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Air System and Drilling Fluid Circulation System for Subglacial Bedrock Sampling in Polar Regions: Design and Testing

Yazhou Li[1, 2], Gansheng Yang[1, 2], Jing Wang[1], Kai Zhang[1], Bing Li[1, 2], Yangxi Lu[3], Zheng Zhou[1], Zufang Wang[1], Ruozhou Huang[1], Xingwen Lai[1]， Yuchen Sun[1], Mingqi Wang[1]

[1]School of Engineering and Technology, China University of Geosciences, Beijing, 100083, China
[2]Key Laboratory of Polar Geology and Marine Mineral Resources (China University of Geosciences, Beijing), Ministry of Education, Beijing, 100083, China
[3]Shaanxi Taihe Intelligent Drilling Co., Ltd, Xi'an, 710086, China

Correspondence to: Kai Zhang (zhangkai66@cugb.edu.cn)

Abstract. A multi-process drilling system (MPDS), comprising an air system and a drilling-fluid circulation system (DFCS) was developed for sampling the subglacial bedrock in polar regions. The air system can produce dry, cold compressed air in high pressure. The DFCS produced low-temperature drilling liquid and could separate ice or rock cuttings from the drilling liquid for recycling. The two systems were integrated into modified 20 ft containers for easy transportation and assembly. The air system comprised a compressor, receiver, freezing dryer, desiccant dryer and cooler. The DFCS comprised a refrigerating machine, heat exchanger, circulation pump, drilling-fluid pump, vibration sieve, vertical centrifuge, circulation tank, stirring tank, and settling tank. Both systems worked with limitations: the failure of the freezing dryer and desiccant dryer led to the breakage of the air cooler in the field, and several problems were found in the drilling-fluid pump, vibration sieve, vertical centrifuge, and circulation tank. This paper presents in detail, the requirements, principles, and design of the air system and DFCS, in addition to the domestic and Antarctic test results. The experiences and learnings gained in this study will contribute to the development of ice and subglacial bedrock drilling technology.

1 Introduction

Polar regions, which mainly include Arctic and Antarctica, are widely covered by ice sheets, ice caps, ice shelves, sea ice, and glaciers. Greenland and Antarctica are home to the only remaining ice sheets in the world. Approximately 20 % of the Greenland land surface and just 2 % of the Antarctica land surface are ice-free (Singh et al., 2011). Subglacial bedrock, buried under tens to thousands of meters of ice, is important for the study of the historical evolution of ice sheets, revealing geological tectonics and paleoclimate (Fountain et al., 1981; Schaefer et al., 2016; Bierman et al., 2024). In recent years, the polar-science community has been very interested in obtaining subglacial bedrock samples from Greenland and Antarctica (Talalay, 2014; Spector et al., 2018; Briner et al., 2022).

Many holes have been drilled in the ice-sheet beds in polar regions, but subglacial rocks have been rarely retrieved (Bentley and Koci, 2007; Talalay, 2013). The first subglacial bedrock core was drilled in 1956 by Soviet Union near Mirny station, Antarctica. The hole was only 66.7 m in depth, and the rock core was 2.2 m in length (Treshnikov, 1960). By the 2010s, another three subglacial bedrock cores had been drilled in Camp Century, Summit, and Taylor Dome by USA (Ueda and Garfield, 1968; Gow and Meese, 1996; Steig et al., 2000). Thereafter, USA drilled several subglacial bedrock cores in West Antarctica and Transantarctic Mountains (Boeckmann et al., 2021; Kuhl et al., 2021; Goodge et al., 2021). China retrieved a short subglacial rock core at the margin of Princess Elizabeth Land, East Antarctica (Talalay et al., 2021a). At present, the deepest hole drilled in Antarctica for subglacial bedrock sampling is only 681 m and the longest subglacial core is only 8 m (Kuhl et al., 2021; Goodge et al., 2021).

Conventional rotary drill rigs with drill pipes have often served as the basis for subglacial bedrock coring systems. Examples include purpose-built adaptations like the Winkie drill, the Agile Sub-Ice Geological (ASIG) drill, and the Rapid Access Ice Drill (RAID) (Truffer et al., 1999; Boeckmann et al., 2021; Kuhl et al., 2021; Goodge et al., 2021). The cable-suspended electromechanical drill can also be used in subglacial-bedrock drilling. For example, the Polar Ice Coring Office-5.2" (PICO-5.2"), Percussive Rapid Access Isotope Drill (P-RAID), and Ice and Bedrock Electromechanical Drill (IBED) were also designed to obtain the bedrock core beneath ice (Kelley et al., 1994; Timoney, et al., 2020; Talalay et al., 2021a; Talalay et al., 2021b). Compared with the cable-suspended electromechanical drill, a conventional drill rig can drill longer rock cores; it has a greater ability to deal with drilling accidents. When a drill rig is used in subglacial bedrock sampling, compressed air or drilling fluid are required to remove drilling cuttings from bottom of borehole and to cool drill bit. At present, the deepest hole drilled by air in ice is only 309 m (Patenaude et al., 1959; Lange, 1973).

Compressed air is generated by a compressor and is usually hot and wet. The compressed air must be cooled and dehumidified before being injected into an ice borehole. Otherwise, the ice borehole wall and ice cuttings may melt and condensed water may freeze on the borehole wall and drill pipes. For example, without cooling and dehumidification, the condensed water caused a stuck drill many times during air drilling in the Churlyenis ice cap, Franz Joseph Land, Russian Arctic (Bazanov, 1961). In past ice drilling projects, the compressed air was usually cooled by passive heat exchanger with the atmosphere (Tongiorgi et al., 1962; Lange, 1973). However, this method is highly reliant on the ambient air temperature. For example, the Rapid Air Movement (RAM) drill used an aftercooler to cool compressed air, and it required ambient temperatures below ~10 °C to cool the compressed air to below 0 °C (Bentley et al., 2009). Arenson (2002) proposed cooling compressed air in a 200 m long hose buried under the snow. However, this warm conduit could eventually melt the snow and freeze after circulation stops. Generally, the humidity of compressed air decreases during cooling, while there is still some water vapor left. To further separate water vapor from compressed air, RAM-2 drill use a coalescing filter (Gibson et al., 2020). Wang et al. (2017) suggested using both a coalescing filter and a desiccant dryer to dry the cooled air.

When liquid is used for drilling, cuttings must be removed from the drilling fluid. Winkie drill used simple filter bags to collect all particles larger than 100 μm (Boeckmann et al., 2021). ASIG drill and RAID used a commercially available screen

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shaker to separate ice or rock cuttings and the collected ice cuttings were melted in a heated melter tank to separate oil-based drilling liquid from melting water (Kuhl et al., 2021; Goodge and Severinghaus, 2016). In the drilling-fluid circulation system (DFCS) of the Winkie drill, ASIG drill and RAID, there is no cooling system to cool the drilling liquid before pumping to the borehole. In low-elevation sites of Antarctica with warm ambient temperatures, the drilling liquid could become warm at the surface and degrade the drill performance, damage the borehole, and create a risk of equipment loss by freezing in the hole. Sometimes, the drill fluid drums had to be buried in the firn to cool it (Braddock et al., 2024). In addition, when the Winkie drill was used in subglacial bedrock drilling, the warm fluid near the bit melted the ice-borehole wall, and the melted water refroze in the casing, resulting in flakes that plugged the casing (Boeckmann et al., 2021). Therefore, a fluid chiller was suggested to cool drill fluid for ambient temperatures approaching −4 °C (Braddock et al., 2024). When drilling in ice, high pressure spikes can easily lead to hydraulic fracture (Chen et al., 2019). The use of pressure-relief valve at the outlet of drilling-fluid pump seems invaluable (Kuhl et al., 2021; Goodge et al., 2021).

The conventional drill rig-based MPDS (Fig.1), was developed in China for sampling at least 10 m bedrock beneath 1000 m ice sheet in polar regions. The MPDS is designed to remove drill cuttings using compressed air or drilling fluid in reverse circulation. The MPDS generally has five subsystems: drill rig, drill-pipe container, generator, air system and DFCS. All the subsystems were integrated in standard 20 ft container and could be easily moved on the ice surface by sledges. During drilling, compressed air with reverse circulation was used to penetrate firn and ice. The process continued until the ice pressure at the depth posed a risk of downhole drill sticking, necessitating operational adjustments. Then, drilling liquid was used to drill the ice that was leftover and the subglacial bedrock.

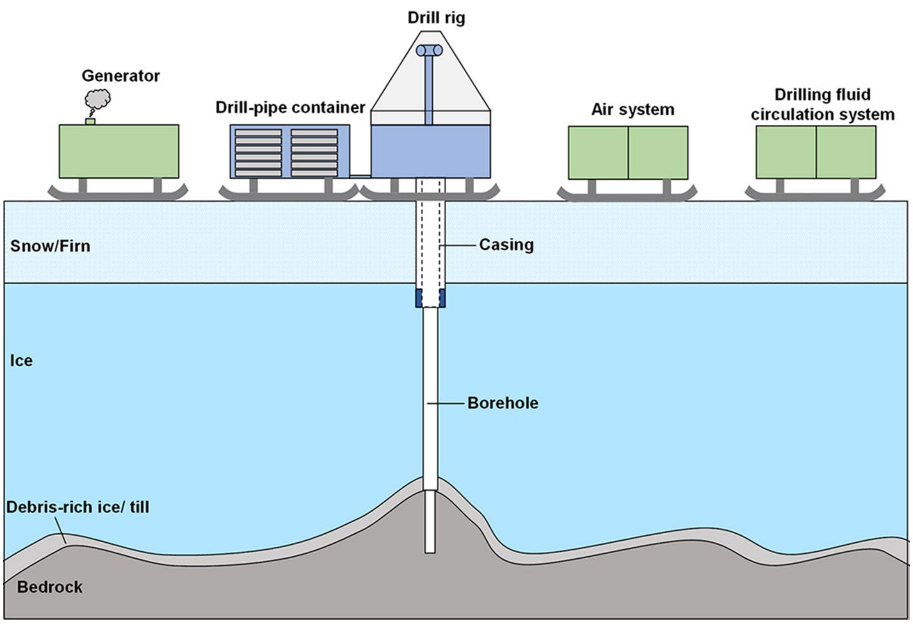

Figure 1: Schematic diagram of the MPDS for subglacial bedrock sampling in polar regions

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This paper presents the design and test of the air system and the DFCS. Both systems were newly designed and were improved based on previous experiences. We believe that our experience and lessons will aid future drill design and promote the development of ice and subglacial bedrock drilling technology. In addition, the two systems are also helpful in preventing permafrost thawing during well drilling in permafrost regions and reduce the subsequent environmental threat (Eppelbaum and Kutasov, 2019; Langer et al., 2023).

2 Air system

2.1 Air-system requirement

Theoretically, the required flow rate and pressure of compressed air is related to borehole depth and diameter, rate of penetration, size of drill pipes, and so on (Cao et al., 2018). According to Cao et al. (2019), a 5.25 $Nm^3 \cdot min^{-1}$ flow rate and 1.06 MPa pressure were required to pneumatically transport an ice core with a 90 mm diameter and a 500 mm length from a 500 m depth to the surface. In general, higher flow rates and pressures of compressed air are better for drilling, but these require heavy compressors, which pose logistical challenges in remote polar regions. The final compressed-air flow rate and pressure was determined to be no less than 10 $Nm^3 \cdot min^{-1}$ and 1.5 MPa.

In theory, the compressed air should be, at least, cooled to below 0 ℃. We expected that a temperature of -5 ℃ would be better for cooling drill pipes and drill bit. The dew point of compressed air was expected to be lower than -40 ℃, which corresponds to a water content of 0.176 $g \cdot m^{-3}$. The air system is required to work at temperature of -30 ℃ and must be integrated into a standard 20 ft container for easy transportation on ice. In addition, the air system must have a modular design, and each module must weigh less than four tons for safe helicopter transportation from the icebreaker *Xuelong* to the ice surface. All the requirements of the air system are summarized in Table 1.

Table 1 Required design parameters of the air system

Parameter	Value
Flow rate of compressed air	≥10 $Nm^3 \cdot min^{-1}$
Pressure of compressed air	≥1.5 MPa
Temperature of compressed air	≤-5 ℃
Dew point of compressed air	≤-40 ℃
Low temperature resistance of the air system	≤-30 ℃
Volume of the air system	Should be integrated into a 20 ft container
Weight of the air system	Should be separable into several unit weighing less than four tons

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2.2 Air-system principle

When air at atmosphereic pressure is compressed to high pressures, its temperature can rapidly increase as high as 80–100 °C (Fig. 2). To lubricate the compressor and to protect it from overheating, cold oil is usually pumped into the compressor and air fans are also used for cooling. Generally, the hot air can be cooled down to 30–50 °C at the outlet of compressor. When the air temperature drops, the water vapor in the air condenses, and a built-in gas-liquid separator is used to separate water or oil drops from the compressed air.

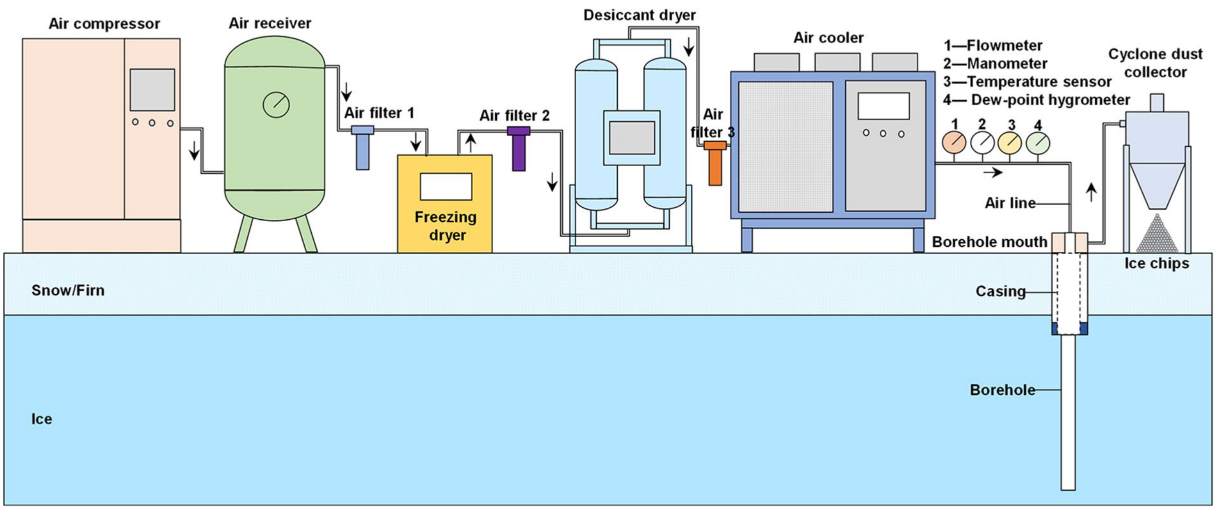

Figure 2: Air-system principle

Then, the compressed air is flowed into a receiver to reduce the pressure pulses caused by the compressor. Here, the compressed air cools slightly owing to heat transfer with ambient atmosphere. In time, the condensed water collects at the bottom of the receiver and is emptied periodically.

Subsequently, the compressed air is dried by the freezing dryer and desiccant dryers, respectively. The freezing dryer uses a heat exchanger to cool the compressed air by refrigerant. During the cooling process, the water vapor continues to condense and is separated from the air. Generally, the dew-point of compressed air can be lowered to 2–10 °C. To further dry the compressed air, a desiccant dryer with two dry towers is used. Different types of desiccants can be used to dry the air, such as silica gel, activated alumina, and molecular sieves. To lower the dew-point of the compressed air below -40 °C, molecular sieves are preferred. When a desiccant dryer is used, one tower works to dry the air and the other is heated to dry the desiccant. In modern design, the two towers can be automatically switched on periodically. To protect the dryers, air filters 1 and 2 were inserted to remove the impurities in the compressed air.

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After passing through the desiccant dryer, the compressed air is sufficiently dry and could be cooled by air cooler. The air cooler uses heat exchanger to cool the air by refrigerant. In this way, the final air temperature wouldn't be affected by ambient atmosphere temperature. The air filter 3 with higher filter precision is added before air cooler to protect it.

In the design, a flowmeter, manometer, temperature sensor, and a dew-point hygrometer were installed at the outlet of the air cooler to monitor the flow rate, pressure, temperature, and dew-point of compressed air injected into a borehole. A traditional cyclone dust collector is used when the air flows out of the borehole, to separate ice chips from the air and collect them for possible scientific research.

2.3 Air-system design

2.3.1 Air-system components

After a detailed market investigation, the main components were selected as per the requirements and principles of the air system (Fig. 3). All the devices were commercially available, except for the cyclone dust collector. The key parameters of the main components used in the air system are shown in Table 2. The compressor selected had a flow rate greater than 10 Nm³/min because 10–20 % of air could be lost during the drying and cooling processes at the surface. The compressor is powered by a three-phase motor and cooled by a large air fan. The compressor uses built-in sensors to monitor the flow rate, pressure and temperature just after air compression. When the pressure exceeds the maximum setting, the compressor stops automatically. The compressor could be independently controlled by its own control board, or remotely controlled.

The air receiver safety valve is top mounted and turned on automatically when the air pressure exceeds 1.78 MPa. The condensate collected at the bottom is periodically discharged to a plastic bucket through a drain valve. The pressure gauge on the receiver displays the inner pressure in real time.

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Figure 3: Main components of the air system: (a) air compressor; (b) air receiver; (c) freezing dryer; (d) desiccant dryer; (e) air cooler, 1-flowmeter, 2-dew-point hygrometer, 3-manometer, 4-temperature sensor; and (f) cyclone dust collector.

The freezing dryer utilize the R404A refrigerant to cool the compressed air and the refrigerant is air-cooled in condenser. The condensate could be discharged periodically by an electronic timed drain valve. The freezing dryer has built-in temperature sensors to monitor the air temperature at its inlet and outlet.

The desiccant dryer uses an alumina molecular sieve to absorb any leftover water vapor. The adsorption tower is externally heated (4.5 kW)—to heat the compressed air and dry the moist desiccant. Generally, it takes about 15–30 minutes to dry a tower. The desiccant in the tower should be changed from time to time.

The air is cooled in two stages using two independently functioning coolers: first, to a temperature below 0 °C, and then to -10 °C. The same as freezing dryer, the air cooler also uses R404A to cool the compressed air by using a plate heat exchanger. The dew-point of the air fed into the air cooler has to be lower than -10 °C. Otherwise, the water vapor would have condensed in the conduit and refrozen, leading to ice plugs. The dew-point at the inlet of the air cooler is always monitored by the built-in dew-point hygrometer. The temperature at the output of the first cooler is monitored in real time by a built-in temperature sensor.

The air filter is mainly used to remove impurities in the air, such as oil droplets, water droplets and micro solid particles. As the compressed air flows from compressor to air cooler, the air filter precision increases. The air-filter drain valves are used to remove the filtered impurities.

Table 2 Key parameters of the main components used in the air system

Components	Type	Key parameters	Manufacturer
Air compressor	2LG-12/15	Flow rate: 12 $Nm^3 \cdot min^{-1}$ Max. pressure: 1.5 MPa Power: 90 kW Weight: 1550 kg	Shanxi Yishan Compressor Co., Ltd.
Air receiver	C-1.0/1.6	Design pressure: 1.68 MPa Max. pressure: 2.1 MPa Air storage capacity: 1 m^3 Weight: 371 kg	Puyang Anuo Energy Technology Co., Ltd.
Freezing dryer	YS-13T	Flow rate: 13.5 $Nm^3 \cdot min^{-1}$ Working pressure: ≤1.6 MPa Required air temperature at inlet: ≤80 °C Dew point of air after drying: 2–10 °C	Zhejiang Dongzhou Boiler Vessels Co., Ltd.

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Desiccant dryer	YS-13R	Power: 2.3 kW Flow rate: 13.5 $Nm^3 \cdot min^{-1}$ Working pressure: ≤1.6 MPa Adsorbent: Alumina molecular sieve Required air temperature at inlet: ≤40 °C Dew point of air after drying: -20–40 °C Heating power: 4.5 kW	
Air filter 1	YS-013T	Flow rate: 13.5 $Nm^3 \cdot min^{-1}$ Working pressure: ≤1.6 MPa Working temperature: ≤66 °C Filter precision: 1 μm Oil remainder: 3 ppm	
Air filter 2	YS-013H	Flow rate: 13.5 $Nm^3 \cdot min^{-1}$ Working pressure: ≤1.6 MPa Working temperature: ≤66 °C Filter precision: 0. 1 μm Oil remainder: 2 ppm	
Air filter 3	YS-013A	Flow rate: 13.5 $Nm^3 \cdot min^{-1}$ Working pressure: ≤1.6 MPa Working temperature: ≤66 °C Filter precision: 0.01 μm Oil remainder: 1 ppm	
Air cooler	FDK-10/10-C	Flow rate: ≤11 $Nm^3 \cdot min^{-1}$ Working pressure: ≤1.5 MPa Air temperature after cooling: -10–0 °C Power: 20 kW Weight: 795 kg	Xi'an Hengmao Power Technology Co., Ltd.
Flowmeter	OPEC-LUGB2G04CYNE	Measurement range: 300–3600 $Nm^3 \cdot h^{-1}$ Max. working pressure: 4 MPa Precision: ±1.5 %;	Shaanxi OPEC Instrument Group Co., Ltd.
Manometer	OPEC-2088SC8M1NM1E	Measurement range: 0–2.5 MPa Precision: ±0.5 %;	

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Temperature sensor	OPEC-SBWZP1KS51YE	Measurement range: -40–150 ℃ Precision: ±0.5 %;	
Dew-point hygrometer	OPEC-DM70ES/N	Measurement range: -60–60 ℃ Precision: ±1 ℃ Max. working pressure: 4 MPa Max. working temperature: 70 ℃	
Cyclone dust collector	/	Flow rate: 10 $Nm^3 \cdot min^{-1}$ Max. pressure: 1.5 MPa Diameter: 300 mm Height: 1.83 m	Customized

2.3.2 Integration of the air system into the container

All the components mentioned in Sect. 2.3.1 were integrated into a customized 20 ft container with left and right parts, connected by bolts (Figs. 4 and 5). The compressor, receiver, and centralized control cabinet were installed in the left part. To prevent container overheating by the waste heat generated by compressor, a thermally insulated cover was added on the top of air fan which guided the hot air to the outside of the container through a window shutter. In addition, there were cooling vents on the front door of left container. The centralized control cabinet controlled the component start and stop and displayed the data collected by the sensors. The operator entrance was a small door near centralized control cabinet. All the components could also be started or stopped by their own control boards.

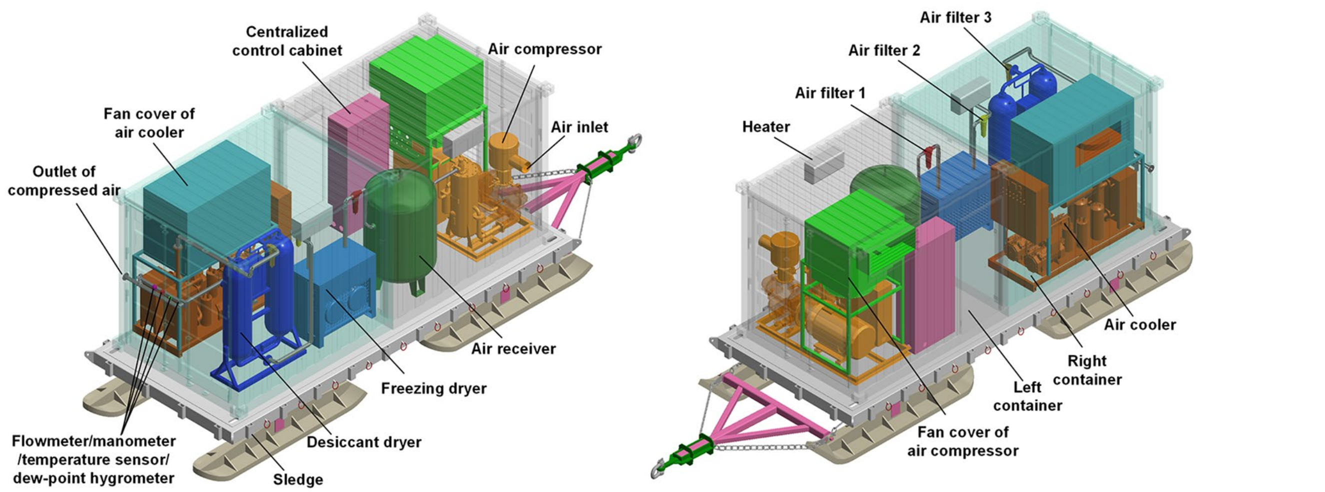

Figure 4: Structure of the air system

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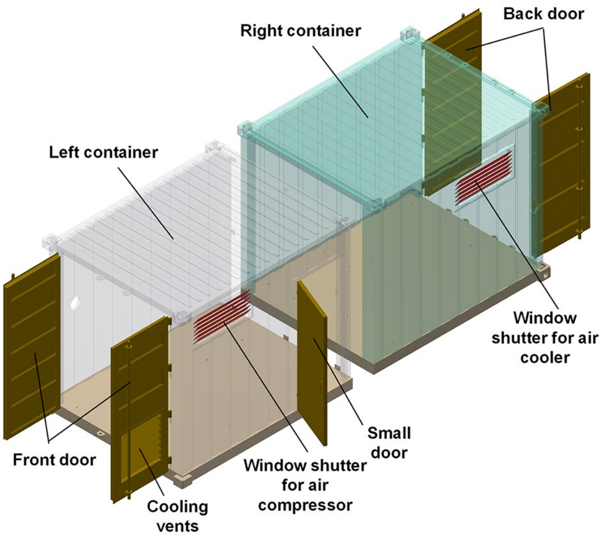

Figure 5: Modified container of the air system

The freeing dryer, desiccant dryer, air cooler, filters and sensors were placed in the right part. The freeing dryer and desiccant dryer were installed to one side and the air cooler to the other side. A small sidewalk between the two sides facilitated the passage of a single person. The air cooler also had a fan cover for heat dissipation through a window shutter on the right container. All the window shutters and the cooling vents had thermally insulated covers to keep the container to prevent snow from entering when the air system was not in use.

All the components were fixed by bolts on the container floor. The total weight of the air system was approximately 7.8 tons. During transportation to polar the regions, the air system could be disassembled into left and right parts. The left part weighed 4.2 tons, while the right part weighed ~3.6 tons. The two parts were reassembled on the field using bolts; the gap between them could be sealed using a sealant to prevent rain and snow from entering. On ice surface, the air system could be easily moved by a sledge. As the compressor and freezing dryer could only be started up above 0 ℃, 2 kW heaters were installed in both the left and right parts. Before starting the whole air system, the heaters were used to warm the container. Once the system starting to work, the heaters would be shut off. Meanwhile, the thermally insulated covers of the cooling vents and window shutter were removed for heat dissipation.

2.4 Air-system testing

2.4.1 Air-system performance

The air system was first tested in China post-manufacturing (Fig. 6a). In domestic tests, the air system worked for two hours and generated 10.9 $Nm^3 \cdot min^{-1}$ compressed air at 1.5 MPa pressure. At an ambient temperature of 27–28 ℃, the air temperature rose to 95–97 ℃ post-compression. The compressed air was cooled to -4.5 ℃ with one cooler and to -10.8 ℃

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with both coolers. After drying using the freezing dryer and desiccant dryer, the dew-point of the compressed air was as low as -48 to -52 °C. After testing, the air system was used to drill the underground soil and rock using the drill rig. However, because of groundwater presence, only the compressor and receiver were used. The freezing dryer, desiccant dryer, and cooler did not work. The drill-rig testing using the compressor, receiver, and cyclone dust collector lasted for approximately two months, during which they performed stably (Fig. 8a).

The MPDS was tested in the summer season of 2024/2025, at the margin of Princess Elizabeth Land, East Antarctica (coordinates: 69°35'10.12" S, 76°23'03.87" E). In the field test, a 110 m borehole was drilled, in which upper the 42 m were drilled using the air system (Fig. 6b).

Figure 6: (a) Domestic test and (b) field test of the air system

The air system began work on January 10th, 2025. The testing results of the air-system from January 12th to 15th, 2025 are shown in Fig. 7. The detailed data regarding to the testing results can be found in the corresponding supplements Table S1. The average flow rate was ~10.5 $Nm^3 \cdot min^{-1}$. The average pressure of compressor was ~0.78 MPa, owing to the pressure loss at the conduit of the surface equipment (freezing dryer, desiccant dryer, air cooler, air hose, swivel, valves etc.). The air temperature increased to approximately 70–90 °C with an average value of 81.08 °C post-compression. After cooling by the built-in air fans and receiver, the compressed air entered the freezing dryer at a temperature of 36.94 °C. However, the freezing dryer did not work well, and the compressed air was cooled only to ~35.27 °C, and the compressed air was not dried to the required dew-point of 2–10 °C. The compressed air was further dried by the desiccant dryer to a dew-point of 9.78 °C. In the air cooler, the compressed air was cooled by the first and second coolers and was injected to the borehole with a lowered dew-point of -9.44 °C. When only the second cooler worked, the compressed air entered the air cooler at a temperature of 29.21 °C, which was 6.06 °C lower than the temperature at the outlet of freezing dryer. After cooling by the second cooler, the compressed air was cooled to be about -8.36 °C. When only the first cooler worked, the compressed air could be cooled to -11.62 °C. However, the temperature of the compressed air increased to -9.11 °C after second cooler, because the second cooler did not work and the compressed air was warmed a little by ambient atmosphere. In general, the compressed air was pumped into the borehole at a temperature of about -9 °C.

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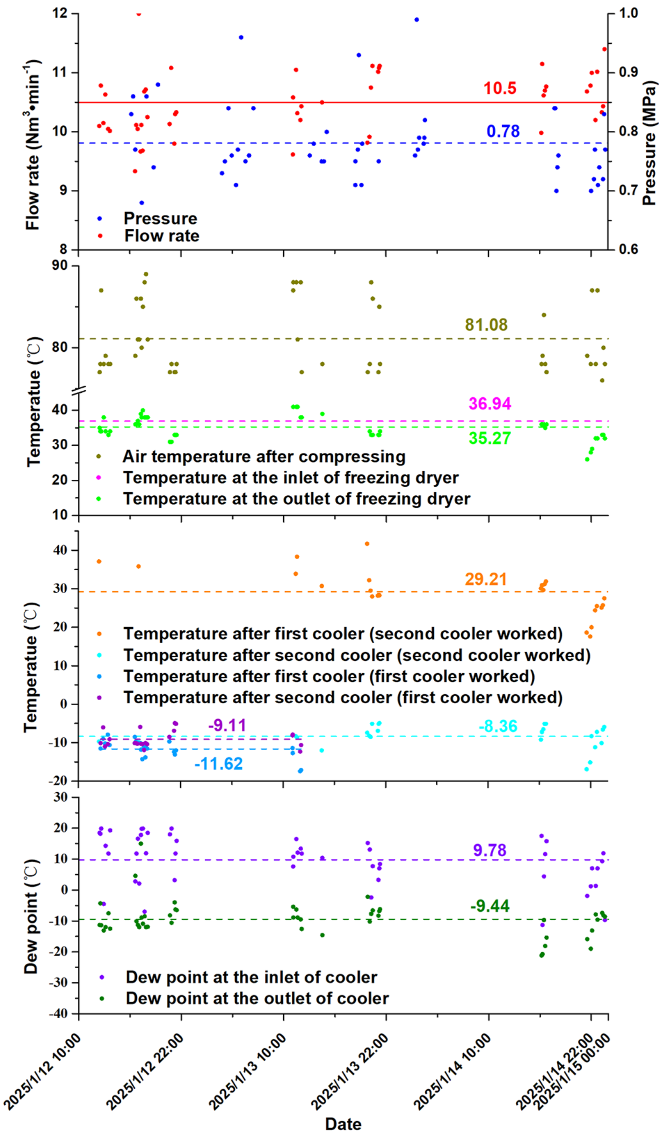

Figure 7: Test results of the air system in Antarctica

As mentioned above, the freezing dryer and desiccant dryer did not work well, and the compressed air could not be dried to a
225 dew-point of -40 °C before flowing through air cooler. In this case, the condensate froze into an ice plug in the air-cooler conduit leading to a rapid rise in the outlet pressure of the air cooler. In common case, after 15–20 minutes, the pressure increased from 0.7 MPa to 1.3 MPa, which was close to the limited maximum pressure of air cooler. In the field, the ice plug was melted by hot compressed air after shutting off the air cooler. In this situation, the drilling work had to be stopped until the pressure dropped to normal values. This process took approximately 5–8 minutes. In addition, another 3–5 minutes were

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required to restart the cooler. In the field, the first and second coolers were used alternately, and the operators spent a lot of time on monitoring the pressure, starting and shutting off the cooler etc. However, the heat exchanger of the first air cooler was accidentally broken by frozen ice on January 16th, and the air cooler stopped working. Later, all the components were carefully checked in the field. It was found that a lot of the condensate was not discharged from the air receiver through the drain valve; due to which the freezing dryer and the desiccant dryer could not dry the compressed air to desired dew-point (Fig. 8b). Manufacturing defects of the freezing dryer and the desiccant dryer were also suspected.

To continue drilling with air, a 140 m rubber hose was buried approximately 10 cm deep in the snow to cool the compressed air (Fig. 8c). This method proved to be partly useful. In Antarctica, compressed air at a temperature of 15–21 °C could be cooled to -1 to -3 °C with an ambient temperature of about -6 °C. However, this method could not decrease the humidity of compressed air, and the condensate refroze on the outer surface of the drill pipe and also forming an ice plug inside (Figs. 8d and 8e).

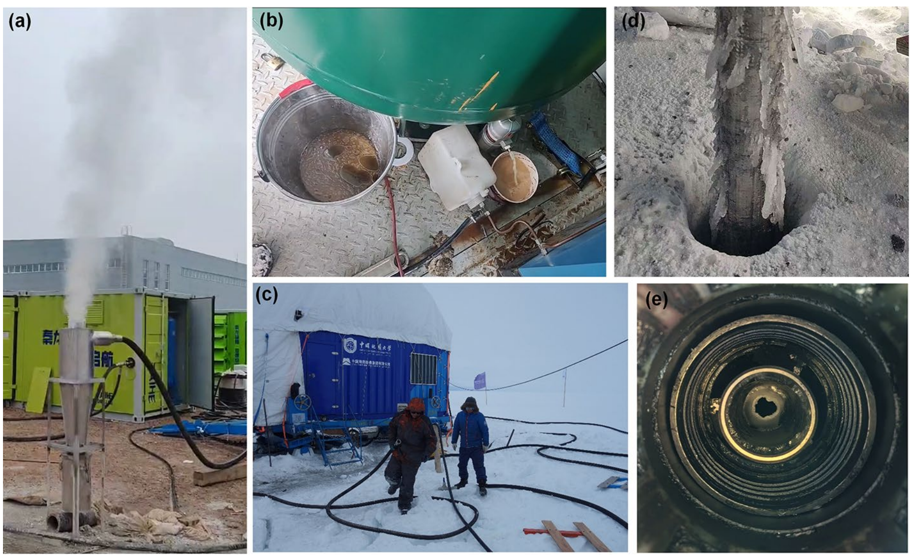

Figure 8: Test phenomena: (a) cyclone dust collector worked well in domestic test; (b) condensed water could not be discharged from the receiver; (c) burying the rubber hose into snow to cool compressed air; (d) condensed water refrozen on the outer surface drill pipe; (e) ice plug formed in drill pipe.

2.4.2 Suggestions for improvement of the air system

The modular design of the air system had some good features. In the field, it could be easily assembled and disassembled. In addition, all components of the air system could meet the design requirements in domestic tests, particularly, the compressor, air cooler, and cyclone dust collector. However, the poor performance of the freezing dryer and the desiccant dryer in the field led to air-cooler breakage and refrozen water on the drill pipes.

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In future, the discharge pathway of condensate in receiver must be redesigned. Besides, freezing dryer and desiccant dryer of good quality must be used. The broken heat exchanger in the cooler must be replaced. A passive heat exchanger is suggested for cooling compressed air in polar regions where the ambient temperature is lower than -20 ℃, because passive heat exchangers are simpler, lighter and more reliable than the air cooler.

3 DFCS

3.1 Requirement of the DFCS

DFCS requirements are shown in Table 3. The flow rate and pressure required for ice and subglacial bedrock drilling below 1000 m was roughly estimated as per the report by Alemany et al. (2021). The final determined flow rate for the DFCS is a little lower than the maximum flow rate of 134 $L \cdot min^{-1}$ used by RAID (Goodge and Severinghaus, 2016). To prevent possible hydraulic ice fracture caused by drilling-liquid overpressure, the DFCS maximum pressure was limited to less than 2 MPa. The SUBGLACIOR drilling probe has a maximum pressure of 2.5 MPa, while the RAID has a maximum pressure of 2.1 MPa during ice drilling (Alemany et al., 2021; Goodge et al., 2021). Compared to SUBGLACIOR and RAID, DFCS is a little safer in avoiding hydraulic ice fracture. The drilling fluid must be colder than -2 ℃ in polar regions before being pumped into a borehole to prevent melting of the borehole ice wall. The DFCS has the same requirements as the air system in low-temperature resistance, volume and weight.

Table 3 Required design parameters of the DFCS

Parameter	Value
Flow rate of drilling fluid	≥100 L·min-1
Maximum pressure of drilling fluid	≤2 MPa
Temperature of drilling fluid	≤-2 ℃
Low temperature resistance of the DFCS	≤-30 ℃
Volume of the DFCS	Should be integrated in a 20 ft container
Weight of the DFCS	Should be separable into several units weighing less than four tons

3.2 Principle of the DFCS

As shown in Fig. 9, the DFCS uses a refrigerating machine to cool the drilling fluid at the surface. The refrigerating machine could cool the refrigerant to a low temperature and then pump it into a heat exchanger by a built-in pump. In the heat exchanger, the drilling fluid is cooled to desired temperature by the cold refrigerant. Generally, a circulation pump is used to pump the drilling liquid from circulation tank to the heat exchanger. The drilling liquid need not be actively cooled if the ambient temperature is low enough to cool the drilling liquid to a temperature below -2 ℃.

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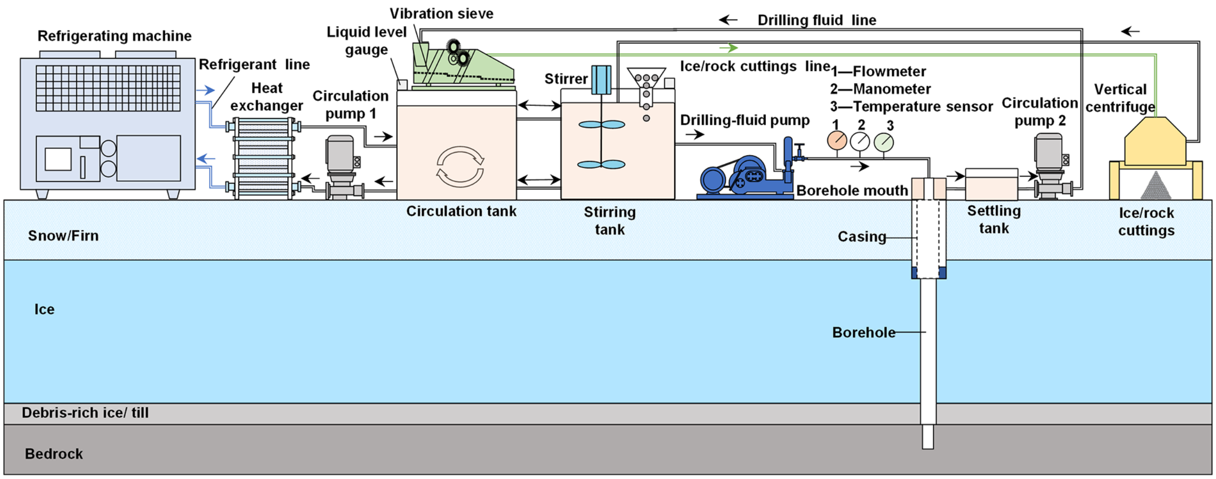

Figure 9: Principle of the DFCS

To make it lighter for easy transportation, the tank for drilling-liquid storage is partitioned into a circulation tank and a stirring tank. The drilling liquid is prepared in the stirring tank, and a stirrer is installed inside to evenly mix the different additives and base fluid. The circulation tank and the stirring tank are hydraulically connected by a pipeline. To monitor the liquid level in the two tanks, liquid-level gauges are installed above the tanks. The prepared drilling fluid is then injected from the stirring tank to the borehole by a drilling-fluid pump. At the outlet of the drilling-fluid pump, a flowmeter, manometer, and temperature sensor are installed to monitor the key parameters of the drilling liquid.

Vibration sieves and vertical centrifuges are used for separating ice or rock cuttings from the drilling liquid. When the drilling liquid returns to surface, it is stored in a settling tank and then pumped through a vibration sieve for separating the ice or rock cuttings. The vibration sieve is installed on the circulation tank, in which the drilling fluid could be stored after separation. The separated ice or rock cuttings are still wet with drilling liquid, so a vertical centrifuge is used to dry them. The residual drilling fluid in the ice or rock cuttings is recycled and only the dried ice and rock cuttings are discarded.

3.3 DFCS design

3.3.1 DFCS components

All the components of the DFCS were selected based on the requirements and were commercially available, except for the stirring, circulation, and settling tanks (Fig. 10). The key parameters of the components are shown in Table 4. The refrigerating machine cools the secondary refrigerant using R404A. The secondary refrigerant is then pumped to the heat exchanger to cool the drilling liquid. In the refrigerating machine, glycol aqueous solution with 60 % volume fraction and freezing point of -50 °C acts as secondary refrigerant. The refrigerating machine could generate a lot of heat during operation, so two large air fans are installed at the back for heat dissipation.

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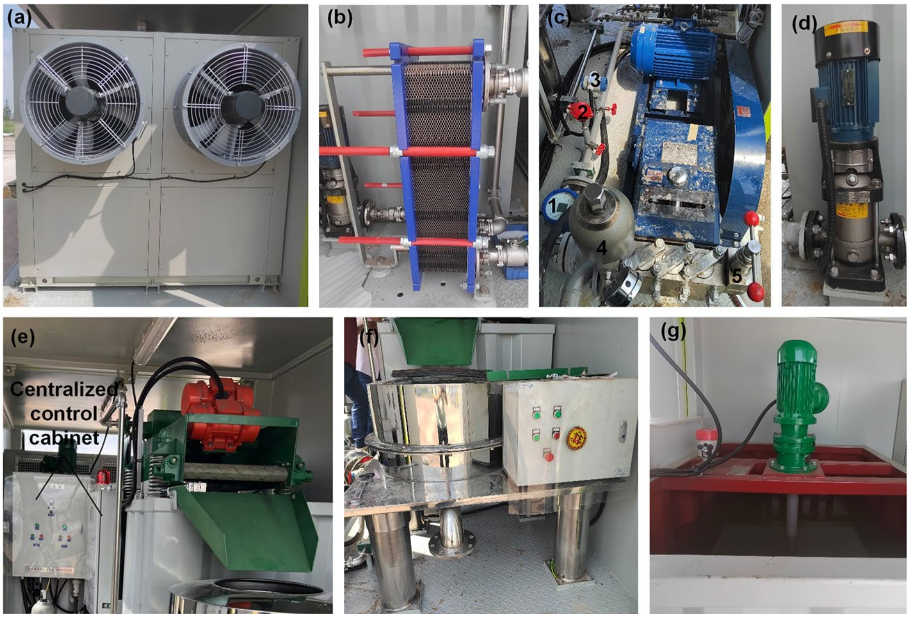

Figure 10: Main components of the DFCS: (a) refrigerating machine; (b) heat exchanger; (c) drilling-fluid pump; (d) vibration sieve; (e) vertical centrifuge; (f) circulating pump; and (g) stirrer.

Different types of heat exchangers were considered in the design, including the plate heat exchanger, finned-tube heat exchanger, shell and tube heat exchangers. Compared with finned-tube and shell and tube heat exchangers, the plate heat exchanger is more compact in size and lighter in weight. There are two types of plate heat exchangers, which are the brazed plate heat exchanger and gasket-type plate heat exchanger. The brazed plate heat exchanger is difficult to clean when solid particles accumulate inside. A gasket-type plate heat exchanger was selected because it uses a bolt-connected plate for easy disassembly during cleaning. The plate in the gasket-type plate heat exchanger is made by stainless steel 316, which has a thickness of 0.5 mm. The plate gap allows solid particles smaller than 1 mm to pass through.

A three-cylinder plunger pump, driven by an AC motor using a cold-resistant rubber belt, was used as the drilling-fluid pump. To reduce the pulse pressure generated by the three cylinders, an accumulator was installed at the pump outlet. A pressure-relief valve was installed to regulate pressure and flow rate. All seals and the pistons in the pump are made of low-temperature resistant rubber, which can work at -30 ℃. Vertical centrifugal pumps were chosen as circulation pump. The centrifugal pumps can be used to pump organic substances such as aviation kerosene and silicone oil at -30 ℃.

The chosen vibration sieve can generate linear motion on the cuttings and have a single layer of mesh. The mesh has an area of ~2 m^2 and can be replaced based on the cuttings size. The vibration sieve was installed above the circulation tank with four springs. The separated cuttings can slide into the vertical centrifuge along a guide groove, fixed at an angle on the circulation tank. The controls for starting and stopping the vibration sieve, drilling-fluid pump, and vertical centrifugal pump are accessible on the centralized control cabinet.

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The vertical centrifuge is powered by a variable-frequency motor, with a maximum rotation speed of 1500 r/min. The drilling fluid remaining in the cuttings is separated by a replaceable filter screen installed in the circular drum and then pumped back to the circulation tank. The dry cuttings can be only manually removed from the drum by the operator when connecting additional drill pipe to the drill string to extend its length. Four large springs were installed at the foot of the vertical centrifuge to reduce its vibration during high-speed rotation. In addition, the motors and the variable-frequency drive are covered by steel to prevent the drilling liquid from entering. The vertical centrifuge could be controlled using its own controller or by the centralized control cabinet.

The stirrer is vertically installed above the stirring tank and has only one layer of plate-type blades. The size of both the stirring and circulation tanks is 1.3 × 1.3 × 1.2 m. Therefore, the largest drilling-liquid volume that could be prepared at the surface is about 4 m^3. Two settling tanks sized 2 × 1 × 0.8 m are used. The tanks are made of 3-mm steel plates and reinforced with square steel tubes.

Radar level gauges is installed on both tanks for real-time liquid-level measurement. The data measured by the radar level gauge, flowmeter, manometer, and temperature sensor are displayed on the centralized control cabinet and sent to the control panel of the drill rig.

Table 4 Key parameters of the main components used in the DFCS

Components	Type	Key parameters	Manufacturer
Refrigerating machine	BLD-25AL	Nominal refrigerating power: 20.1 kW Total power: 23 kW Refrigerant: R404A Secondary refrigerant: Glycol aqueous solution by 60 % volume Weight: 750 kg Flow rate of pump for secondary refrigerant: 15 $m^3 \cdot h^{-1}$ Head of pump for secondary refrigerant: 30 m Tank volume for secondary refrigerant: 200 L	Shenzhen Polyde Refrigeration Technology Co., Ltd.
Heat exchanger	T6-PFG	Number of plates: 20 Maximum heat-transfer power: 46.9 kW Heat-exchange area: 7.2 m^2 Design pressure: 1 MPa Weight: 163 kg	Alfa Laval (Shanghai) Technologies Co., Ltd.
Drilling-fluid pump	3SP40-2/6	Power: 7.5 kW Max. outlet pressure: 2 MPa Displacement: 6–7 $m^3 \cdot h^{-1}$	Wuxi Terui High Pressure Pump Valve Co., Ltd.

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		Weight: 370 kg	
Vibration sieve	ZZSD-01	Processing capacity of drilling fluid: 8 $m^3 \cdot h^{-1}$ Power: 0.25 kW×2 Number of the mesh: 40–150 Weight: 150 kg;	Xi 'an Xingqing Petroleum Equipment Co., Ltd.
Vertical centrifuge	PSL600	Power: 4 kW Separation factor: 755 Max. rotation speed: 1500 $r \cdot min^{-1}$ Working volume: 38 L Weight: 700 kg;	Zhangjiagang Guohua Machinery Co., Ltd.
Circulating pump	CDLF4-5	Power: 1.1 kW Flow rate: 6 $m^3 \cdot h^{-1}$ Head: 31m	Shanghai Sunshine Pump Co., Ltd.
Stirrer	WHNJ-1.5	Rotation speed: 84 $r \cdot min^{-1}$ Power: 1.5 kw Weight: 50 kg	Cangzhou Huacang Drilling & Extracting Oil Equipment Co., Ltd.
Liquid-level gauge	80G	Measurement range: 0.08–10 m Precision: ±3 cm	Hangzhou Supmea Automation Co., Ltd.
Flowmeter	LZ-FK-DN40	Measurement range: 0.8–8 $m^3 \cdot h^{-1}$ Precision: ±1.5 %	Hangzhou FULLKON Instrument Co., Ltd.
Manometer	FK-P400-E	Measurement range: 0–5 MPa Precision: ±0.5 %	
Temperature sensor	FK-WZPK-	Measurement range: -200–350 ℃ Precision: ±1.5 %	

3.3.2 Integration of the DFCS into the container

All the components of the DFCS were integrated into a standard 20 ft container, except for the two settling tanks (Fig. 11). The standard container was partitioned into right and left containers, which could be connected by bolts (Fig.12). The refrigerating machine, the heat exchanger, circulation pump 1, and the stirring tank with a stirrer on top were installed in left

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container. The left container had front and side doors. The front door had two cooling vents for refrigerating-machine heat dissipation during operation. The side door was close to the heat exchanger. The side-door entrance had sufficient space for operating the refrigerating machine and preparing the drilling liquid in the stirring tank.

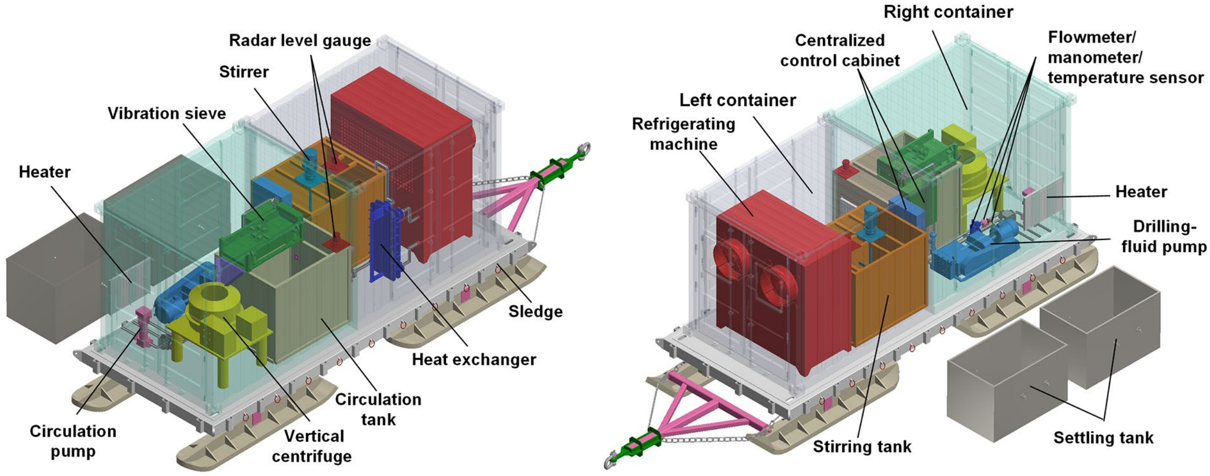

Figure 11: Structure of the DFCS

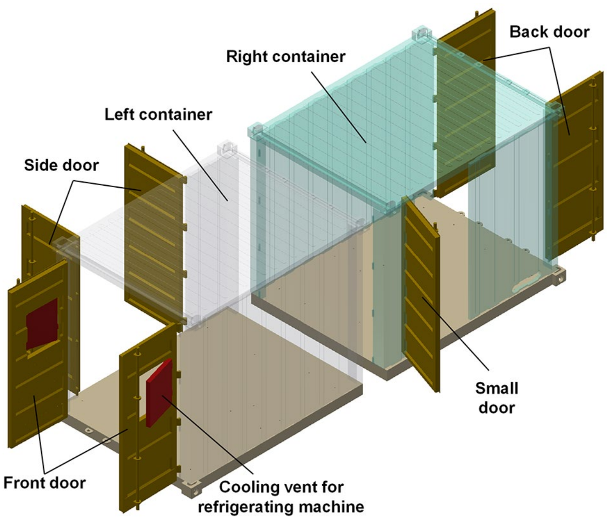

Figure 12: Modified container of the DFCS

The rest of the components were installed in the right container. The circulation tank, vibration sieve, and vertical centrifuge were fixed on one side. The drilling-fluid pump, circulation pump 2, and the sensors were installed on another side. The vibration sieve was installed above the circulation tank, and a guide groove was used to transport the separated cuttings from the vibration sieve to the vertical centrifuge. The right container had a small door and a back door. The small door was close to the centralized control cabinet for easy operation.

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All the components were fixed to the floor of the container by bolts. Each half container with all its components inside weighed about 3.7 tons. A 2 kW heater was installed in each half container. A centralized control cabinet was used to control all the components and display the measured data from sensors. To save space, the centralized control cabinet was divided into two parts, the first was fixed on the stirring tank, and the second was fixed on the circulation tank. The settling tank was lower than borehole mouth and below the snow surface in the field. The returned drilling fluid can flow from borehole mouth into the settling tank owing to gravity.

3.4 DFCS testing

3.4.1 DFCS performance

The DFCS was tested both in China and in Antarctica (Fig. 13). The domestic test used water, and the maximum flow rate of drilling-fluid pump was as high as 110 $L \cdot min^{-1}$. The vibration sieve and the vertical centrifuge were tested with mud, containing both soil and sand. In general, the vibration sieve and the vertical centrifuge worked well, and the solid particles could be separated from water. To test the capability of the refrigerating machine and the heat exchanger, clean water was circulated at flow rate of 100 $L \cdot min^{-1}$. In the test, 2 m^3 water could be cooled from 24.8 to 7 °C in 50 minutes.

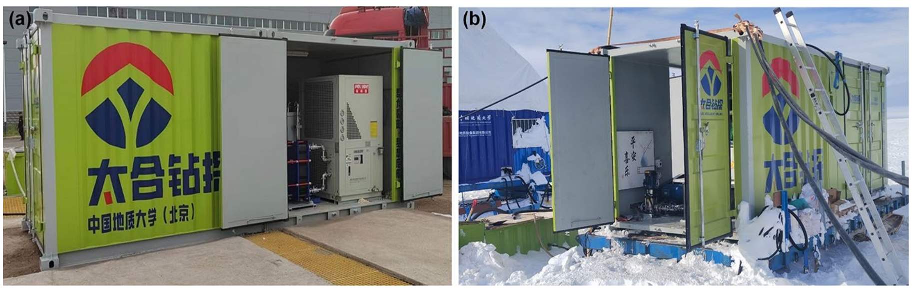

Figure 13: (a) Domestic test and (b) field test of the DFCS

The DFCS was used to drill an ice borehole in Antarctica from 31–110 m in the summer season of 2024/2025. In the field test, the average flow rate of the drilling-fluid pump was controlled to ~79.6 $L \cdot min^{-1}$ while the pressure drop was maintained at ~0.18 MPa (Fig. 14). The detailed data regarding to the Figure 14 can be found in the supplements Table S1. The drilling fluid was kept at approximately -10.12 °C at surface, so the refrigerating machine and the heat exchanger were never used in the field.

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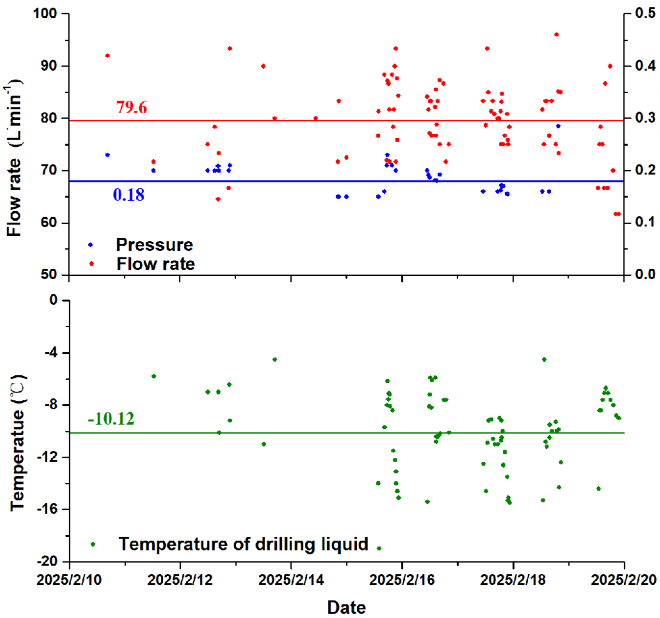

370 **Figure 14: Test results of the DFCS in Antarctica**

The 100 meshes and 120 meshes screens were tested for separating ice cuttings (Fig. 15). In general, the 100-mesh screen worked much better than the 120-mesh screen. When the 100 meshes screen was used, the ice chips aggregated into small balls on the screen, and most of the drilling liquid leaked into the circulation tank below. However, some very fine ice chips could not be filtered from the drilling liquid with 100 meshes screen. The vertical centrifuge was operated at its highest rotation speed in the field. When the ice-chip balls fell into the vertical centrifuge, almost all the ice chips could be removed from the drilling liquid. The 120 meshes screen was much better in removing fine ice chips. However, the ice chips and the clay additives in the drilling liquid clogged the small holes on the screen, and some of the drilling liquid did not reach the circulation tank; some ice chips remained in the drilling fluid even after filtering by the vertical centrifuge.

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Figure 15: Performance of vibration sieve and vertical centrifuge: (a) small ball of ice chips formed on 100 meshes screen; (b) cleaned drilling fluid when using 100 meshes screen; (c) clogging of 120 meshes screen by ice chips and clay additives; (d) ice chips remaining in the drilling liquid when using 120 meshes screen.

In the Antarctic test, other problems were found with the DFCS. The drilling-fluid pump could not be controlled by frequency modulation. In the field, the flow rate had to be regulated by pressure-relief valve. Besides, the circulation pump could not suck the drilling liquid from settling tank to vibration sieve, as required, because the circulation pump was a type of centrifugal pump. Centrifugal pumps must be primed before operation. However, the liquid level in settling tank was lower than the circulation pump, and the drilling liquid could not fill the circulation pump automatically. The ice chips became very hard after being vertically centrifuged. Removal of the hard ice chips from centrifuge drum was difficult and labor-intensive. In addition, there was no brake on the vertical centrifuge, so much time was wasted in waiting for it to stop before cleaning it up. The circulation tank had no stirrer, and the clay added in the drilling liquid settled down after a while. Also, the settled clay could get pumped into heat exchanger and block the flow channels, as there was no filter screen between circulation pump 1 and the circulation tank.

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3.4.2 Suggestions for improvement of the DFCS

In general, the DFCS was reasonably designed and met the basic usage requirements. However, some problems remained. Here, the following suggestions are given for future improvement of the system. First, the flow rate of the drilling-fluid pump should be adjustable by variable-frequency drive for easy operation. Second, the pump with suction capacity should be used as circulation pump, such as self-priming pumps and submersible pumps. Third, a high-capacity vibration sieve with double layer of screens is suggested. Fourth, the vertical centrifuge should be replaced by one with brake and self-cleaning function. Additionally, small stirrer should be added on the circulation tank and a filter screen are strongly suggested to add between the circulation pump and the heat exchanger.

4 Conclusions

In this study, an air system and a DFCS for subglacial bedrock sampling in polar regions were designed and tested, leading to a gain in experience and lessons.

(1) Standard 20 ft containers were successfully partitioned into two. The two half containers integrated with components almost weighed the same and could be easily transported and assembled in the field.

(2) Although the selected freezing dryer and desiccant dryers did not work well, the design principle of the air system was proved to be feasible. In future designs, the compressed air must be dried to a dew point of less than -40 °C using better dryers before being cooled by the air cooler. Burying a long hose under snow appears to be an effective way of cooling compressed air in polar regions. However, this method is only suggested for drilling shallow holes in a region with cold surface-air temperatures. For atmospheric temperatures lower than -20 °C, a passive heat exchanger with a large air fan is strongly recommended for cooling compressed air.

(3) The refrigerating machine and heat exchanger were proved to be useless in field test because of low temperature at this drilling site; however, they could be helpful in warmer polar regions. The possibility they would be helpful in cooling the drilling bits during subglacial rock drilling must be verified by future theoretical research or practical drilling engineering. As the variation of drilling-fluid temperatures during subglacial rock drilling is still unknown, a prediction model of the drilling-liquid temperature in reverse circulation is an urgent need.

(4) A flow rate of 79.6 $L \cdot min^{-1}$ and pressure of 0.18 MPa have been proven sufficient to drill a 110 m ice borehole with no hydraulic fracturing events. A well-designed vibration sieve and a centrifuge could separate ice cuttings from the drilling liquid. In our opinion, a vertical centrifuge with a self-cleaning function would be better than the melter used by RAID and ASIG for further separation of drilling fluid from the ice chips, owing to efficiency and power savings.

Using the aforementioned experiences and lessons, improvements are planned to the DFCS and the air system. In the next summer season, the two systems are expected to drill a 1000 m borehole in Antarctica.

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Data availability

All raw data can be provided by the corresponding authors upon request.

Author contribution

YG designed the project; LYa, YG designed the two system with the contribution from WZ and HR; LYa, YG, WJ, ZK, LB, LYan, ZZ, LX, SYu and WM carried out domestic test; LYa, ZK, LYan, ZZ, LX and SY carried out field test in Antarctica. LYa wrote the manuscript draft; YG, LB and ZK reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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