

## **ANALYSIS ON CHARACTERISTICS OF DRILLING FLUIDS INVADING INTO GAS HYDRATES-BEARING FORMATION**

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### **ABSTRACT**

Formations containing gas hydrates are encountered both during ocean drilling for oil or gas, as well as gas hydrate exploration and exploitation. Because the formations are usually permeable porous media, inevitably there are energy and mass exchanges between the water-based drilling fluids and gas hydrates-bearing formation during drilling, which will affect the borehole's stability and safety. The energy exchange is mainly heat transfer and gas hydrate dissociation as result of it. The gas hydrates around the borehole will be heated to decomposition when the drilling fluids' temperature is higher than the gas hydrates-bearing formation in situ. while mass exchange is mainly displacement invasion. In conditions of close-balanced or over-balanced drilling, the interaction between drilling fluids and hydrate-bearing formation mainly embodies the invasion of drilling fluids induced by pressure difference and hydrate dissociation induced by heat conduction resulting from differential temperatures. Actually the invasion process is a coupling process of hydrate dissociation, heat conduction and fluid displacement. They interact with each other and influence the parameters of formation surrounding the borehole such as intrinsic mechanics, pore pressure, capillary pressure, water and gas saturation, wave velocity and resistivity. Therefore, the characteristics of the drilling fluids invading into the hydrate-bearing formation and its influence rule should be thoroughly understood when analyzing on wellbore stability, well logging response and formation damage evaluation of hydrate-bearing formation. It can be realized by establishing numerical model of invasion coupled with hydrate dissociation. On the assumption that hydrate is a portion of pore fluids and its dissociation is a continuous water and gas source with no uniform strength, a basic mathematical model is built and can be used to describe the dynamic process of drilling fluids invasion by coupling Kamath's kinetic equation of heated hydrate dissociation into mass conservation equations.

*Keywords:* gas hydrates-bearing formation, drilling fluids, hydrate dissociation, invasion, model

### **NOMENCLATURE**

$A_s$	total surface area of hydrates in a unit volume	$k_{rw}$	relative permeability coefficient of water
$k$	absolute permeability coefficient of porous medium[m <sup>2</sup> ].	$k_{rg}$	relative permeability coefficient of gas
$K_d'$	dissociation constant of hydrate under constant-pressure heated	$M_g$	methane molecular weight
		$M_w$	water molecular weight,
		$m_g$	mass rate of gas which is decomposed from hydrate[kg/s]

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$n_w$	amount of water molecules in hydrate molecule
$P_w$	flow pressure of water[MPa]
$P_g$	flow pressure of water and gas[MPa]
$P$	pore pressure
$S_h$	hydrate saturation
$S_w$	water saturation
$S_g$	methane saturation
$T$	temperature of unit volume
$T_{eq}$	phase equilibrium temperature of hydrate under $P$

#### *Greek letters*

$\rho_w$	water density[kg/m <sup>3</sup> ]
$\rho_g$	gas density[kg/m <sup>3</sup> ]
$\rho_h$	hydrate density[kg/m <sup>3</sup> ]
$\mu_w$	kinetic viscosity of water[Pa• s]
$\mu_g$	kinetic viscosity of gas[Pa• s]

#### *Subscripts*

$d$	dissociation
$eq$	equilibrium
$g$	gas
$h$	hydrate
$w$	water
$s$	surface

## INTRODUCTION

Gas hydrates are regarded as the potentially replaceable energy in the future. According to Klauda and Sandler[1], there is 74 400Gt of CH<sub>4</sub> trapped in hydrates buried in oceanic zone, which is 3 orders of magnitude larger than worldwide conventional natural gas reserves. And in order to explore and exploit the gas hydrate stored in the deep underground, drilling is inevitably needed.

During the drilling process, drilling fluids (water-based drilling fluids are mentioned in this paper) inevitably contact with the gas hydrate-bearing formation and exchange energy and substances with it. Just as drilling activities prove that the interactions between drilling fluids and formation, such as seepage, diffusion, and heat transfer, can change the stress status of rocks surrounding borehole. Especially during drilling in marine hydrate-bearing formation, the formation is a porous medium with comparatively high permeability and temperature and pressure in the borehole is changing during drilling, which will break the equilibrium condition of hydrate's thermodynamics and rocks mechanics in-situ. As a result, it will lead to hydrates dissociation and

affect the wellbore stability and drilling safety[2]. Collett et al[3]and Maurer[4] once had detailed discussions about the issues of wellbore stability and drilling safety involved in hydrate drilling. Sheila et al[5], Tan et al[6] and Freij-Ayoub[7] had a further discussion of how to establish a model of hydrate wellbore stability. Therefore, the interactions between drilling fluids and formations during the drilling process in hydrates-bearing formations can not be neglected. The researches of wellbore stability and borehole safety are all based on the analysis and understanding of interaction of heat and fluids between drilling fluids and hydrate-bearing formation.

## ANALYSIS ON INTERACTIONS BETWEEN DRILLING FLUIDS AND HYDRATE-BEARING FORMATION

The interactions between drilling fluids and hydrate-bearing formation is more complicated than that of the ordinary oil or gas formation, and its representations can be concluded into following aspects.

### Mass exchanges

Considering environmental protection and operating cost, the most widely used mud is water-based drilling fluids system in the oceanic drilling of oil and gas. In the same way, the hydrate also exists in/under seafloor sediments of deep oceans, and the water-based drilling fluids have a good inhibitive ability towards hydrate[8].Therefore, the popularly used system in the drilling for exploration and exploitation of oceanic hydrate is the water-based drilling fluids. The higher the density of drilling fluids is, the higher the bottom hole pressure will be. When the pressure is higher than pore pressure, the drilling fluids will flow through the filter cake and permeate into the formations surrounding the well, thus will displace the original pore fluids and affect the pore pressure and permeability of formation. Contrariwise, the bottom hole pressure will be lower. When it is lower than the formation pressure, the fluids surrounding the well will reversely flow into the well, and this is not good for the balance of borehole mechanics. At the same time, hydrate will decompose under depressurization, it is worse for the wellbore stability and borehole safety. Therefore, to keep the pressure in borehole higher than the pore pressure (but not higher than fracturing pressure) is an advisable safe manner for hydrate drilling. Besides, the mineralization of

drilling fluids is different from that of the symbiosis water in formation. A large amount of salt is always added into the drilling fluids for gas hydrate as inhibitors and the dissociation of hydrates will also decrease the mineralization degree of the pore water in formation, both will cause that the mineralization degree of the drilling fluids is higher than that of the pore water in hydrate-bearing formation, therefore, the difference of chemical potential will drive pore water towards hole which is opposite to the hydraulic differential pressures exists between hole pressure and formation. But under the condition of over-pressure drilling, filter cake can be regarded as a semi-permeable membrane, water as well as positive and negative ions penetrate into the formation through this layer, and it is independent of mineralization degree of pore water. So, under the aforementioned condition, one of interactions between the drilling fluids and hydrate-bearing formation around the borehole is represented as the seepage and displacement under hydraulic differential pressure.

#### **Dissociation of hydrate surrounding borehole**

At the moment of opening the borehole, the pressure release and friction heat inside the well will cause inevitable dissociation of the hydrate surrounding the well. Besides, hydrates are buried under shallow marine sediments, the formation temperature is low. So the temperature of drilling fluids is often higher than the formation temperature in-situ. After the circulation of drilling fluids is established, the hydrate-bearing formation will be heated and thus the hydrate dissociation will be speeded up. Because the mechanical properties of the hydrate-bearing formation are quite different from those of the formation without hydrate[9-11], the hydrate dissociation will influence the stress distribution of rock surrounding borehole[7]. What's more, it will add water and gas in the bore, causing the increase of pore pressure[7][12], which also influence the effective stress distribution of rock surrounding borehole. Therefore, the dissociation of hydrate surrounding well caused by the heat-transfer between the drilling fluids and hydrate-bearing formation is another main representation of interactions between them, and it is also the key factor to affect the wellbore stability and drilling safety of the hydrate-bearing formation.

#### **Heat exchange**

The change of hole temperature makes hydrate unable to keep stability, and it also causes borehole to generate additional heat stress, which will influence the mechanical stability of borehole. But then, because the storage location of marine hydrate is over 300m water depth, the temperature of drilling fluids circulation is not high. While the hydrate formation often lies under seafloor within 0-800m distance, so formation temperature is not high either. Owing to both of the aspects, the difference in temperature between drilling fluids and formation is not large, and the heat stress caused by heat exchange is not as obvious as that in the high-temperature deep well and can be neglected. The heat exchange mainly influences the hydrate stability near borehole.

Thereby, the interactions between drilling fluids and hydrate-bearing formation during drilling process are mainly represented as drilling fluids invading into the hydrate-bearing formation through seepage and displacement under differential pressures and the heated dissociation of hydrate by heat transfer under difference in temperature (Fig.1). These two is coupled together. Both the invasion of drilling fluids and hydrate dissociation will increase the pore pressure and decrease the effective stress. At the same time, they also change the formation permeability, acoustics parameters and resistance rate. Therefore, the research on characteristics of drilling fluids invading into hydrates-bearing formation is the basis for future analysis of wellbore stability as well as evaluation of well logging response and formation damage.

### **ANALYSIS ON CHARACTERISTICS OF DRILLING FLUIDS INVADING INTO HYDRATES-BEARING FORMATION**

#### **Invasion process of drilling fluids**

Drilling fluids will seep into the hydrate-bearing formation and displace the water and gas in the formation under differential pressures. At the same time, their higher temperature cause dissociation of hydrate surrounding borehole. The decompose water and gas as well as the drilling fluids invasion will flow deep into formation driven by the newly-invaded drilling fluids. Therefore, the invasion of drilling fluids in the hydrate-bearing formation is coupled with hydrate dissociation and heat transfer.

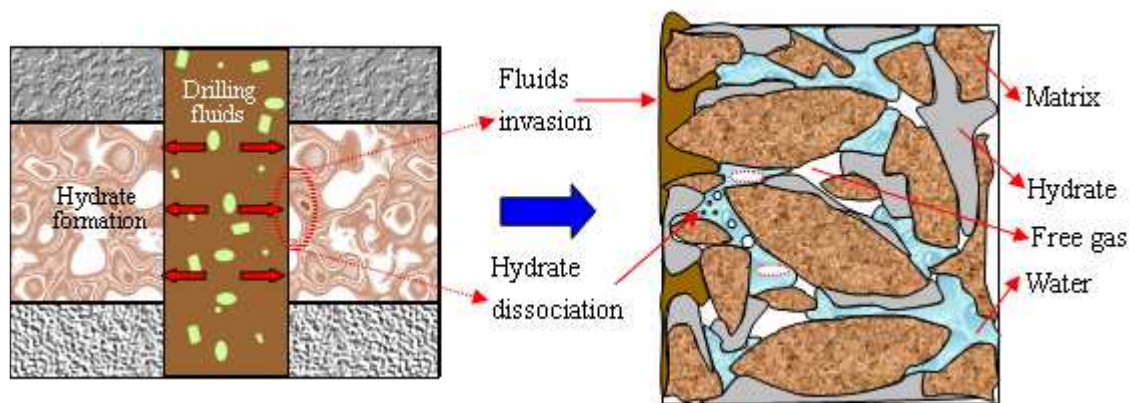


Fig.1 Interactions between drilling fluids and hydrate-bearing formation

When the borehole is opened, the solid-phase and liquid-phase in drilling fluids immediately penetrate into the borehole, which causes the water content surrounding the borehole to increase largely. At the same time, the hydrate surrounding borehole is quickly decomposed into water and gas because of the rapid change of temperature and pressure, thus the water content surrounding the borehole is further increased. If the formation medium is sandstone, it will possibly be liquefied. The dissociation of hydrate improves the penetrability and speeds up the invasion speed, which makes against forming filter cake. Therefore, during the period from the opening of borehole to the completed dissociation of hydrate surrounding the borehole, the borehole is the most unstable. With the drilling going on, the filter cake is formed gradually, and the mud filtrate seeps through the filter cake and further invades into formation. At this stage, the temperature change is not dramatic, thus the speed of hydrate dissociation is comparatively slow. In addition, the invasion and hydrate dissociation increase pore pressure, which also slows the hydrate dissociation. During the later phase of invasion, gas and water content increase and pore pressure continuously rises, the gas is compressed, and mud filtrate almost stops seeping, but diffusion still exists. At this stage, if the temperature and pressure inside pores are appropriate, part of the gas and water will reform hydrate again.

Therefore after the invasion becomes stable, the invasion section surrounding the borehole can be divided into five layers. As Fig. 2 illustrates, the first layer contains filter cake, all the components of drilling fluids touch directly with it, and the

thickness of this layer may range from several millimeters to several centimeters. It does not contain hydrate or free gas but muds. The second layer does not contain hydrate and free gas too, but contains mud filtrate. In the third layer, there exists mud filtrate and free gas and no hydrate. In the third layer, water (including water in the filtrate, water dissociated from hydrate and connate water), gas (gas dissociated from hydrate and connate gas) and hydrate are three-phase coexistence, and they are in dynamic equilibrium. The last layer is the hydrate-bearing formation which keeps its natural characteristics during the whole drilling process, and it does not interact with mud filtrate as well as the gas and water decomposed from hydrate at all. So the invasion of drilling fluids can be described as an issue of hydrate boundary movement during dissociation, its essence is an equilibrium issue of dynamics and thermodynamics. Only the existence of seepage and displacement makes this issue become comparatively complicated.

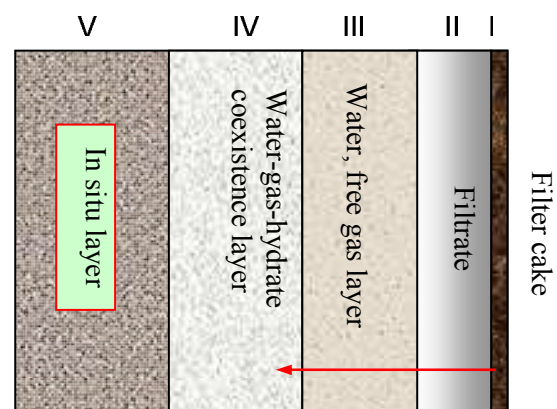


Fig.2 Invasion layers of drill fluids

### **Analysis on heat transfer during the drilling fluids invasion**

The invasion of drilling fluids into the oil and gas-based formation used to be regarded as an isothermal seepage process, and the influence caused by temperature is always neglected. Actually, drilling process is a nonadiabatic process. The circulation of drilling fluids and invasion of filtrate into borehole formation are always accompanied with heat transfer. Especially during the drilling of hydrate-bearing formation, because of the combined actions of driller friction, comparatively high circulation temperature of drilling fluids and short distance between storage location of marine hydrate and seafloor (the ground temperature is comparatively low), heat will transfer from drilling fluids to hydrate-bearing formation through framework conduction and convective heat transfer of invading fluids, which causes formation temperature to rise and the hydrate surrounding borehole to be decomposed. Under the condition of over-pressure drilling, temperature becomes a main impetus to the hydrate dissociation. Therefore in analyzing the invasion of drilling liquid into hydrate-bearing formation and its influence to wellbore stability, it can not be regarded as an isothermal process. Furthermore, hydrate dissociation itself is an endothermic reaction during the decomposing process. The formation temperature will be influenced, and the change of temperature will influence the speed of hydrate dissociation at the same time. Therefore, in analyzing the characteristics of the invasion of drilling fluids into hydrate-bearing formation, temperature should be considered as an important element, and it is a non isothermal process.

### **Mathematical model of drilling fluids invasion coupled with hydrate dissociation**

According to the aforementioned analysis on invasion process of drilling fluids and characteristics of heat transfer, the main feature of the invasion into hydrate-bearing formation is that temperature change and hydrate dissociation are accompanied with the invasion process. Under the condition of over-pressure drilling, temperature is the main factor in hydrate dissociation, and it controls the speed and range of the dissociation. The invasion of drilling fluids and the hydrate dissociation change the pore pressure, and thus influence the flow of pore fluids and speed of hydrate dissociation. Therefore, the invasion process is actually a coupling process of hydrate

dissociation, heat conduction and fluid seepage. They interact with each other and influence the parameters of formation surrounding the borehole such as intrinsic mechanics, pore pressure, capillary pressure, water and gas saturation, wave velocity and resistivity. Therefore, building an adequate invasion numerical model becomes an effective approach to evaluate these influences and analyze log data, wellbore stability and formation damage evaluation.

Holder et al.[13] built a mathematic model of hydrate dissociation under depressurization, the model is based on the transfer of heat and mass in formation, and they thought the sensitive heat transfer in formation provided energy for the hydrate dissociation. Makogon[14] supposed that the depressurized dissociation process of gas hydrate is similar as the solid melting. He used the classical Stefan problem to describe the process, and built a basic lineal equation to describe the movement of natural gas in porous medium and heat transfer, but his model neglected the influence caused by the water generated from hydrate dissociation. The model of Goel et al.[15] also neglected the influence on the gas flow caused by the water flow in the reservoir. Actually, the water will block the hydrate dissociation. A one dimensional model of Yousif et al.[16] considered the movement of water phase. As a result, they found the maximal water content will occur in formation during the hydrate dissociation process, it reduced the relative permeability of gas phase, influenced gas flow and thus increased pore pressure, and further conversely influenced the hydrate dissociation. Moridis et al.(2002,2003) simulated the release, phase behavior and nonisothermal flow of methane in deep sea and permafrost area with universal numerical simulator TOUGH2 and program module HYDRATE. Their mathematical model was realized through resolving the coupled mass and thermal conservation equations. All of the aforementioned scholars considered the coexistence area of gas-liquid-hydrate as a border to separate gas-liquid area and hydrate-liquid area, and regarded hydrate dissociation as a quasi-static system.

In fact, from the beginning of the forming of the hydrate-bearing formation, the gas-liquid-hydrate three phases coexist in it. The invasion of the drilling fluids can be regarded as a reverse-process of depressurization exploitation, but because the invasion of drilling fluids and the dissociation of hydrate dynamically happen at the same time, they

don't last for a long time, and the hydrate dissociation itself will influence fluids seepage and heat transfer. Therefore, the aforementioned models can not accurately describe the dynamic process of invasion, and they can not make sure the changes of water, gas and hydrate saturation and permeable characteristics of a certain area during the invasion process. So, the kinetic behavior of hydrate dissociation should be considered into the mass equations and build a new mathematical model.

Without regard to diffusion effect, the invasion of drilling fluids in the hydrate-bearing formation can be described as a seeping displacement and heat transfer of multiphase fluids with phase change (hydrate dissociation) in porous medium. Obviously, the influence of hydrate dissociation on seepage is the key point in model building. In this way, hydrate dissociation can be treated as a portion of pore fluids and a continuous water source and gas source with no uniform strength. Kamath's et al. [17-18] kinetic equation of heated hydrate dissociation as well as Brown's thermodynamics equation of hydrate phase balance are coupled into mass conservation equations, and a thermal-flow-hydrate coupled theoretical model is established by considering the invasion of drilling fluids and hydrate dissociation in hydrate-bearing formation, its basic equations is like as following:

$$\phi \frac{\partial}{\partial t}(S_w \rho_w) = \nabla \cdot \left[ \frac{kk_{rw} \rho_w}{\mu_w} \nabla P_w \right] + \frac{m_g n_w M_w}{M_g} \quad (1)$$

$$\phi \frac{\partial}{\partial t}(S_g \rho_g) = \nabla \cdot \left[ \frac{kk_{rg} \rho_g}{\mu_g} \nabla P_g \right] + m_g \quad (2)$$

$$\phi \frac{\partial}{\partial t}(S_h \rho_h) = -\frac{m_g}{M_g} (n_w M_w + M_g) \quad (3)$$

$$(\rho C)_e \frac{\partial T}{\partial t} + q_h \frac{m_g}{M_g} = \nabla \cdot T \left[ \left( \frac{kk_{rw} \rho_w C_w}{\mu_w} \nabla P_w + \frac{kk_{rg} \rho_g C_g}{\mu_g} \nabla P_g \right) + \lambda_e \nabla^2 T \right] \quad (4)$$

Where  $S_h$  is hydrate saturation,  $S_w$  is water saturation,  $S_g$  is methane saturation.  $\rho_w$  is water density,  $\text{kg/m}^3$ ;  $\rho_g$  is gas density,  $\text{kg/m}^3$ ,  $\rho_h$  is hydrate density,  $\text{kg/m}^3$ .  $m_g$  is the mass rate of gas which is decomposed from hydrate,  $\text{kg/s}$ ,  $M_g$  is the

methane molecular weight,  $M_w$  is water molecular weight,  $n_w$  is the amount of water molecules in hydrate molecule, for methane hydrate,  $n_w \approx 6$ .  $k$  is the absolute permeability coefficient of porous medium,  $\text{m}^2$ . Ecker et al.[19] regarded it as the function of hydrate saturation.  $k_{rw}$ ,  $k_{rg}$  is relative permeability coefficient of water and gas, Bondarev et al. regard them as only function of water saturation.  $\mu_w$ ,  $\mu_g$  is the kinetic viscosity of water and gas,  $\text{Pa} \cdot \text{s}$ .  $P_w$ ,  $P_g$  is the flow pressure of water and gas,  $\text{MPa}$ .

According to Kamath et al.[17-18], kinetic equation of heated hydrate dissociation is:

$$m_g = K_d' A_s M_g (T - T_{eq}(P)) \quad (5)$$

Where  $K_d'$  is dissociation constant of hydrate under constant-pressure heated.  $A_s$  is the total surface area of hydrates in a unit volume, and may be regarded as a function of hydrate saturation.  $T$  is the temperature of unit volume.  $T_{eq}$  is the phase equilibrium temperature of hydrate under the average pore pressure  $P$ . By using Dickens et al.[20] data, Brown (1996) made a more precise fitting, and gained the temperature and pressure equilibrium function of brine-methane-hydrate system, which is

$$\frac{1}{T_{eq}} = 3.83 \times 10^{-3} - 4.09 \times 10^{-4} \log_{10} P + 8.64 \times 10^{-5} (\log_{10} P)^2 \quad (6)$$

Then state equations, assistant equations are combined with the aforementioned basic equations (1)- (4), and initial condition and boundary condition are given, the basic equations can be solved by numerical method. If it is simplified as radial displacement process, then the basic formula (1)-(4) can be rewritten in polar coordinate, and the position relationship between the invasion frontier of mud filtrate and the movement frontier of hydrate dissociation can be discussed and understood as well as the change rules of pore pressure and water-gas-hydrate saturation during the invasion process. Here we just discussed how to build the corresponding model and didn't give numerical resolution and examples about the model.

## CONCLUSION AND SUGGESTION

Drilling fluids will inevitably invade into the hydrate-bearing formation and take place heat and mass transfer action under the drive of differential pressures and temperature, which will cause displace and hydrate surrounding borehole to be decomposed. The invasion process is actually coupled with heat conduction and the hydrate dissociation, and the interactions between drilling fluids and formation influence the mechanics, pore water pressure, capillary pressure, water-gas-hydrate saturation, permeability, wave velocity and resistivity of the formation surrounding borehole. Therefore, in order to guide the actual drilling operation in the future, the characteristics of the drilling fluids invading into the hydrate-bearing formation and its influence rule should be thoroughly understood when analyzing on wellbore stability, well logging response and formation damage evaluation of hydrate-bearing formation. It can be realized by establishing numerical calculation model of fluid invasion coupled with hydrate dissociation. On the assumption that hydrate is a portion of pore fluids and its dissociation is a continuous water and gas source with no uniform strength, it can describe the dynamic process of drilling fluids invasion by coupling Kamath's kinetic equation of heated hydrate dissociation or Kim's kinetic equation of depressurization dissociation into mass conservation equations. But there also exists some problems such as hard to quantify relationship between hydrate saturation and permeability, the distribution pattern of hydrate in sediment and its surface area in porous medium. Besides, the kinetic equations of hydrate dissociation themselves are not perfect. All these require studying thoroughly and discussing deeply in the future.

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