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Geological Exploration in the Cryolite Zone: Reducing Environmental Risks by Ensuring the Temperature Condition

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Abstract:***The article suggests one of the directions to solve the ecological problem of cryolite zone destruction during geological exploration. For the first time, the authors offer to use vortex tubes for this purpose. The technique is given and the results of experimental work on the use of a vortex tube to provide subzero temperatures of permafrost during drilling operations are considered. A scheme is proposed and mathematical modeling of the process is performed. As a result of the model study, the technological parameters ensuring the preservation of the cryolite zone are obtained.***

Keywords: ***vortex tube, geological exploration, cryolite zone, permafrost, ecology.***

I. INTRODUCTION

Conducting geological exploration works in the Far North in the conditions of the cryolite zone requires solving the problems of thermal protection of permafrost. In terms of the area, the cryolite zone roughly coincides with the permafrost region, in which permafrost rocks are developed occupying 25% of the land and spreading over almost half of the territory of Russia. The destruction of the cryolite zone can lead to an environmental disaster with irreversible consequences. Therefore, the subject of the conducted work related to the development of methods and technological solutions that prevent the destruction of permafrost when conducting mining and geological exploration is relevant and significant [1-5].The geological exploration technique and technology, developed for rocks with positive temperatures, cannot be completely transferred to the areas of permafrost development. The heat generation on the tool in the destruction of rocks when constructing mines and wells in the area of frozen rocks leads to the accumulation of heat that causes melting of ice-cement and intense destruction of the walls of the well and the core in cryolite zone.

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This disturbs the ecological balance and requires certain protective measures [7-9]. For successful drilling of wells (without environmental complications and accidents) in permafrost, it is necessary to fulfill the main requirement throughout drilling, namely, to keep the relevant temperature condition of the rock [10-13]. In order to improve the environmental and technical and economic indicators of exploration, the task was set to find such purging agents and determine their parameters which would not destroy the cryolite zone and ice-cemented core and well walls, as well as provide effective well cleaning from sludge, and ensure sufficient cooling of rock-breaking tools. Much better environmental, economic, and qualitative indicators of drilling wells in permafrost were obtained by replacing the liquid with compressed air [14, 15]. In the West, the first experiments of drilling with cleaning the bore-hole bottom with air were carried out in 1932 in the Eastern part of Texas but were later discontinued due to negative results. They then resumed in 1936 while drilling exploratory wells. At present, the Yakut Geological Department applies air purging on a large scale; drilling in small volumes is carried out in the Northern geological departments and in many other regions of Russia [11-13, 17]. The heat capacity of air is four times less than that of water. At the same initial temperature, the air carries 60-80 times less heat than the flushing fluid. This significantly reduces the risk of environmental complications associated with the thawing of frozen rocks. Air is much more efficient than a salt solution, which, although it does not freeze in the well, can easily disrupt the natural aggregate state of ice in frozen rocks by dissolving it [11-13, 17]. The idea of the present work concerns the development of theoretical fundamentals to calculate and model processes that ensure the specified temperature condition during the development of mining and exploration workings in the cryolite zone. The authors consider ways to reduce environmental risks during the exploration drilling using air purge and normalize the temperature factor by using a vortex refrigerator, whose operation principle is based on the Ranqueeffect.

II. PROPOSED METHODOLOGY

A. The Possibility of Using Vortex Tube to Provide Temperature Condition in Air-Purged Drilling

To eliminate the negative environmental effects of the temperature factor when drilling wells using air purging, various cooling devices are used which are quite expensive and energy-intensive. In order to create a more advanced and at the same time environmentally and cost-effective equipment, the authors propose to use a vortex tube as a cooling and heating device, operating based on the Ranque effect.

Improved vortex tube designs have also been developed, such as nonrefrigerated vortex tubes (Fig.1), which allow obtaining low and high-temperature air flows at the same time.

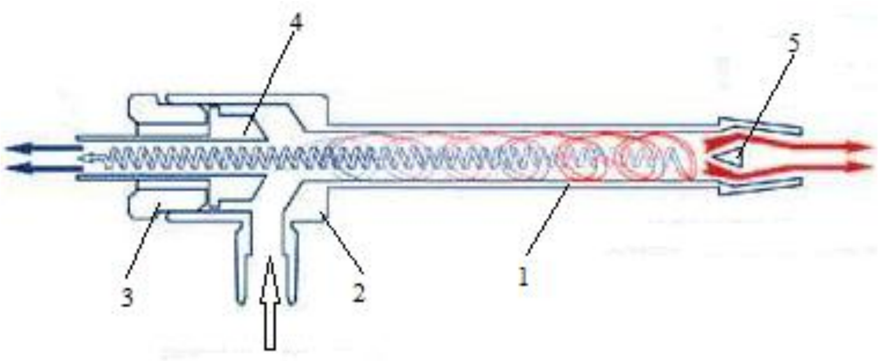

Fig. 1: Vortex tube:
1 – tube, 2 – casing, 3 – nut, 4 – cold fraction generator at the cold outlet,5 – throttle at the hot outlet.

At the air outflow through the nozzle, an intense circular flow is formed, whose near-axial layers are significantly cooled and are discharged through the diaphragm opening in the form of cold flow, while peripheral layers are heated and outflow through a throttle in the form of hot flow [18]. The throttle is designed to adjust the flow rate of cold and hot air flows. This design allows extending the temperature range of the air and getting, when operating in optimal mode, a cold flow with a temperature of -40°C. A replaceable brass generator of cold is located inside the tube. It can change the temperature and flow rate of the air in the vortex tube. There are two main types of such cold generators: C-type cold generator to obtain the lowest possible temperature, and H-type cold generator to obtain the maximum cooling power.

To carry out geological exploration, it is necessary to calculate the vortex tube taking into account the temperature of rocks in the cryolite zone [17, 19, 20]. The temperature at the outlet of the vortex tube is affected by pressure and air flow rate, so there is a need for experimental studies to determine the dependence of temperature changes in different operating modes.

Consider the approximate calculation of the vortex tube for exploration drilling with air purging for the well with a diameter of 76 mm. The determination of the main dimensions of the vortex tube is carried out in the following order [20].

The following initial data are required for calculation: air flow G_c=0,1 kg/s (required air flow rate for core drilling with purging at well diameters of 76 mm), cold air flow temperature T_c = -30°C, heat removal from cold source Q=10 kW, the weight fraction of cold flow μ = 0.3, inlet pressure p_1 =5 kgf/cm^2, isobaric heat capacity c_p = 1 kJ/(kg°·C), permissible heating of cold flow Δt=10°C, air temperature entering the vortex tube T_1=40°C, and nozzle discharge coefficient α_c = 0.95 [21, 22].

The necessary cooling effect is calculated as:

$$\Delta tc = T_1 - Tc = 40 + 30 = 70^\circ C \qquad (1)$$

Total air flow rate:

$$G = \frac{Gc}{\mu} = \frac{Q}{\mu \cdot c_p \cdot \Delta t} = \frac{10}{0.3 \cdot 1 \cdot 70} = 0.48 \text{ kg/sec}; \qquad (2)$$

Nozzle flow area:

$$F_c = \frac{G \cdot \sqrt{T_1}}{0.4 \cdot \alpha_c \cdot p_1} = \frac{0.48 \cdot \sqrt{313}}{0.4 \cdot 0.95 \cdot 5} = 4.46cm^2 = 446mm^2 \qquad (3)$$

Nozzle dimensions:

$$h = \sqrt{\frac{F_c}{2}} = \sqrt{\frac{446}{2}} = 15mm \qquad (4)$$

$$b = \frac{F_c}{h} = \frac{446}{15} = 30mm; \qquad (5)$$

Tube diameter:

$$D = 3.5\sqrt{F_c} = 3.5\sqrt{446} = 74mm \qquad (6)$$

The length of the vortex zone:

$$L = 9 \cdot D = 9 \cdot 74 \approx 700mm. \qquad (7)$$

The calculation allows determining the technical parameters of the vortex tube for a given air flow rate and temperature.

High temperatures at the bore-hole bottom, emerging during the operation of the equipment have negative impact on the rock-breaking tool and cause various irreversible environmental consequences. Such complications can be eliminated only by applying forced air flow cooled to a temperature sufficient to neutralize the heat released at the bore-hole bottom. Thus, it is necessary to develop technical means and effective temperature control technology of the well.

The temperature condition of the well is understood as the temperature distribution of the circulating flushing fluid in the inner channel of the drill stem and in the annular channel, which depends on a large number of factors dissimilar in terms of their impact. One of the simplest solutions in relation to drilling wells with air purging is described in detail in the works [10-13, 19] as well as in earlier works.

In certain conditions, drilling of wells with air and other gaseous agents purging is the most progressive and highly efficient drilling method. In air-purged drilling, air temperature exceeds the temperature of the rocks in the bottom-hole zone which is continuously moving during drilling. Elimination of a sharp increase in air temperature in the bore-hole zone can be achieved based on the use of cooled compressed air.

Purge air can be cooled using a vortex tube, but first, it is necessary to know operating parameters of the tube, i.e. the dependence of the temperature change at the cold outlet of the tube on the air pressure and flow rate. Therefore, it is necessary to assess in detail the cooling effect and its impact on environmental safety in the air-purged drilling process. This necessitates conducting experimental studies to determine the temperature of the cold fraction at different air flow rates and pressures.

B. Experimental Research Technique of Vortex Tube

In order to determine the main regularities in parameter variations in different modes and obtain data for vortex tube modeling, experimental studies of the vortex tube were carried out at the research test site of the Russian State Geological Prospecting University (MGRI-RSGPU).

The main objectives of the experimental studies included:

- determining air flow rate at the cold and hot outlets;
- determining the thermal power of the vortex tube at the cold and hot outlets;
- determining the dependence of the cold flow temperature on the air pressure and flow rate;
- determining the dependence of the cold flow temperature on the type of cold generator;
- determining the dependence of cooling power on air pressure;
- developing and justifying the analytical model of the vortex tube;

The following devices and equipment were used when conducting experimental studies:

- PKSD-5.25 DM(R) piston compressor;
- 50008n vortex tube;
- replaceable cold generators of 2C and 8H types;
- pressure reducing valve with a pressure gauge (pressure regulator);
- IRT-4 multichannel temperature meter;
- Flir thermal imager for imaging the temperature field;
- AR816 brand anemometer smart sensor;
- expansion tubes with a diameter d=50mm.

The Nex Flow™ 50008h vortex tube is made of stainless steel and includes a brass generator of cold and valve with an O-ring seal.

Experimental works with the vortex tube were carried out using the 2C and 8H type generators for the cold fraction. The vortex tube experiment was conducted as follows.

The vortex tube was connected to the compressor receiver using connecting hoses. The pressure reducing valve with pressure gauge intended for setting and maintaining a predetermined pressure was installed on the hoses between the vortex tube and the compressor receiver.

The cold generator was installed on the vortex tube, and an extension tube with a diameter of 50 mm was attached to the cold and hot outlets to measure the air velocity. By means of throttle 5, minimum flow rate of cold air was set in the vortex tube, then the compressor was turned on and pressure of 0.8 MPa was set using the pressure regulator. After achieving temperature stabilization, the temperatures at the cold tc, and hot th outlets of the vortex tube, as well as the ambient temperature were measured by means of IRT-4 multichannel temperature meter. The air velocity at the cold and hot outlets of the vortex tube was measured by an anemometer (Fig. 2).

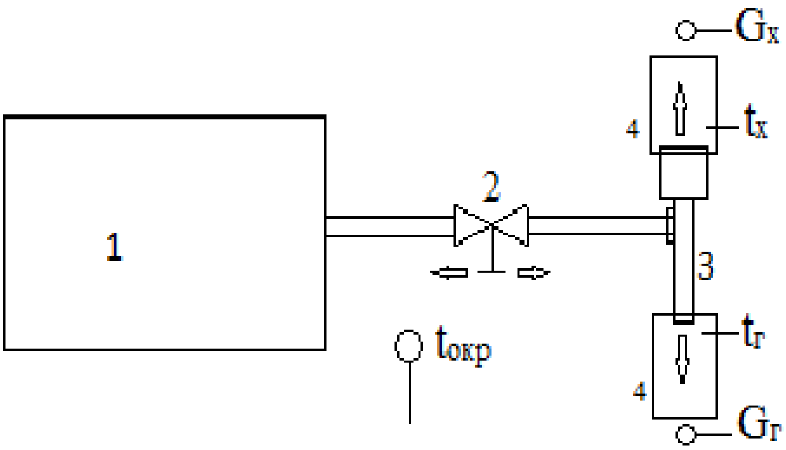

Fig. 2: Schematic diagram of experimental installation with vortex tube.

1 – compressor, 2 – pressure regulator, 3 – vortex tube, 4 – expansion tubes. t_x– temperature at the cold outlet of the vortex tube, °C; t_h– temperature at the hot outlet of the vortex tube, °C; G_c– measurement point of air velocity at cold outlet, m/s; G_h – measurement point of air velocity at hot outlet, m/s; t_{amb} – ambient temperature, °C.

In the images (Fig. 3) obtained by means of the thermal imager at an air pressure of 0.7÷0.8 MPa, it is visible that temperature has decreased to -40°C. Images were obtained at a temperature of the air arriving from a receiver of the compressor, equal to 50÷60°C.

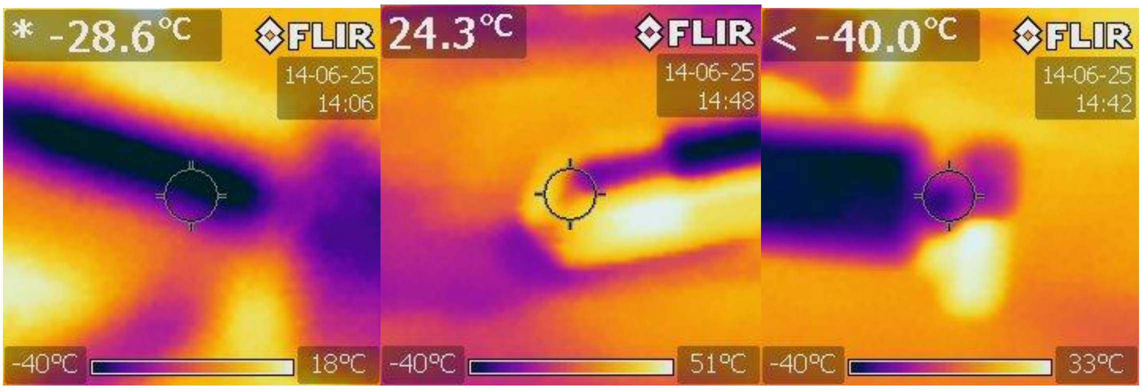

Fig. 3: Images of the temperature field at the cold outlet of the vortex tube,obtained by means of a thermal imager.

Measurements were repeated every 10 minutes three times for each set pressure. Further, the next pressure was set by means of regulator 2, and the measurements were repeated. Measurements were carried out within the pressure range from 0.7 to 0.2 MPa with a pressure step equal to 0.1 MPa.

After performing measurements on a vortex tube with the 2C-type cold generator and a minimum flow rate of cold air, without replacing the cold generator, the vortex tube was adjusted by means of throttle to an average flow rate of cold air. After that, the whole set of measurements was repeated with a new adjustment of the vortex tube at the average air flow within the pressure range from 0.8 to 0.2 MPa with the same pressure step equal to 0.1 MPa.

The vortex tube equipped with the 8H-type cold generator was tested exactly in the same way [19, 20, 23].

III. RESULTS ANALYSIS

A. Results on Experimental Studies of The Vortex Tube

According to the results of experimental studies of the vortex tube, the dependence of the temperature of the cold flow on the pressure of compressed air was established.

When testing a vortex tube with the 2C-type cold generator (Fig. 4), the cold flow temperature at an initial pressure of 0.2 MPa was -18°C, while at a maximum pressure of 0.8 MPa it amounted to -43°C. When repeating the experiment with the 8H-type cold generator, the cold flow temperature at an initial pressure of 0.2 MPa was -16°C, while at a maximum pressure of 0.8 MPa it was -30°C.

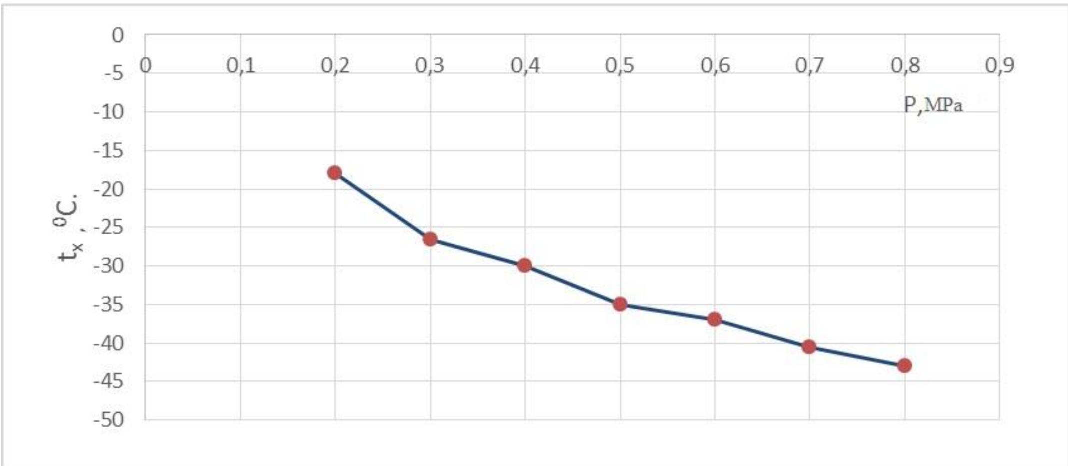

Fig. 4: The dependence of the temperature change (t) of the cold flowon the pressure (P), using the 2C-type cold generator.

Thus, C-type cold generators are designed to obtain the lowest possible temperature, while H-type cold generators are designed to obtain the maximum degree of cooling. When using a vortex tube with the 2C-type cold generator, the air consumption was less than that when using the 8H-type cold generator.

For a more detailed explanation, consider the dependence of temperature (t_c) on air flow rate (G_c) (Fig. 5). The temperature of the cold flow for a vortex tube with the 2C-type cold generator, at an initial air flow rate of 0.003 kg/s, was -26.7°C, while at a flow rate of 0.0052 kg/s, it was -43.5°C. Thus, the temperature of the cold flow (t_c) decreased by 3.5-4.5°C for each increase in the air flow rate by 0.0003-0.0005 kg/s.

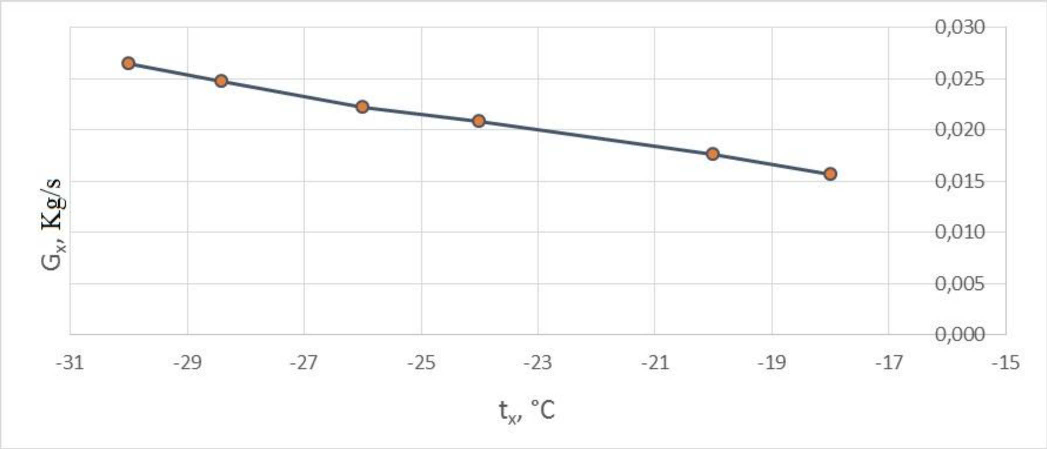

Fig. 5: The dependence of the cold flow temperature (t_x) on the air flow rate (G_x), when using the 8H-type cold generator.

With the 8H-type cold generator, at the initial air flow rate of 0.016 kg/s, the temperature of cold flow was -18°C, while at a maximum flow rate of 0.026 kg/s, it amounted to -30°C. In this case, cold flow temperature changed by 2-4°C at each increase of air flow rate by 0.002-0.003 kg/s.

The dependence of the cold air flow temperature (t_c) on the type of cold generator is shown in Fig. 6.

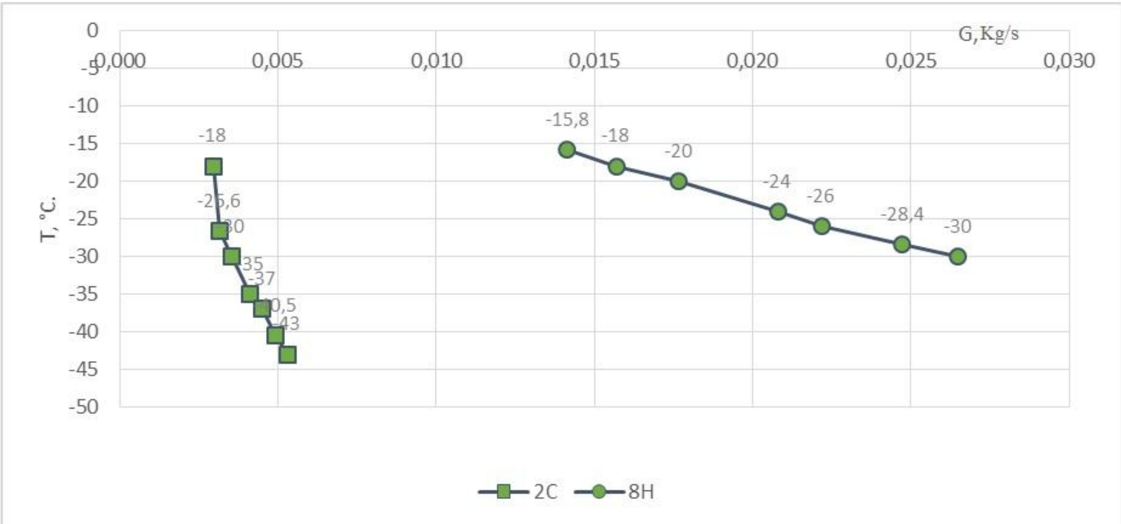

Fig. 6: Temperature (t_c) dependence on the type of cold fraction generatorfor generators of 2C and 8H types.

Figure 6 shows the dependence of the cold air flow temperature on the type of cold fraction generator for two types of generators, namely, 2C and 8H at an average air flow rate. The cold air flow temperature when using the cold generator 2C at the initial pressure of the air supplied to the vortex tube equal to 0.2 MPa, was -18°C; at that, the air flow rate was 0.0029 kg/s. At a maximum air pressure of 0.8 MPa, the cold flow temperature was -43.5°C at the air flow rate equal to 0.0053 kg/s.

When using the 8H-type cold generator with the same air flow rate, the temperature of cold flow at an initial air pressure of 0.2 MPa was -16°C; at that, air flow rate equaled to 0.014 kg/s. At an air pressure of 0.8 MPa, the air temperature was -30°C, and the air flow rate was 0.026 kg/s.

Analysis of the temperature variations of cold air flow in the vortex tube depending on the type of cold fraction generator shows that the temperature of the cold flow depends on the type of cold fraction generator. The air flow rate of the 2C-type cold generator is five times less than that of the 8H-type cold generator, while the average temperature of the cold air flow is lower by 10-15°C. However, the use of the 8H-type cold generator allows obtaining high cooling capacity due to the higher air flow.

The dependence of the cooling power (Q_c) of the cold flow of the vortex tube on the air pressure (P) is shown in Fig.7.

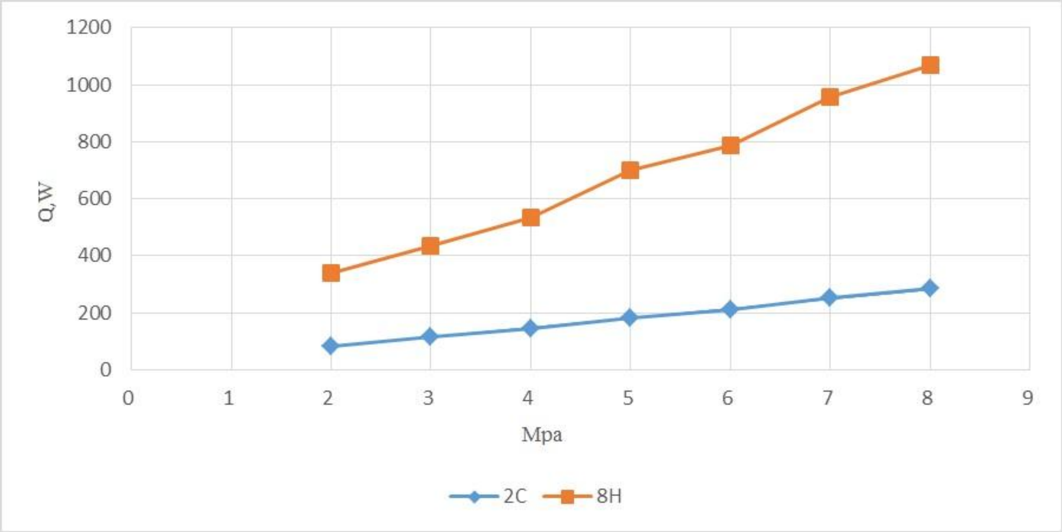

Fig. 7: The dependence of the cooling power (Q_c) on the pressure (P), when using types 2C and 8H cold generators

The cold flow temperature of the vortex tube, when using the 8H-type cold generator is less than that when using the 2C-type cold generator, but the cooling capacity of the vortex tube with the 8H cold generator is higher (Q) due to the higher air flow rate.

In consequence of the study of the vortex tube, the dependences of the cooling power (Q) of the cold flow when using cold generators of 2C and 8H types were obtained at the average and minimum air flow rates [19, 20].

Cooling capacity when using the 2C-type cold generator (Fig. 7) at an average air flow rate and initial pressure of 0.2 MPa was 82.9 W, while at 0.8 MPa it was 284.6 W. Increase in the air pressure by 0.1 MPa resulted in increase of the cooling power by 27-42 W. When using the 8H-type cold generator at an initial pressure of 0.2 MPa, the cooling capacity was 373.2 W, while at a maximum pressure of 0.8 MPa it amounted to 1046 W. In this case, when increasing the air pressure by 0.1 MPa, the cooling power increased by 90-177 W.

Thus, at an average air flow rate, the cooling capacity of the vortex tube with the 8H-type cold generator is 3.5-4.5 times higher relative to that obtained when using the 2C-type cold generator.

B. Modeling the Temperature Condition of The Well

The vortex tube can be built into the tool string above the core barrel (Fig. 8).

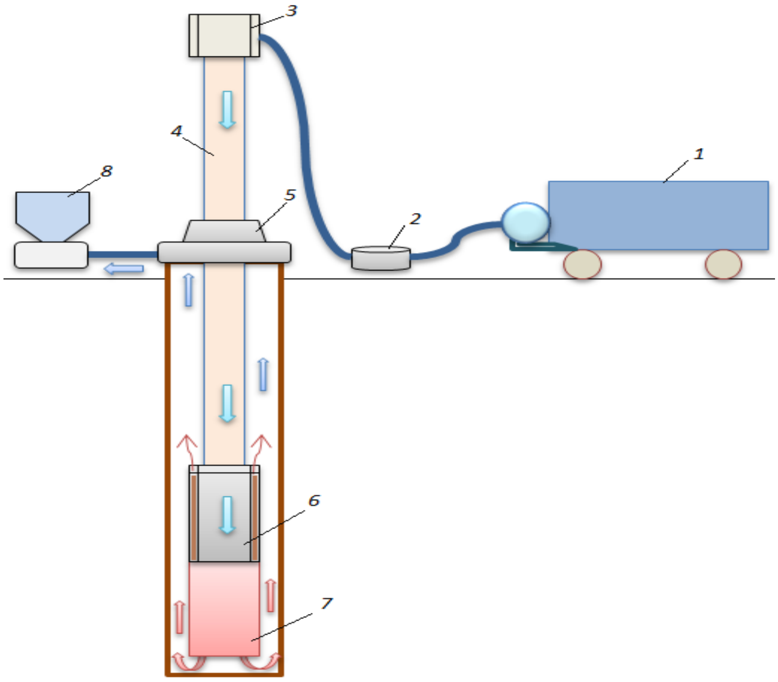

Fig. 8: Schematic diagram of air flow at the location of the vortex tube above the core barrel.

1 – compressor, 2 – dehumidifier, 3 – swivel, 4 – drill stem, 5 – sealer, 6 – vortex tube,7 – column tube, 8 – sludge collector.

The compressed air is fed from the compressor into the vortex tube through the drill pipes, where it is separated into cold and hot flows.

The cold flow is directed into the core barrel, gets to the bore-hole bottom and then is directed upwards through the narrow annular gap between the walls of the well and the core barrel, transporting sludge from the bore-hole bottom. Hot air is released directly into the wide gap between the walls of the well and the drill pipes, where it mixes with the cold flow.

Calculation parameters are as follows: a well with a diameter of 76 mm and air flow rates of 400 and 600 kg/h; length of the core barrel L=5 m; sandstone type rock with the following properties: δ=2600 kg/m^3; c_r=1.05*10^3; λ_r=1.86 W/(m°C); rock temperature T_r = 10°C; and power at the bore-hole bottom 2.5 kW [10-13, 22].

The simulation results using the Mathcad program are shown in Fig. 9.

At the initial temperature t_{i1}=-20°C and air flow G=400 kg/h at the final depth, the temperature in the core barrel is 1°C, while in the annular channel it is 11°C.

While increasing the purge air flow rate to 600 kg/h (Fig. 9), the final temperature in the core barrel decreases to -8°C, while in the annular channel it becomes -1°C. Here the temperature also depends on the air flow rate.

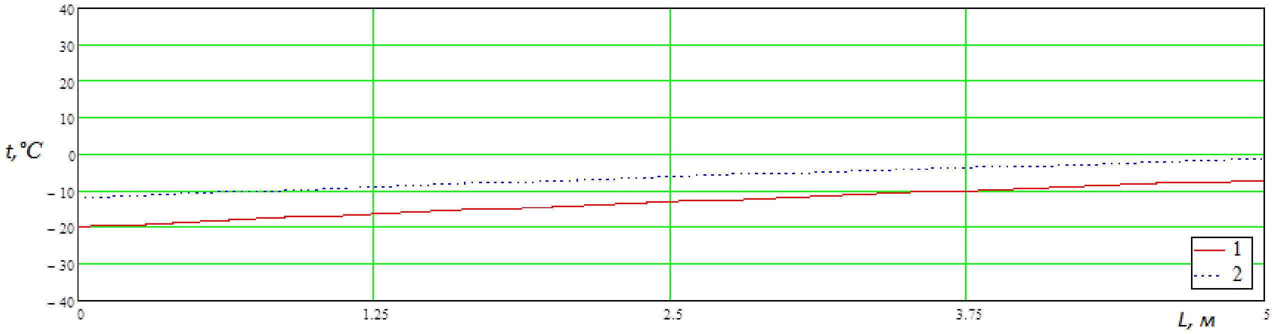

Fig.9: Temperature distribution when installing a vortex tube into the tool string above the core barrel: 1 – in the core barrel; 2 – in the annular channel.

Based on the results of the calculation of borehole thermal condition, it can be concluded that the use of cooled purge air greatly reduces the temperature in the well that creates favorable temperature conditions for rock cutting tool, preventing the negative impact of high temperatures on the ecological balance of cryolite zone.

The best cooling at the bore-hole bottom can be achieved by installing a vortex tube into the tool string above the core barrel. But in this case, there is a need to develop a reliable design of the bottomhole tool string, ensuring failure-free operation.

IV. CONCLUSION

Analyzing the results of experimental studies of the vortex tube, the following conclusions can be drawn.

1. The temperature and cooling capacity of the cold flow (tc) of the vortex tube depend on the pressure (P) and air flow rate (G). By changing air pressure or flow rate, one can adjust the temperature of the cold flow.

2. The temperature and cooling capacity of the cold flow (tc) of the vortex tube depend also on the type of the cold generator. During the experiment, two main types of cold generators were used: to obtain the lowest possible temperature (C-type cold generator) and to obtain the maximum cooling degree (H-type cold generator).

3. The optimal model of the vortex tube in terms of obtaining the maximum cooling degree is a vortex tube with an H-type cold generator when adjusting the throttle ensuring average air flow rate.

4. The results of experimental studies of the vortex tube allowed developing a mathematical model, whose study made it possible to obtain the temperature distribution and identify the parameters that preserved the temperature condition of perennial rocks and environmental safety of the cryolite zone.

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