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Experimental investigation of cutting temperature in ice drilling

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ABSTRACT

Cutting heat generated during rotary drilling easily melts warm ice, which has a temperature that is nearly close to or even reaches its pressure melting point. This phenomenon results in low penetration rate, poor core recovery and frequent sticking accidents. In order to measure the cutting temperature in ice drilling, a special testing stand was designed based on the principle of a wireless signal communication system as described in this paper. Factors affecting cutting temperature were discussed and studied, including bit load, rotation speed of the drill head, and rake angle of the cutter. Experimental results show that the temperature of the cutter can rise by 5.49 °C when drilling in ice sample A (frozen in outdoor natural environment), and to approximately 4.38 °C when drilling in ice sample B (frozen in a special device) with a bit load of 560 N. The rotation speed of the drill head also has a major effect on cutter temperature. The temperature rise of the cutter can increase from 2.57 °C to 4.27 °C for ice sample A, and from 3.51 °C to 4.56 °C for ice sample B when rotation speed increases from 80 rpm to 140 rpm. In addition, the rake angle of the cutter affects cutting temperature to a certain degree. The temperature rise is about 4.39 °C with a rake angle of 15°, while it is about 3.36 °C with a rake angle of 30° for ice sample A. Moreover, compared with dry drilling, the temperature rise can be greatly reduced with drilling fluid circulation. The temperature rise is only about 0.72 °C and 0.66 °C for ice samples A and B, respectively, with a bit load of 700 N.

1. Introduction

In deep ice core drilling, difficulties in using an electromechanical drill are most frequently encountered when the in-situ temperature of the ice is close to or reaches its pressure melting point (namely warm ice). It is generally considered that ice chips melted partially by the heat of the cutting process refreeze, blocking the pathway of chips into the chip chamber. Or ice chips refreeze on the cutters and shoes of the drill head, which prevents further progress of the drill (Augustin, et al., 2007 and Taylor et al., 2005).

One possible way to ease this problem is to use an ethanol-water solution around the drill head, which has been used successfully at several deep drilling sites, such as in NorthGRIP in Greenland, EPICA Dome C and EPICA Dronning Maud Land in Antarctica (Johnsen et al., 2007). However, use of EWS generates its own set of difficulties (Severinghaus et al., 2004). EWS can cause partial dissolution of the ice core and the generation of cracks in the core. These cracks can compromise ice core quality for certain types of analysis because of the subsequent infiltration of the drilling fluid into them (Talalay and Gundestrup, 2002). Another problem is the sticking of the core in the core barrel due to refreezing of the ice melted by EWS between the core and core barrel during pull-up (Johnsen et al., 2007). Moreover, clathrate hydrate forms when melted ice mixes with the HCFC 141b used as a densifier in the drilling fluid under warm ice conditions (Murshed et al., 2007).

Another way to overcome the problem is to change the cutting angle at the cutter–ice interface or to coat the cutter with Teflon (Kudryashov et al., 2002; Vasiliev et al., 2007). For example, a new geometry of cutters was successfully applied in a KEMS-135 electromechanical drill used at No. 5G hole, Vostok Station (Vasiliev et al., 2007, 2011). The bottom of the cutter was designed to have a dihedral shape to increase the clearance angle by up to 30°. Several special grooves were also designed at the bottom of the cutter, which really helped to keep the drilling process stable. Meanwhile, warm ice was encountered at depths below 3000 m in the second deep ice coring project at Dome Fuji, and consequently, the performance of the JARE drill used in the project deteriorated rapidly (Motoyama, 2007). Thus the normal drill was replaced with a special short Teflon-coated drill in an attempt to solve the problem. The drill reached a depth of 3035.22 m with an average core length of about 10 cm.

Azuma et al. (2007) analyzed the heat generated during ice coring based on metal cutting theory. The factors that affect cutting heat were investigated and discussed in their study, including the rake angle of cutters, rotation speed, pitch height, cutter material and the contact length between the ice chips and the cutters. They believed that ice chips can be prevented from melting by reducing cutting heat to overcome drilling difficulties in warm ice. It is beneficial to understand and solve the warm ice drilling problems. However, this work

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was performed using theoretical calculation without accurate experimental validation. Theoretical modeling for analyzing the cutting temperature requires major simplification of the problem and this may not be able to provide accurate results (Liu and Zhao, 2008 and Zhang, 2009). Even in the field of metal machining, it is difficult to predict the temperature in a precise manner because of the highly non-linear nature of the process and the complex coupling between deformation and temperature fields. Although considerable research effort has been made on the thermal problem in metal cutting, there is hardly a consensus on the basic principles. Accurate and repeatable heat and temperature prediction remains challenging due to the complexity of the contact phenomena in the metal cutting process (Abukshim et al., 2005).

Several studies have been conducted to investigate temperature generated during the rock cutting process in oil and gas drilling (App et al., 1993; Che et al., 2012; Glowka and Stone, 1985). Loui and Karanam (2005) installed a copper-constantan thermocouple into the cutter to measure interface temperature between the pick of the drag bit and the rock. Martin and Fowell (1997) used a thermocouple to monitor cutting temperature with and without the assistance of a high pressure water jet. To the knowledge of the authors, no test has yet been conducted to measure cutting temperature during the ice drilling process. The present study describes the results from a series of experiments that investigated cutting temperature during ice drilling with and without low temperature drilling fluid circulation.

2. Testing equipment

2.1. Drilling test stand

The testing stand consists of an OE-230 motor fixed on a frame, an oil cylinder, a steel box, a filling pump, a mud tank and various sensors as shown in Fig. 1. The tested ice block, approximately 300 × 300 × 250 mm in size, is fixed in the steel box using two strong screw-bolts. The OE-230 motor drives the single core barrel with an attached drill head. The oil cylinder drives the steel box to move up and down, with a maximum stroke of approximately 450 mm. The drill head cannot move up and down but can only rotate in all the experiments. By contrast, the ice sample can only move up and down with the steel box, but cannot rotate. The low temperature drilling fluid delivered by the filling pump from the mud tank into the swivel passes continuously over the core inside the barrel, and then down to the drill head across the face. Subsequently, the fluid is ejected with cuttings to the outside surface of the drill head. Then the drilling fluid flows into the steel box and enters into the mud tank, after sedimentation of the ice chips the fluid is circulated back into the swivel by the filling pump.

The bit load, rotation speed and flow rate of the drilling fluid are controlled in real time. The oil pressure exerted by the hydraulic system to the oil cylinder is adjusted using the proportional relief valve on the control panel of the hydraulic system within the range of 0–16 MPa. The rotation speed of the OE-230 motor can be smoothly regulated up to 700 rpm. The nominal power of the rig motor is 3.9 kW.

Five parameters including the bit load, rotation speed, torque, depth, and penetration rate, are continuously measured and recorded at one-second intervals during coring runs. Two pressure sensors of SSI-P50 type are installed in the upper and lower chambers of the oil cylinder to measure pressure in the hydraulic system. Then, the load is estimated by dividing the pressure difference in the upper and lower oil chambers by the section area of the piston rod. According to the weight of ice samples and steel box, the bit load can be calculated. Here, the influence of fluid weight on bit load is disregarded because the drilling fluid flows into the mud tank when it reaches a certain height. The effect of the weight changes of the ice samples caused by the ice chips carried out by the drilling fluid is also disregarded in the whole test, because the maximum error of the load is no more than 1.5% according to our calculation.

A torque sensor of LKN-200 type is installed between the motor axis and the swivel to measure the torque and the rotation speed of the drill head. The stators of the sensor and the swivel are fixed to the frame. The measuring limit of the torque sensor is 200 Nm, with an accuracy of ±0.2%.

A WEP-50 drawstring displacement sensor is installed on the shell of the oil cylinder, and the end of the drawstring is fixed to the body of the steel box. Thus the sensor can move up and down with the steel box, while the end of the drawstring remains stationary. The sensor measures the length of the drill run and the relative displacement is converted into the penetration rate.

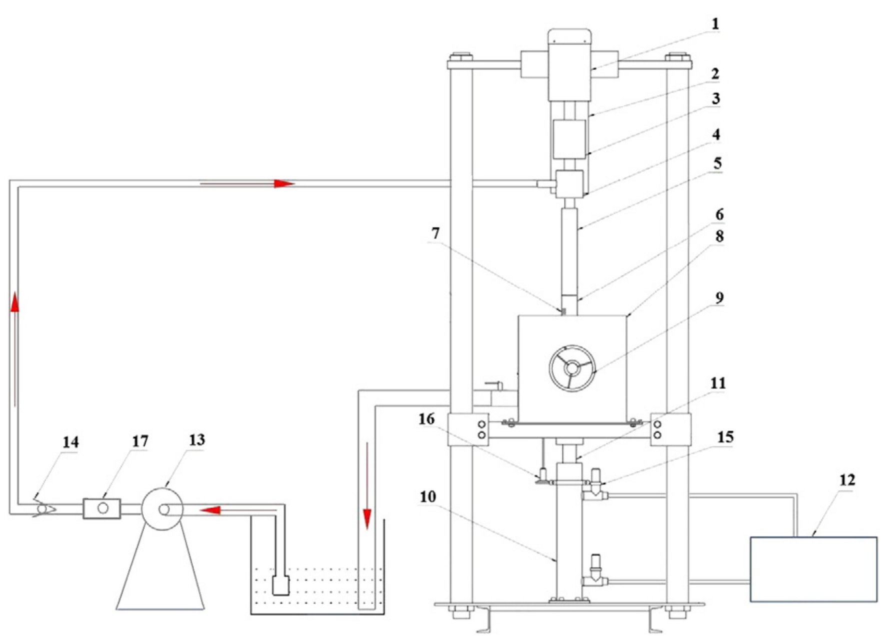

Fig. 1. Testing stand: 1—motor; 2—frame; 3—torque sensor; 4—swivel; 5—core barrel; 6—drill head; 7—thermocouple; 8—steel box; 9—screw bolt; 10—oil cylinder; 11—piston rod; 12—hydraulic system; 13—filling pump; 14—check valve; 15—pressure sensor; 16—drawstring displacement sensor; 17—flowmeter.