas hydrate curves represent the stability of the gas hydrates with different chemical composition. The gas hydrate stability phase diagram illustrates that the variations in temperature, pore-pressure and gas composition can affect the thickness of the gas hydrate stability bearing sediments. Permafrost thickness and geothermal gradient affect the stability zone of gas hydrates, and the stability zone of gas hydrates is thicker coupling with thicker permafrost and smaller geothermal gradient [15].

Gas hydrate bearing sediments may unavoidably dissociate during permafrost exploration as a part of gas extraction from the hydrate itself, which will directly change the strength of the gas hydrate bearing sediments [16]. We have to try our best to inhibit the dissociation of gas hydrates to ensure safe drilling operations according to using rational drilling fluids. The drilling fluids should possess good stability and rheological properties to prevent the dissociation of gas hydrates at low temperature [17].

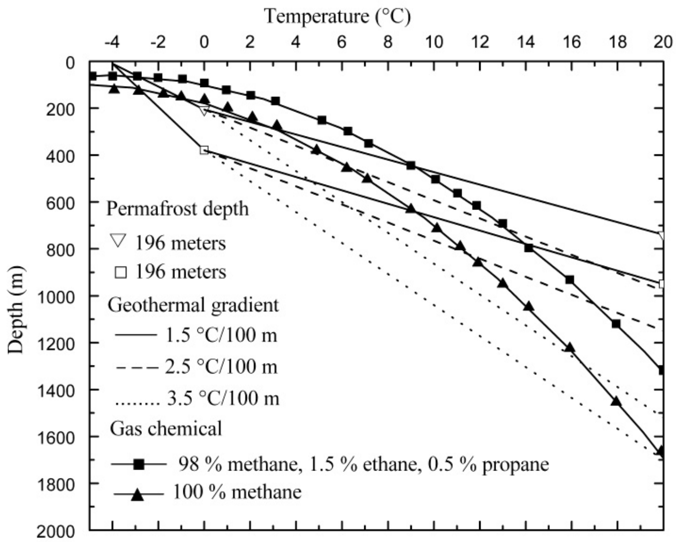

Fig. 1 Gas Hydrates Stability Phase Diagram

1.2. Wellbore Stability Conditions

Drilling the wellbore is the first and essential step to explore the gas hydrate bearing sediments in permafrost regions [18]. The nature of borehole instability essentially is a common problem caused by mechanically unbalanced borehole pressures. An adequate mud density and necessary borehole hydrostatic pressure are the necessity and primary guarantee for obtaining a stable borehole [19]. In the permafrost exploration, wellbore instability as the most serious problem mainly occurs as a result of four primary mechanisms such as heat transfer, fluid flow, gas hydrate dissociation and pressure redistribution in drilling the wellbore [20].

There exists the temperature gradient between the drilling fluids and gas hydrate bearing sediments [21]. The law of heat conduction, also known as Fourier's law, states that the time rate of heat transfer through a medium to the negative gradient in the temperature. Heat transport is described by Fourier's law:

$$q_x = -k\frac{\Delta T}{\Delta x} \tag{4}$$

Where q_x is the local heat flux, k is the heat conductivity, $\Delta T/\Delta x$ is the temperature gradient. The minus shows that the direction of heat flux and temperature gradient is opposite.

Darcy's law is a phenomologically derived constitutive equation that describes the flow of a fluid through a porous medium. It also forms the scientific basis of fluid permeability used in the earth sciences, particularly in geological exploration. Fluid flow is described by Darcy's law:

$$\Delta V / \Delta t = s\Delta P / \eta e A \tag{5}$$

Where ΔV is filtrate volume after t, η is the viscosity of the liquid, A is the cross-sectional area to flow, e is cake thick after t and s is cake permeability.

2. Preparation and Optimizing Drilling Fluids

2.1. Wellbore Stability Conditions

It is most important to control the density and viscosity of base mud [22]. The viscosity of prepared low solid phase mud system will get too high to hold the suitable shear force and rheological behaviour when the density of base mud is high. The desired density of base mud should is prepared between 1.02 and 1.05. API filtration of the base mud should be no more than 15 ml/0.7 MPa.30 min.

The clay as the essential part of base mud determines the drilling effect of drilling fluids. The hydration property of clay especially influences the efficiency of the base mud. The main mud-making clay belongs to natural calcium bentonite in china. Calcium ion is easy to combine with the surface negative charge of clay particles to make the hydration and mud-making property of the natural calcium bentonite weak. The sodium ion added to base mud can exchange the calcium ion which absorbs in the surface of clay particles to improve the rheological behaviour and API filtration. According to our study, the optimized formula of base mud is water + natural calcium bentonite (5%) + sodium carbonate (6%).

2.2. fi Wellbore Stability Conditions

Because of the specially geological and drilling environment, exploration and exploitation of gas hydrates in plateau permafrost requires the drilling fluids to hold good rheological and uncongealable behavior at -10 °C. The foundation liquids can provide low temperature and low solid phase condition for drilling fluids in the permafrost regions to mainly depress the freezing point and keep suitable property of the drilling fluids. At present, there are three major categories including halide, formate and organic alcohol used as antifreezing foundation liquids. The freezing points of three categories of antifreezing foundation liquids are listed in Tab. 1. From the data of Tab.1, we have found that the difference of freezing points of three categories of antifreezing foundation liquids is little. NaCl is used as the main antifreeze agent because of low price, easy use and good antifreeze effect. KCl with evident anticollapse effect is often used at 5 % mass fraction to keep borehole stability. In addition, the added moderate NaOH can adjust the hydrogen ion concentration (PH value) of the drilling fluids. In our study, we selected the 10 % NaCl + 5 % KCl + 1 ‰ NaOH solution as antifreezing foundation liquids.

Table 1 The Freezing Point of Antifreezing Foundation Liquids[a]

Added material	15 % NaCl	10 % NaCl + 5 % KCl	15 % Sodium formate	20 % Ethylene glycol
Freezing Point / °C	-12	-11	-11	-10

[a]The all foundation liquid is water solution.

2.3. Selecting Additives for Low Solid Phase Mud System

Adding NaCl to the drilling fluids can make the system to keep good rheological behaviour at low temperature. However, the concentration over 3 % of NaCl can make the little clay particles to coalesce into large particles and increase the API filtration. As we known, chemical additives have prominent effect on diluting and lowering the API filtration in low solid phase drilling fluid systems. We often need select suitable chemical additives to make NaCl less likely to bring adverse effect to the mud system and improve the mud property to better work on the permafrost exploration.

Ferric chomium lignin sulfonate (FCLS) is commonly used as an effective thinner for water base drilling fluids for salt water of varied salt concentration. The common dosage of FCLS is usually 0.2 % - 1.0 %. Sulfomethylated tannin (SMT) is free-flowing powder used as an appropriate thinner with accompanying API filtration reduction effect. The regular dosage of SMT is 0.5 % - 2.0 %. SHR and HT are anti-salt specialty resins as effective thinner and filtrate reducer used to enhance the stability and reduce the API filtration of drilling fluids. The regular dosage of specialty resins is 0.2 % - 2.0 %. In our experiments, we respectively researched the four additives as thinner and API filtration control agent for designing an optimized formula of drilling fluid systems.

3. Apparatus and Procedure

All tested drilling fluid systems were placed into an inclosed thermostat at a constant temperature of -10 °C for

6h. After thermal equilibrium has been achieved at the required temperature, the drilling fluid systems were tested for obtaining the rheological and physical properties [23].

The density ρ was measured with Ostwald-Sprenge-type pycnometers having a bulb volume of 10 cm^3 and an internal capillary diameter of about 1 mm. The density is determined from the mass of the sample and the volume of the pycnometers. The readings from pycnometers are averaged. The absolute uncertainties in the density measurements are estimated to be within (± 0.005) g/cm^3. The Marsh funnel viscosity η_m was measured by marsh funnel with a 4.7 mm inside diameter. The time of flowing out the funnel in seconds was reported as the Marsh funnel viscosity. The plastic viscosity PV and apparent viscosity AV were measured with 6 speed viscometer driven rotational type. The values were obtained from the reading of 300 and 600 r/min when the dial disc had got into a steady value. The uncertainty of viscosity measurement was ± 0.02 mPa·s.

$$PV = \theta_{600} - \theta_{300} \quad (6)$$

$$AV = 1/2\theta_{600} \quad (7)$$

Where PV is the plastic viscosity; AV is the apparent viscosity;θ_{300} andθ_{600} are the reading of 300 and 600 r/min, respectively.

The API filtration was measured using API filtration press under a pressure of 7.0 ×10^5 Pa applied with nitrogen gas and a 9 cm filter paper. A dry graduated cylinder was placed under the drain tube to receive the filtrate. The volume of filtrate was recorded at the end of 30 minutes.

Penetrating property of drilling fluids was measured with CST- osmoscope (type CST-2, Shanghai Mining Instruments Factory, China) composed with a filter tunnel, Standard filter paper and a calculagraph. The values of calculagraph were obtained from the time of filtrate penetration from one electrode to the other electrode. The uncertainty of time measurement was ± 0.1 s. Lubricating property of drilling fluid systems was measured with lubrication coefficient determinator (type DNR-1, Baroid Drilling Fluids Inc, USA). The uncertainty of lubricating property measurement was ± 0.01.

Hydration expansion of permafrost as an essential property is used to select the suitable drilling fluid to maintain borehole stability. In the experiments, kilndried artificial sodium soil was stirred with deionized water and pressed under 20 MPa to form standard rock sample at -10 °C. The standard rock sample then was immersed in the drilling fluid systems. The entire system was frozen in a thermostat (FM25-ME, JULABO Laortechnik GmbH 77960 Seelbach, Germany) with a thermal stability (± 0.01) °C at -10 °C. After thermal equilibrium has been achieved, the vertical expansion of standard rock sample was tested each half an hour.

4. Results and Discussion

The measured values and effect on rheological and physical properties of density ρ, Marsh funnel viscosity η_m, plastic viscosity PV and apparent viscosity AV for all drilling fluid systems are listed in Fig. 2 and Fig.3. It is shown that, with increasing concentration of four additives, all density ρ, Marsh funnel viscosity η_m, plastic viscosity PV and apparent viscosity AV have increasing trends. The rheological parameters of additive HT are higher at the same concentration than the parameters of the other three additives. These results indicate that the additive HT has better performance of stability and rheological behaviour at low temperature.

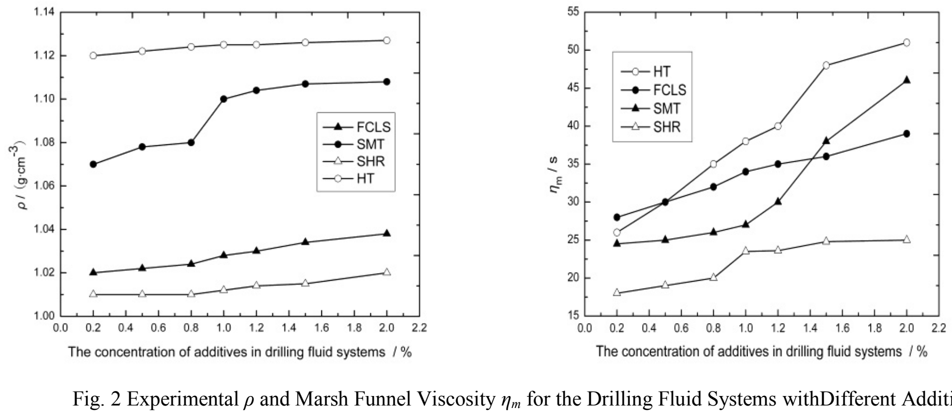

Fig. 2 Experimental ρ and Marsh Funnel Viscosity η_m for the Drilling Fluid Systems withDifferent Additive

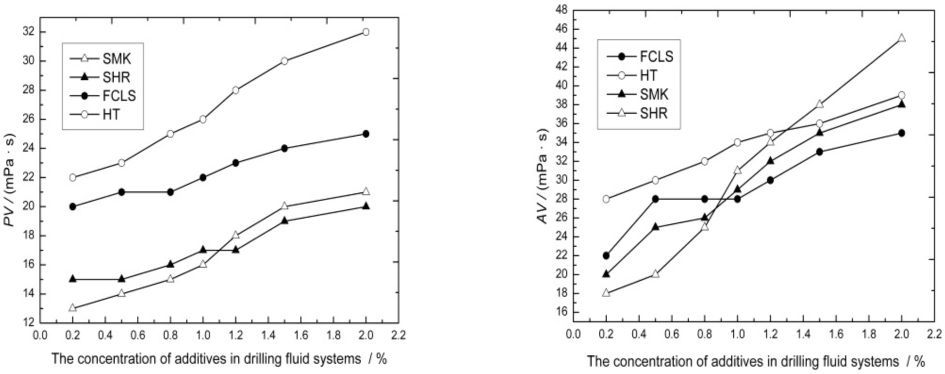

Fig. 3 Plastic Viscosity *PV* and Apparent Viscosity *AV* for the Drilling Fluid Systems with Different Additive

The experiments were done for evaluating the potential filtration reduction effect and borehole stability of the additive HT in different concentrations of drilling fluids. The measured values of API filtration, penetrating and lubricating property are listed in Tab. 2. The API filtration is 8 ml for 30 minutes with a 0.8 mm tough and homogeneous filter cake when the drilling fluid with 1 % HT is used. The API filtration can be lesser with the addition more HT. However, as a special polymer treatment agent, too high concentration of HT inevitably results in excessive shear viscosity to the disadvantage of permafrost exploration at low temperature. Penetrating time and lubricating coefficient of this drilling fluid with 1 % HT are 8324 s and 0.19 respectively which implies desirable physical performance. It is showed that the drilling fluid added 1 % HT has suitable filtration and physical property.

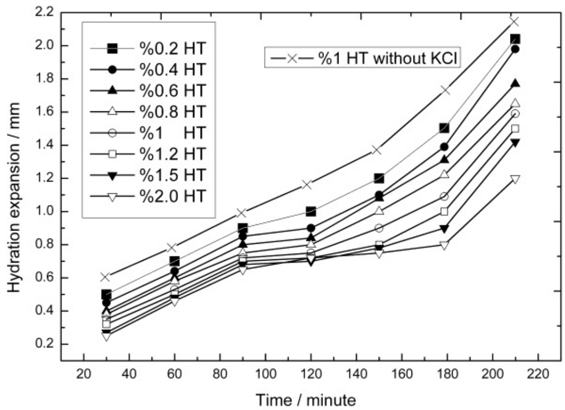

Fig. 4 Hydration Expansion for the Drilling Fluid Systems with Additive HT at Different Concentration and Time

The hydration expansion of permafrost for the drilling fluid systems with different content of HT was presented in Fig. 4. It is showed from the Fig. 4 that the hydration expansion is almost linear increase with the incremental time and concentration of HT in drilling fluids. The drilling fluid with 1 % HT has appropriate hydration expansion to show the potential capacity to solve the borehole instability problems. At the same time, potassium ion added in drilling fluids has obvious effect on keeping borehole stability because potassium ion as an exchangeable cation often can locate between unit layer and act as an interlayer cation to weaken t0he hydration expansion and stabilize the borehole.

Table .2 API Filtration, Penetrating Time, Filter Cake Thickness and Lubricating Coefficient for Drilling Fluid Systems with HT at -10 °C

Content of HT (%)[b]	API filtration (ml)	Filter cake thickness (mm)	Penetrating time (s)	Lubricating coefficient

0.2	24	5	5879	0.26
0.4	20	4	6543	0.25
0.6	18	4	6987	0.24
0.8	16	1	7012	0.22
1	10	0.8	7568	0.20
1.2	8	0.8	8342	0.19
1.5	9	0.8	8897	0.18
2.0	7	0.9	10325	0.15

[b]The base formulation is base mud + 10 % NaCl + 5 % KCl + 1 ‰ NaOH.

5. Conclusions

In this study, a novel drilling fluid formula with low solid phase is designed and optimized for putting into Qinghai–Tibetan Plateau use in exploration and exploitation of gas hydrates at low temperature. HT as a specialty resins additive is added into the drilling fluids to improve the rheological and filtration properties for meeting the low temperature drilling requirements. The relationship between borehole stability and drilling fluids is studied. According to experiments, it is found that potassium ion as an instability inhibitor plays an important role in preventing borehole collapse. The optimized drilling fluid formula is determined as: base mud + 10 % NaCl + 5 % KCl + 1 ‰ NaOH + 1 % HT. Permafrost exploration in Qinghai–Tibetan Plateau using this drilling fluid formula is under way.

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