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Laboratory investigations on the effects of surfactants on rate of penetration in rotary diamond drilling

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ABSTRACT

Laboratory investigations were carried out on sandstone to research the effects of three representative surfactants, including Triton X-100, sodium dodecyl benzene sulfonate (SDBS) and 1-hexadecylpyridinium chloride (CPC), on the rate of penetration (*ROP*) in the process of rotary diamond drilling. Properties of the sandstone, the surfactant solutions as well as the solution–sandstone interfaces were determined to study the influences caused by these surfactants. The results showed that either Triton X-100 or SDBS can increase the ROP while the effect of CPC is marginal. Both Triton X-100 and SDBS can help the flushing water to spread on the sandstone surface fully. SDBS and CPC can reduce the indentation hardness of the sandstone to some degree. A detailed discussion was presented in order to understand these results in depth, and then a comprehensive mechanism was proposed for explanation. Spreading behavior of the flushing media, Zeta potential, rock-breaking mode and rock properties all contribute to the effect of a given chemical environment on *ROP*. At various stages of drilling process, the roles performed by the chemical environment may be drastically different.

1. Introduction

Drilling is one of the most important operations in mining and petroleum industries, starting from the exploration stage and continuing through each part of production until mining activity is completed. In the various drilling methods, rotary diamond drilling takes a unique place owing to the importance of intact-core recovery to identify the physico-mechanical behavior of the rock strata and the classification of the rock mass (Bhatnagar et al., 2010). In the process of rotary diamond drilling, rock fragmentation at the bit–rock interface occurs because of the combined action of vertical thrust forces as well as horizontal torque.

As a parameter, rate of penetration (ROP) reflects drilling speed. It is considered as a crucial economic and technical indicator in the drilling process. In view of the heavy dependence of the mining/petroleum industry on rock drilling, an enhancement in *ROP*, even if it is small, can result in substantial cost savings. A commonly used method of increasing *ROP* is to modify the flushing media by chemical ways thereby conditions for optimum performance of drilling can be created. Flushing media, usually in the form of a liquid (also referred as drilling fluid), gives a number of functions such as: carrying cuttings; cooling and cleaning the bit; reducing friction between the drilling string and the sides of the hole; maintaining the stability of the borehole; preventing the inflow of formation fluids (well-control); forming a filter cake to seal pores; and assisting in the collection and interpretation of information, etc (Johannes, 2012). Therefore, most of drilling operations are performed in flushing media, that is, fluid environments containing various chemicals. It is well known that the fluid–rock interaction performs a role in drilling and a number of attempts have been made to achieve chemically enhanced drilling (CED). As early as the 1940s, Rehbinder and his colleagues made use of environmental effects to reduce the rock hardness and increase the efficiency of rock drilling (Rehbinder et al., 1948). In the 1970s, Westwood et al. (1974) carried out diamond drilling experiments on quartz, granite and feldspar using water, toluene and n-alcohol. They found that by controlling the chemistry of the drilling environment, the *ROP* could be enhanced. They attributed this phenomenon to adsorption-induced changes in the near-surface region at bit-rock interface. In the 1980s, Ishido and Mizutani (1981) researched into the relationship between crack growth on rock surface, drilling efficiency and Zeta potential. They believed that when the Zeta potential equals zero, rock materials would be of

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Nomenclature

c	concentration, mol/L
FA	fluid absorption, %
IH	indentation hardness (Schreiner hardness), kg/mm^2
IR	increased *ROP*, %
ROP	rate of penetration, mm/min
SA	spread area, cm^2
γ_{g-l}	fluid surface tension, mJ/m^2
ΔG_a	Gibbs free energy change of adhesion, mJ/m^2
ΔG_s	Gibbs free energy change of spreading, mJ/m^2
ζ	Zeta potential, mV
θ	contact angle, °

greater frangibility. Its compressive strength would become lower, and the subcritical crack growth rate would be raised by over one magnitude. Besides, Watson and Engelmann (1985) and Engelmann et al. (1988) established the concept of chemically enhanced drilling (CED), and finally summarized the results of the laboratory and field experiments in terms of additives in flushing media. The additives they studied include various surfactants, organic liquids and inorganic salts. More recently, Watson et al. (1991) reported that polyethylene oxide (PEO), a water-soluble non-ionic polymer could enhance drilling performance. This effect has been confirmed on different rocks such as Sioux quartzite (Pahlman et al., 1989; Rao and Misra, 1998), Minnesota taconite (Tuzinski et al., 1989) and marble (Bhatnagar et al., 2011). Zhao and Gao (2013) discussed the effects of different inorganic salts on the *ROP* in rotary diamond drilling and the relevant mechanism.

Many investigations have indicated the complexity of rock fragmentation mechanism in rotary drilling process (Howarth, 1986; Rao and Misra, 1998). Furthermore, the application of commercial chemical additives such as polymers and surfactants in the drilling fluids is affected by the limited understanding of the very chemomechanical process itself. Hence, in the absence of a method of quantitative assessment for the determination of drilling performance, laboratory drilling experiment remains an important source of information to enhance drilling performance (Rao et al., 2002).

In this paper, the effects of three surfactants which belong to different types respectively on the *ROP* in the process of rotary diamond drilling on sandstone were studied with the mechanical parameters fixed. Properties of the sandstone, the surfactant solutions as well as the solution–sandstone interfaces were determined. A mechanism of the solution–sandstone interaction during drilling was also proposed in order to explain the results observed.

2. Materials and methods

2.1. Drilling experiment

A modified TZ-2 Model Coring Machine (Petroleum Science and Technology Instrument Factory, Haian, China) with a thin walled diamond impregnated coring bit (wall thickness: 2 mm; internal diameter: 25 mm) was used to drill the rock (Fig. 1). As one of the most important equipments in the present investigation, the coring machine has a turnplate of which axis connected with an up-down wheel. By hanging a given weight object on the turnplate, the coring bit is forced to press vertically against on the rock which has been fixed on the test table in advance. Thus, a constant bit thrust can be applied. When the drilling experiment is carried out, with a constant thrust, the coring bit rotates horizontally and the flushing fluid is pumped by a boost pump from the fluid vessel, through the machine and the hollow bit, eventually onto the rock surface at a constant flow rate. Hence the drilling is conducted and the flushing fluid plays a role in this process for interacting with the rock, and clearing the cuttings away. The cutting-fluid

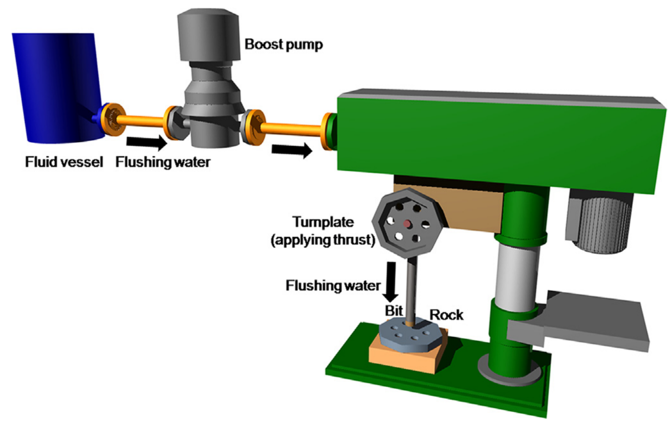

Fig. 1. Schematic diagram of the modified drilling machine.

suspension generated during the drilling process is collected by a waste fluid tank beneath the rock holder.

The most important response in the present investigation is increased *ROP* (*IR*). To measure *IR*, following procedure was carried out: Firstly, the *ROP* with distilled water is considered as the control test. At load (bit thrust)=4.0 kg, rotary speed=300 rpm, flow rate=0.6 L/min, the rock was drilled with distilled water and the *ROP* under this condition, ROP_0, was tested for reference. It must be pointed out that the flushing water can clear the cuttings away fully and timely under this condition. This is demonstrated by the fact that the bit thrust selected (4.0 kg) here is located in the "linear area" of the ROP_0-thrust curve with other parameters fixed, as shown in Fig. 2. According to the "perfect-cleaning" theory presented by Maurer (1962), only in this occasion can the "chip hold down" effect be neglected. Secondly, a variety of surfactant solutions with different concentrations were prepared. After that, drilling experiments were performed with these

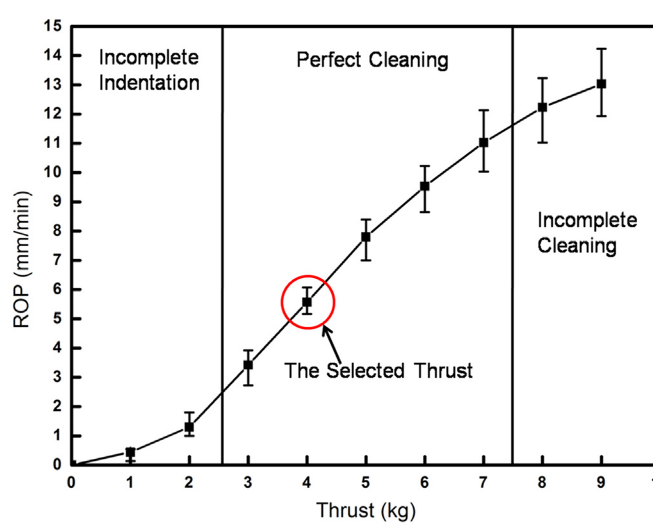

Fig. 2. ROP_0-thrust curve at rotary speed=300 rpm, flow rate=0.6 L/min.