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Theory calculation and testing of air injection parameters in ice core drilling with air reverse circulation

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ABSTRACT

Drilling with air reverse circulation is considered one of the most promising technologies in ice core drilling, especially in firn-ice drilling, as it has many advantages in preventing air circulation loss, improving stability of the borehole, and promoting penetration rate. The effectiveness of this technology depends on whether or not the ice chips and cores can be conveyed to the surface through the central channel of the drill tool. In order to determine the adequate volume flow rate of the gas needed to satisfy the demand for continuous return of the ice cores and chips, a mathematical model to evaluate the injection pressure was studied. A series of experiments were carried out to test the actual air velocity required to move ice cores and ice chips with different sizes and clearances between the ice cores and the inner wall of the pipe. Based on the calculation and testing results, the minimum air volume requirements with different borehole depths in ice core drilling with air reverse circulation were confirmed. For a borehole with depth of 1000 m and diameter of 134 mm, the volume flow rate and pressure of air under standard atmosphere condition are at least 6.27 m^3/min and 0.70 MPa to transport ice chips and ice cores with diameter of 60 mm and length of 250 mm.

1. Introduction

Drilling in the polar ice sheet and mountain glaciers is crucial for many scientific studies. The analyzed data from the ice core can be used to understand the earth's paleo-climatic and paleo-environmental information, which is important to elucidate the mechanisms of climate change, evolution of the earth's glaciology, and resilience of the life forms exposed to extreme conditions. In some cases, full face drilling (non-core drilling) is also very useful for borehole measurements. Various properties of the surrounding ice can be investigated by installing sensors in the hole. Ice shear, basal sliding, and ice flow also can be monitored in real time. Therefore, ice drilling is an essential part of research in glaciology and polar sciences. However, as a tedious work, drilling in these regions is challenged by adverse weather conditions, extremely low surface temperatures, and very short field seasons. The development of powerful, fast drilling systems, which can penetrate the ice sheet with high drilling speed, has become an important task in many projects. Some rapid access ice drill (RAID) systems have been developed and tested, including hot water drilling (Benson et al., 2014), wire-line drilling with conventional drill rig (Goodge and Severinghaus, 2016), coiled tubing drill (Clow and Koci, 2002), RADIX drilling (Schwander et al., 2014) and SUBGLACIOR drill (Alemany et al., 2014).

Recently, dual-wall air reverse circulation drilling for fast, continuous coring in shallow snow-firn and intermediate ice has been proposed by Talalay and Wang (Wang et al., 2017; Talalay, 2016). It is a fast and cost-efficient method, which was developed to retrieve clean and high-quality samples in exploration and mine drilling. The main characteristic of this method is that the compressed air used to carry out the cuttings is circulated in a reverse manner. High-pressure air coming from an air compressor flows through a dual channel swivel and the annular space in double-wall drill pipes, and enters into a reverse circulation drill bit. Here it is divided into two groups. One group of gas ejects from ejector nozzles at a high speed, which causes the nearby pressure to decrease. In this manner, a pressure difference is generated between the central passage and bottom of the drill bit. Other groups of gas emerging from flushing nozzles sweeps the ice chips toward the drill bit's central passage as a result of the pressure difference. All of the air, ice chips and ice core are mixed within the vicinity of the ejector nozzles, and then directed up to the surface (Rowley et al., 2000; Cao et al., 2016). At the end of the discharge hose, a cyclone is usually used to separate the cuttings as shown in Fig. 1. Because the formation samples are continuously returned to the surface as drilling proceeds, core barrel retrieval is not needed after each run, which saves considerable time. In addition, representative samples can be obtained with a high recovery rate, and these samples have not been contaminated by other borehole-section materials as the cuttings travel directly to the

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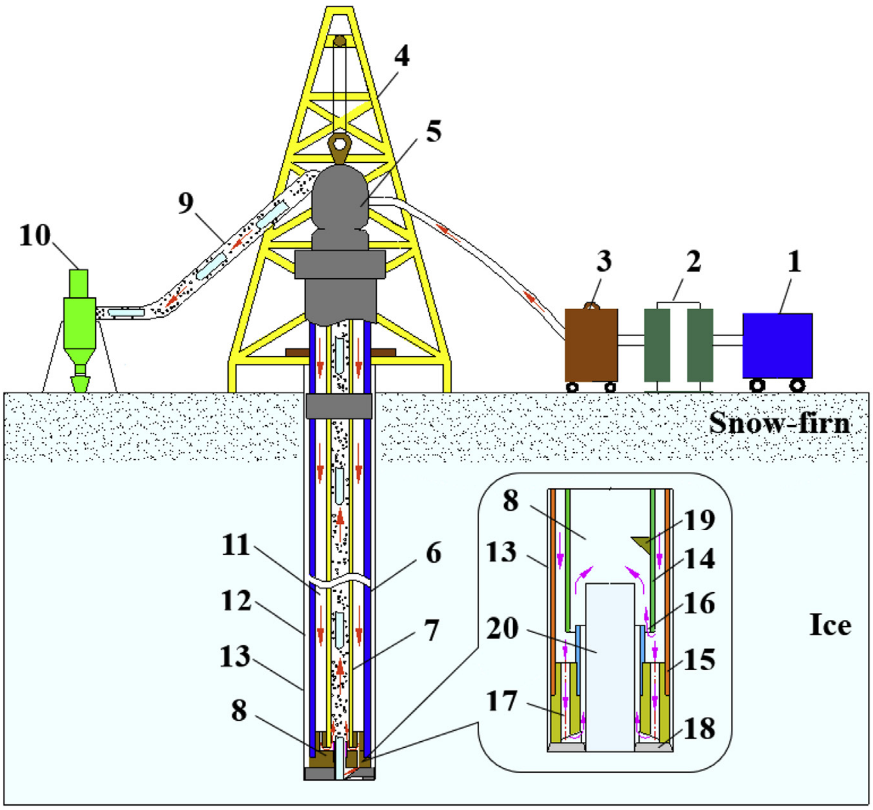

Fig. 1. Schematic diagram of air reverse drilling: 1-air compressor; 2-cooler; 3-dryer; 4-drill tower; 5-swivel with dual wall; 6-outer pipe of drill pipe; 7-inner pipe of drill pipe; 8-drill bit; 9-discharge pipe; 10-cyclone; 11-annulus of the drill pipe; 12-annular space between drill pipe and borehole wall; 13-borehole wall; 14-inner connector of drill bit; 15-outer connector of drill bit; 16-ejector nozzle; 17- flushing nozzle; 18- cutter; 19-core breaker.

surface through the inside of the drill string. Compared with direct circulation drilling, the borehole wall is relatively stable because no fluid or cuttings flow against the walls after the drill bit has passed (Luo et al., 2016; Cao et al., 2018). Moreover, this drilling technology can effectively address the problem of circulation loss in broken or fractured formations as the air does not flow through the annulus between the formation and the drill pipes, which is exactly what the snow-firn drilling requires.

Depending on the site, especially the local temperature and amount of snowfall, the firn zone near the surface can be between 50 and 120 m thick (Bentley et al., 2009). If air drilling with normal circulation is used in this zone, the air with ice chips will easily be lost into the permeable borehole walls, which results in low penetration rate, poor ice core quality, and even a stuck drill. That is why, in a snow-firn layer, the borehole is cased along a distance down from the surface. The recent experience in drilling with the rapid air movement system shows that the firn permeability and condition greatly affect the actual depth to which it is possible to drill (Bentley et al., 2009; Whelsky and Albert, 2016).

Compared with air direct circulation, air flowing in a reverse manner is more applicable when drilling in snow-firn zones. It is commonly recognized that adequate volumetric flow rates of gas are crucial for the success of air drilling. Therefore, the most important step in the planning procedure is to confirm the minimum gas volume requirements to drill, which can be used to estimate the bottom hole pressure, surface injection pressures, and compressor power (Guo and Ghalambor, 2002). Although there are several models to calculate the gas volume required in air reverse circulation drilling, they cannot be directly used in ice core drilling. In these studies, the air velocity needed to lift the rock core is ignored because the air reverse circulation is mainly used to collect rock cuttings in most drilling operations around the world, including mineral deposit exploration, oil and gas drilling, and hydrological drilling. Wang used the Bernoulli equation to calculate the pressure drop and airflow velocity for conveying an ice core in reverse circulation drilling (Wang et al., 2017). This causes significant errors because the air is regarded as uncompressed gas to simplify the calculation in that study. Obviously, the pressure varies in a large scale when the gas flows from the borehole bottom to surface, which means the air stream should be handled as compressed gas. In this work, the pressure drop in ice core drilling was studied based on the pressure calculation model derived by Guo (Guo and Ghalambor, 2002; Lyons et al., 2009). A series of tests were performed to study the actual gas velocity required to lift ice cores and ice chips with different sizes. The minimum gas volume rate and injection pressure requirements with different borehole depths were investigated.

2. Theory calculations on air injection pressure

The injection pressure required for ice drilling with air reverse circulation should be not less than the total pressure drop of the air circulation, which can be given as

$$P_{in} = S_f \Delta P = S_f (\Delta P_c + \Delta P_a + \Delta P_{bit} + \Delta P_{core}) \tag{1}$$

where ΔP is the total pressure drop, Pa; S_f is the safety factor, dimensionless, and $S_f = 1.2$ in this study; ΔP_c is the air pressure drop in the central passages of the drill string; ΔP_a is the air pressure drops in the annular passages of the drill string; ΔP_{bit} is the pressure drop when the air flows through the drill bit; and ΔP_{core} is the pressure drop owing to the conveying of ice cores.

2.1. Air pressure drop in central passage of drill strings

As in all compressible flow problems, the process of solution must start from known pressure and temperature values. Therefore, the derivation will begin with the analysis of the central passage of the double wall pipe, because the pressure and temperature exits at the surface is known (Lyons et al., 2009). Two-phase flow occurs when the pressured air with ice cuttings and cores moves upward in the central passage of the drill string. It is assumed that the gases can be treated as an ideal gas. Ice cuttings can be assumed as uniform in size and density, and