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The complexity of thermal effect on rock failure in gas-drilling shale-gas wells

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ABSTRACT

Gas drilling is a technique used to drill mining boreholes, oil and gas wells, and geothermal wells with air, natural gas, or nitrogen as the circulating fluid. Recently it has been employed to drill shale gas wells and proven to be effective. However, the performance of gas drilling is very unpredictable in many areas due to the lack of proper design of drilling parameters because of limited knowledge of rock failure mechanisms. This paper addresses the issue of thermal rock failure that has been controversial in the past few years.

On the basis of analyses of thermal stresses induced by the frictional heating of drill bit and the cooling by gas expansion, this study reveals that the thermal effect on rock failure in gas drilling is significant. It is understood that both the frictional heating and the gas cooling can promote rock failure. However it not clear how the gas cooling will affect the frictional heating in the rock failure process. The thermal failure of rock is a complex process that requires further investigations by the means of experimental studies.

1. Introduction

Air, nitrogen, and natural gas have been widely used as the working fluid in drilling mining boreholes, geothermal fluid wells, and oil and natural gas recovery wells (Lyons et al., 2001). This technique is referred to as gas drilling. The rate of penetration is usually over 10 times higher in gas drilling than that in liquid drilling (drilling with water, mud, or oil). However, the performance of gas drilling is highly inconsistent in many areas. The reason is not clear to engineers. It is generally believed that this inconsistency is related to the mechanisms of rock failure which are not fully understood.

The first knowledge of rock failure in well drilling was from rock mechanics analysis for liquid drilling. Moore (1958) documented five factors that affect rock failure and thus drilling rate. The primary rock failure mechanism was identified as the mechanical action of drill bit teeth that causes wedging, scraping and grinding, and crushing of rock. The secondary rock failure mechanism was believed to be the erosion by fluid jet action (Bourgoyne et al., 1986). These mechanisms do not explain why the rate of penetration increases as the bottom hole pressure decreases. A number of technical documents have addressed the effects of confining stress and fluid pressure on rock failure (Murray and Cunningham, 1955; Cunningham and Fenink, 1959; Black and Green, 1978) in liquid drilling. It has been commonly recognized that reducing bottom hole pressure can significantly increase the rate of penetration. This is because the low-level bottom hole pressure causes high-level of unbalance of stress in the rock, making the rock softer and easier to break down under the mechanical action of drill bit teeth. The effect of bottom hole pressure on rock failure seems to explain the extremely high rate of penetration in gas drilling (Sheffield and Sitzman, 1985; Li et al., 2006; Wang et al., 2008).

The frictional heat, if not controlled to a safe level, can damage drill bits. Bit manufacturers provide temperature limits for their products. Drilling operators control bit temperature via adding water to the gas stream. It is commonly recognized that adding water (misting), even a very small amount (<3% in volume), in the gas stream significantly reduces rate of penetration in gas drilling. Since the amount of water does not cause noticeable change in bottom hole pressure, the mechanism of rock failure due to pressure-effect is not evident. A logical explanation is that the water can lubricate the contact area between the drill bit teeth and the bottom hole rock, resulting in lower rate of penetration. However, the insignificant change in drilling torque after misting does not support the theory of lubrication. Result from this study indicates that the frictional heat at the bottom hole rock surface

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should induce thermal stress and thus promotes rock failure; while the misting water should absorb the heat and reduce rock failure.

2. Field observations

There are field observations supporting the hypothesis of thermal failure of rock during gas drilling. It has been found that drill cuttings collected from gas drilling are much smaller than that from liquid drilling. Fig. 1 shows a comparison of drill cuttings collected from gas drilling and liquid (mud) drilling at similar depths in the same region (Li et al., 2013a). The cuttings samples were obtained from drilling a shaly formation in the North-west Sichuan, China. The depth interval was from 305 m to 2000 m with mudstone-dominated overall lithology. Fig. 1 shows that the drill cuttings collected from gas drilling are dust-like, which are at least thousand-times smaller than the drill cuttings from liquid drilling. The reason is generally believed to the re-grinding of large cuttings at the bottom hole in gas-drilled wells (Guo and Ghalambor, 2002). However, re-grinding would significantly reduce the rate of penetration, which does not occur in gas-drilling. Another explanation is the theory of cuttings-crashing by drill string and other cuttings during flowing up the borehole annulus (Li et al., 2013a,b). This is possible due to the vibrations while drilling with high rotary speed. Crashing can occur between drill pipe and borehole wall, turbulent flow of fluids, uneven and out of gauge borehole, doglegs, etc. The significance of the cuttings-crashing has not been well investigated. Li et al.'s (2013b) work indicates that the energy required to crash cuttings from 6 mm to 1 mm is nearly equal to the energy required to transport the cuttings from bottom hole to surface, which was considered to be not realistic. A reasonable explanation is that the cuttings created by drill bit are much smaller than 6 mm. The dust-like cuttings are created at the bottom hole due to the fictional heating effect, or thermal failure of rock. This effect is similar to the weathering effect where the temperature at the surface of rock alters rapidly, causing the fast failure of rock surface, generating small cuttings. If this is the case, the cuttings size should depend on the level of frictional heat generated at bit teeth. High level of frictional heat should promote generation of fine cuttings. According to the theory of frictional heat generation (Kulchytsky-Zhihailo and Evtushenko, 1999; Evtushenko and Pauk, 2002), the heat flux is proportional to the contact pressure (stress). The contact pressure between drill bit and rock is higher at deep depth than that at shallow depth in gas drilling. This is because low weight on bit is used to drill soft rocks at the shallow depth with high-rate of penetration and high weight on bit is used to drill hard rocks at the deep depth to maintain high-rate of penetration. As the weight on bit increases with depth, the contact stress (weight on bit divided by bit tooth contact area) increase, and thus the frictional heat increases. It is therefore expected that the size of drilling cuttings decreases with depth. Fig. 2 from Li et al.'s (2012a) investigation demonstrate the trend of change of cuttings size with depth. As the well deepens, the proportion of large-size cuttings drops and that of small cuttings increases. This trend of cuttings size change may be explained by three principles: 1) rock drillability drops with depth, 2) more cuttings-collision in deep holes, and 3) more thermal failure of rock in friction-heated deep/hard formations. The fact that cuttings are much finer in gas drilling than in mud drilling at the same depth tends to support the principle of thermal failure more than the other two principles.

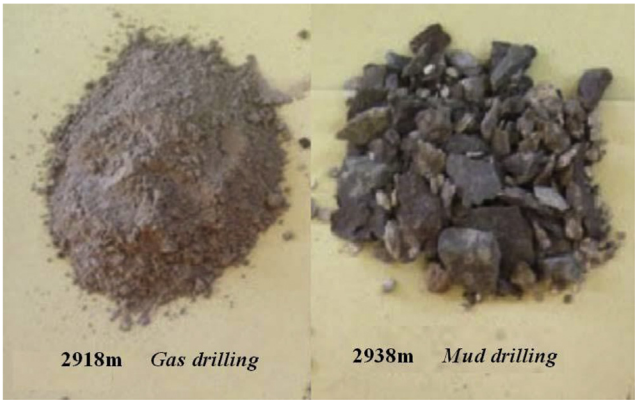

Fig. 1. Comparison of drill cuttings collected from gas- and mud-drilled wells at similar depths in the same area (Li et al., 2013a).

3. Thermal failure of rock

Consider a piece of rock (cuttings) expelled by the drill bit cutter. Its temperature is expected to be higher than the in-situ geothermal temperature due to the frictional heating of the bit cutter. Thermal expansion will cause tensile stress at its surface expressed by the following equation (derivation is available upon request from the authors):

$$\sigma = E\alpha_L \Delta T \tag{1}$$

where E is Young's modulus and α_L is linear thermal expansion coefficient of rock, and ΔT is temperature increase. Rocks have tensile strengths that are much lower than their compressive strengths. Crack will develop at the surface of cuttings when the tensile stress exceeds the tensile strength of rock, resulting thermal failure of cuttings. The temperature increase required to cause tensile failure of rock is therefore expressed as:

$$\Delta T > \frac{\sigma_{ten}}{E\alpha_L} \tag{2}$$

where σ_{ten} is the tensile strength of rock. Table 1 presents mechanical and thermal properties of rocks commonly encountered in borehole drilling. The last column of Table 1 summarizes the expected values of the minimum temperature increase required to cause tensile failure predicted by Eq. (2). Because these values were calculated on the basis of the maximum possible tensile strength of rocks, they are considered as the upper bounds of temperature increase. However, these values are in the practical range of temperature variations observed in gas drilling operations. Therefore, it is expected that rocks in contact with drill bit during drilling are in failure condition due to thermals stress.

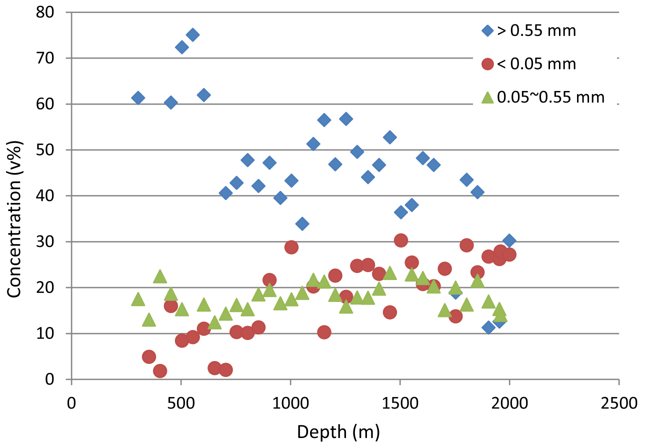

Fig. 2. Concentrations of different cutting sizes versus broehole depth (Li et al. (2012a,b)).