Journal of Petroleum Science and Engineering 168 (2018) 507–520

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Experimental study and numerical modeling of methane hydrate dissociation and gas invasion during drilling through hydrate bearing formations

Lu Yu, Yan Xu, Zhiwu Gong, Feng Huang, Liang Zhang, Shaoran Ren*

School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, Shandong 266580, China

ARTICLE INFO

Keywords:
Gas hydrate
Hydrate dissociation
Deep water drilling
Gas invasion
Shallow hazards
Heat transfer

ABSTRACT

Gas hydrate has been concerned as a potential shallow hazard during deepwater drilling. In this study, hydrate dissociation and gas flow into wellbore induced by circulation of high temperature drilling fluid when drilling through hydrate bearing formations have been investigated. A specially designed experimental setup based on sandpack model was used, which can simulate the process of methane hydrate dissociation and gas production in wellbore with circulation of drilling fluid. The experimental results show that the rates of hydrate dissociation and gas production are greatly influenced by the temperature of drilling fluid, hydrate saturation and pressure. A mathematical model was derived to simulate the process of hydrate dissociation and gas invasion into wellbore within a few hours when hydrate zones being penetrated during drilling. The effects of various parameters on gas invasion rate have been evaluated, including the inlet temperature and circulation rate of drilling fluid, the rate of penetration, the wellbore size, and the circulation condition with or without drilling risers. The results show that small to moderate gas invasion can occur when drilling through hydrate zones mainly depending on the inlet temperature of drilling fluid and hydrate saturation in near wellbore formation, which can be manageable when low-temperature drilling fluid is used and with a low circulation rate. Optimizing penetration rate, reducing wellbore size and drilling without risers are also beneficial to decreasing the gas invasion from hydrate zones into the wellbore.

1. Introduction

Deepwater geohazards includes a range of geologic phenomena that can cause risks to deepwater drilling activities (Bouma, 1981; Campbell, 1999). Appropriate geohazard assessment that can address shallow subsurface hazards is routinely conducted for offshore drilling campaigns (Krastel et al., 2006; Evans et al., 2007; Ren et al., 2018). The shallow sedimentary section is a critical window of vulnerability in which the well must drill through relatively weak unconsolidated sediment to a depth where sediment strength can allow casing to be set. Therefore, the main aim of shallow subsurface geohazard assessment is to determine whether the well could tolerate fluid flows from shallow sediments before well control equipment is in place (McConnell et al., 2012).

Gas hydrates are considered as the most common constituent of the shallow sedimentary zone where water depth exceeds approximately 500 m (Boswell et al., 2012). The minimum water depth at which gas hydrates have been found is about 440 m (Milkov et al., 2000). In fact, most operators have either avoided hydrate or drilled through probable hydrate deposits blindly without major incidents (Smith et al., 2005). As a result, encountering shallow hydrate in deepwater drilling might be largely overlooked as a potential risk.

However, there have been many documented cases of hydrate-linked well accidents in the Arctic, the Southeast Asia, the North Africa and Gulf of Mexico. For example, during drilling and cementing in the Russian Yamburg gas field, severe gas flows were often encountered in the shallow permafrost sequence (Yakushev and Collett, 1992). Some of these gas flows had resulted in fires. As reported in the Southeast Asia, when a well was once drilled in the region where BSRs was observed and with hydrate sampled, persistent gas flows and seafloor cracks were observed in the vicinity of the wellsite (Nimblett et al., 2005). These all demonstrate that shallow hydrates can pose considerable risks to drilling operations so that oil and gas industry must pay sufficient attentions.

Many problems related to shallow hydrate hazards in drilling process have been described in literature. Wu et al. (2007) summarized some potential risks associated with drilling-induced hydrate dissociation, mainly including well control failure and the gasification of

---

* Corresponding author.
E-mail address: ssrr123@hotmail.com (S. Ren).

https://doi.org/10.1016/j.petrol.2018.05.046
Received 10 September 2017; Received in revised form 12 March 2018; Accepted 16 May 2018

drilling fluid due to gas invasion into wellbore. Wu et al. (2014) described the process of hydrate posed drilling hazards. Once shallow hydrate bearing formation being penetrated, hydrates near wellbore formation can be dissociated driven by high temperature drilling fluid along with gas and water release, which can cause gas invasion into the wellbore, gas blowout, open-hole enlargement and wellbore collapse. Reformation of hydrate on seafloor equipment during gas erupting along the annulus can also occur (Gong et al., 2015). Addressing these scenarios is therefore of primary importance to the offshore industry. Nimblett et al. (2005) stressed the main operational difficulties attributable to drilling through hydrates, and made three suggestions on mitigating the risks associated with drilling through hydrate bearing formations: accurate estimation of the location of hydrate zone, effective modeling of the response of hydrate sediment zone to thermal and pressure stimuli, and accurate estimation of hydrate saturation.

Numerical modeling can be an effective tool that enables the simulation of mechanisms leading to hydrate risks. Freij-Ayoub et al. (2007) coupled a thermo-dynamic model for the stability of hydrates to mass and thermal transport in porous media, which is useful in predicting the responses of hydrate bearing formation to drilling processes. Golmohammadi and Nakhaee (2015) built up a radical numerical model to simulate hydrate dissociation during drilling and analyzed the effects of wellbore pressure and temperature on hydrate dissociation, the velocity and location of dissociation front, and the rate of released gas. Khabibullin et al. (2011) developed a relative semi-analytical 1-D model for heat and fluid transport in the reservoir coupled with a numerical model for temperature distribution in the wellbore. Gong et al. (2017) also established a heat transfer model to evaluate hydrate dissociation and gas and water production after well cementation.

A few large research programs have been conducted to assess the risks related to offshore drilling, such as the JIP Leg II program (Jones et al., 2008). Methods and techniques have been proposed in order to avoid hydrate risks in drilling using existing industry drilling protocols from the studies (Birchwood et al., 2005, 2007, 2008), such as cooling down the drilling fluid, increasing the mud weight, accelerating drilling by running casing immediately after hydrate is encountered and managing the wellbore temperature by controlling the circulation rate etc. However, there still has been lack of quantitative description of these methods in terms of experimental and mathematical proof to justify their significance in addressing gas flow and relevant risks induced by hydrates.

In this study, hydrate dissociation and gas flow into wellbore induced by hydrate dissociation in drilling through hydrate bearing sediment were investigated via laboratory experiments and mathematical modeling. Over-balanced drilling operation can be applied when drilling through hydrate bearing formations, but for a safety study and in order to quantify the hydrate risks, a normal or balanced drilling operation was assumed in the study. Experiments were conducted using a specially designed setup to simulate the process of methane hydrate dissociation and gas production induced by circulating high-temperature drilling fluid. A numerical model considering real-time drilling process through hydrate zones was established to calculate the gas invasion rate for quantifying the hydrate hazards. The dynamic advancement of drilling through hydrate sediment zones was considered in terms of the penetration rate and transient heat transfer between drilling fluid and near wellbore formations. The effects of practical engineering factors on gas invasion rate were examined using the model, including inlet drilling fluid temperature, the use of drilling risers, rate of penetration, borehole size and circulation rate of drilling fluid.

2. Experimental

2.1. Experimental setup

Fig. 1 shows the experimental setup used for mimicking hydrate formation and dissociation in a sandpack, in which the circulation of drilling fluid in wellbore can be simulated along with the measurement of temperature, pressure and gas production. The quartz sands were packed into a stainless cylinder vessel of 200 mm in diameter and 400 mm long, in which an annulus tubing with 14.4 mm of diameter and 360 mm long was located in the center of the sandpack to simulate the wellbore, and a 6 mm (diameter) tube was inserted inside the annulus tubing as a simulated drill pipe. The annulus tubing was slotted, allowing gas and water invading into the simulated borehole through the tubing. To prevent sand particle migration and clogging, meshes were applied on the slotted holes. The reactor vessel (12.51 L) can tolerate pressure up to 15 MPa, and the temperature of the sandpack was controlled by a water jacket that can work at constant temperature in the range from 0 °C to 80 °C. Three temperature sensors were inserted into the sandpack along with four pressure sensors. The precisions of the measured temperature and pressure were 0.1 °C and 0.01 MPa. Constant-flux pumps and piston containers were used for methane, seawater, and drilling fluid injection or circulation at the set pressure. A water bath (heater and chiller) was used to heat or cool the drilling fluid to the set temperature. During the circulation of drilling fluid, the pressure in the vessel and the annulus tubing was controlled by a backpressure regulator. Once hydrate was dissociated driven by the drilling fluid with higher temperature than its equilibrium temperature, gas was released and invaded into the annulus and flow with drilling fluid into the gas separator. The cumulative gas flow was measured using a gas flow meter, and all the measured data were collected using a data acquisition system.

2.2. Experimental materials

Methane was purchased from Qingdao Tianyuan Gas Co., Ltd, China with a purity of 99.99%. Quartz sands of 20–60 meshes were used in the experiments. The sands were washed twice to clean out fines and clay materials. Distilled water combined with 3.5 wt% NaCl was used throughout the experiments to simulate seawater and drilling fluid.

2.3. Experimental procedure

A certain volume of gas was firstly injected into the sandpack for the simulation of hydrate formation process. After hydrate formation was completed, circulation of drilling fluid with temperature higher than corresponding hydrate equilibrium temperature at the prevailing borehole pressure was conducted, which can cause the dissociation of hydrate. The details of the experimental procedures are described as below.

1. To make a sandpack in the reactor vessel, quartz sands were compressed into the vessel manually. The sandpack was the vacuumed, and saline water was injected into the vessel until the pore pressure rose to 0.1 MPa. For the large permeability of the sandpack, the volume of injected water can be used to calculate the pore space and porosity (about 0.42 in this case). Then saline water injection was continued until pressure of approximately 10 MPa was achieved for gas sealing testing, and then the pressure was reduced to 1 MPa prior to hydrate formation.
2. Methane gas was injected into the sandpack at a constant rate of 10 ml/min and at 1 MPa and 20 °C. The backpressure was also set at 1 MPa allowing water to be displaced out until the scheduled water volume was reached or methane broke through. A special tubing for water drainage was in use and its inlet was placed in the bottom of vessel. After that, the vessel pressure was increased to the set value (e.g. 8–10 MPa) with more methane injected. The volume of injected gas can be obtained by measuring the water volume discharged and pressure changes (Li et al., 2016). The volume of injected gas usually exceeded the required volume for the scheduled hydrate saturation. The hydrate saturation can be controlled by adjusting the volume of