—研究ノート—
Scientific Note

Ice Core Hot-Fluid Drilling

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熱水氷コア掘削

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要旨：熱水氷コア掘削により，迅速な穿孔が可能である．本論文は，熱水フラックス，熱水温度，液体の物理的特性，ドリルヘッドの寸法や氷の諸性質に依存するドリルの掘進速度の計算方法を述べる．また，熱水氷コア掘削機の実験用モデル機に関する形状とその説明，および得られた実験データについても記述する．計算および実験による掘進速度についても比較し論じる．

Abstract: Fast hole production is possible using ice core hot-fluid drilling. The present paper describes a method for calculation of drill penetration rate dependent on the fluid flux, fluid temperature, physical properties of fluid, size of hot-fluid drill head and properties of ice. The design and description of an experimental model of an ice core hot-fluid drill and the experimental data obtained are given. Calculated and measured rates of the drill penetration are compared.

1. Introduction

Melting of ice needs much more energy than mechanical destruction of the same volume of ice in core drilling operations. However, simplicity of design and reliability of thermal drilling devices are important advantages that have made this method widely used in drilling operations conducted by Russian specialists. Three deep bore-holes were drilled up to depths of more than 2000 m at Vostok Station (East Antarctica) by thermal drills (KUDRYASHOV *et al.*, 1991).

In our new device we place the high power thermal energy source in a thermally isolated long boiler situated above a core barrel (MENSHIKOV *et al.*, 1988). If the bore-hole is filled with a liquid (aircraft fuel TS-1 for example), part of this fluid can be heated in the boiler mentioned above and used as a source of heat to melt the hole down. It is possible to use a system of thermally isolated pipes to bring this fluid to a specially shaped ring drill head, which would form the hole leaving an ice core in the middle. The ring drill head is made like a turned over thin wall ring metal "glass" (Fig. 1). The hot fluid is supplied to the bottom under action of decompression created by a pump located in the water collection tank. Hydrodynamical action of the jet promotes efficient melting of ice. A mixture of melted water and postworking

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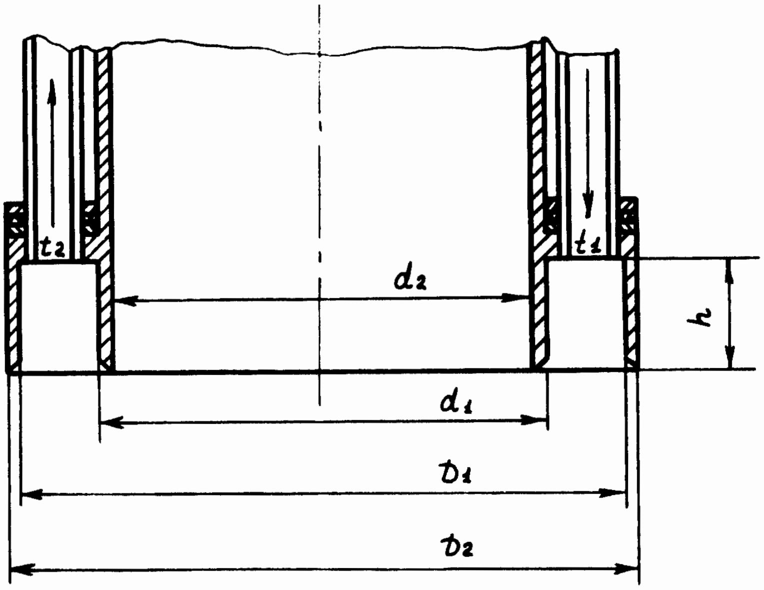

Fig. 1. Scheme of hot-fluid drill head.

fluid is lifted to the water collection tank where working fluid and water are separated due to the difference of densities. After filtration the pure fluid returns to the boiler. Simultaneously, hole liquid is cleaned from sludge ice.

Decompression under the ring drill head presses the head side of the ring metal "glass" against the ice and prevents leaking of hot fluid out of the ring space. This is necessary for forming smooth hole walls and core surface. In addition, the hydrocarbon hole liquid has high boiling point, particularly at the high pressure encountered at large depth, which promotes ice melting.

In this paper we attempt to analyze the heat-mass-exchange processes that occur in ice core hot-fluid drilling.

2. Basic Equations

We make the following assumptions:

- Thermal drilling has reached a steady state,
- The steady state temperature field in front of the drilling head face is one-dimensional,
- Heat properties of the mixture of hot fluid with water inside the drill head are additive and can be determined by the average temperature;
- The mixture temperature inside the drill head is the arithmetic mean temperature between the primary and final temperatures;
- The upper butt end of the drill head is isolated.

Here a mathematical model of hot fluid drilling is suggested as the basis of the heat balance equation (KUDRYASHOV and MENSHIKOV, 1993):

$$Q = Q_1 + Q_2 + Q_3 + Q_4, \qquad (1)$$

where Q is the total heat in unit time required for thermal drilling, J/s;

Q_1 is the heat in unit time for overheating melt water, J/s;
Q_2 is the heat in unit time for ice melting, J/s;
Q_3 is the heat in unit time for warming ice from its temperature *in situ* to the melting point, J/s;
Q_4 is the heat in unit time directed at hole wall and core, J/s.

These heats may be determined as:

$$Q_1 = \frac{\pi}{4} (D_2^2 - d_2^2) \ c_w p_i \ (t_2 - T_i^{mp}) \ v; \tag{2}$$

$$Q_2 = \frac{\pi}{4} (D_2^2 - d_2^2) \ \rho \ p_i v; \tag{3}$$

$$Q_3 = \frac{\pi}{4} (D_2^2 - d_2^2) \ c_i p_i \ (T_i^{mp} - T_i) \ v; \tag{4}$$

$$Q_4 = K \ (\frac{t_1 + t_2}{2} - T_i); \tag{5}$$

where d_1, d_2, D_1, D_2 are diameters of the drill head (see Fig. 1);
c_w, c_i are thermal heat capacities of water and ice, J/(kg • °C);
p_i is density of ice, kg/m;
t_1, t_2 are primary and final temperatures of hot fluid in the drill head, °C;
T_i, T_i^{mp} are ice temperature *in situ* and melting point of ice, °C;
ρ is the specific heat of ice melting, J/kg;
v is the drill rate, m/s;
K is the coefficient of heat transfer from the hot liquid to the ice in the hole below the drill head, W/(m² • °C).

The total heat in a unit time required for thermal drilling may be determined as

$$Q = G_T c_T \ (t_1 - t_2) + \frac{\pi}{4} (D_2^2 - d_2^2) \ c_w p_i \ (t_2 - T_i^{mp} \ ) \ v, \tag{6}$$

where G_T is the mass flow of hot fluid, kg/s;
c_T is the thermal capacity of hot fluid, J/(kg • °C).

After equating (1) with (6), taking into account formulas (2)-(5) and supposing that $T_i^{mp} = 0$°C, we obtain the equation for final temperature of hot fluid:

$$t_2 = \frac{2G_T c_T t_1 - K \ (t_1 - 2T_i) - \frac{\pi}{2} (D_2^2 - d_2^2) \ p_i \ (\rho - c_i T_i) \ v}{2G_T c_T + K}. \tag{7}$$

The heat in a unit time that passes from hot fluid to the ice face may be determined as

$$Q_5 = \frac{\pi}{4} (D_2^2 - d_2^2) \ \alpha^* \ (\frac{t_1 + t_2}{2} - T_i^{mp} \ ), \tag{8}$$

where α^* is the coefficient of heat irradiation of hot fluid to the ice face, W/(m² • °C).

It is known that

$$Q_5 = Q_2 + Q_3. \tag{9}$$

Using formulas (3), (4) and (8) we obtain the following equation for the final temperature of hot fluid:

$$t_2 = \frac{2p_i \ (\rho - c_i T_i) \ v}{\alpha^*} - t_1. \tag{10}$$

After equating (7) with (10) and transforming to coordinates relative to the drilling rate we obtained the following equation:

$$v = \frac{\alpha^*}{2p_i\ (\rho - C_i T_i)} \left[\frac{2G_T c_T t_1 - K\ (t_1 - 2T_i)}{2G_T c_T + K} + t_1 \right] - \frac{\alpha^* F v}{2G_T c_T + k}, \qquad (11)$$

where $F = \pi/4\ (D_2^2 - d_2^2)$ is the area of the ring bottom, m^2.

The coefficient of heat irradiation of hot fluid may be determined from a nondimensional approach to heat transfer. Then:

$$\alpha^* = Nu \frac{\lambda_f}{d}, \qquad (12)$$

where Nu is the Nusselt number;

λ_f is the coefficient of heat conductivity of a mixture of hot fluid and melt water, W/(m °C);

d: typical size, m.

For a heat transfer calculation in our case we use an experimental nondimensional formula for the heat transfer of liquid moving in a channel, which was suggested by M. A. MIKHEEV (MIKHEEV and MIKHEEVA, 1977):

$$\mathrm{Nu} = 0.03 Re^{0.8}\ Pr^{0.43}, \qquad (13)$$

where Re: Reynolds number,

Pr: Prandtl number.

The typical size of a channel in this case is equal (KUDRYASHOV and MENSHIKOV, 1993):

$$d = \frac{2(D_1 - d_1)h}{2h + D_1 - d_1}. \qquad (14)$$

To check this method for calculation of drilling rate, laboratory tests were carried out in the Antarctic Research Laboratory of St. Petersburg Mining Institute.

3. Laboratory Tests

Laboratory tests were carried out on a special stand (Fig. 2) that consists of an ice block 1, a turbocompressor 7, a drill head 2, a tank for liquid 10, forcing tubes 3, draining tubes 4, and a thermal measuring device 11.

Ice blocks were prepared in a freezer with temperature −7°C. Two models of drill head were tested. The first had a rectangular radial cross section, the second a round radial cross section. They were produced from brass. The drill head had these sizes: $d_1 = 80$ mm, $d_2 = 76$ mm, $D_1 = 110$ mm, $D_2 = 114$ mm, $h = 15$ mm. The barel has three forcing and three draining tubes of inner diameter 8 mm for each.

During experiments seven bore-holes were drilled with hot water circulation up to depth 0.2 m. In all tests an ice core was obtained. The test results are shown in Table 1.

The ice face looked like the inner form of the drill head. Hollows were formed

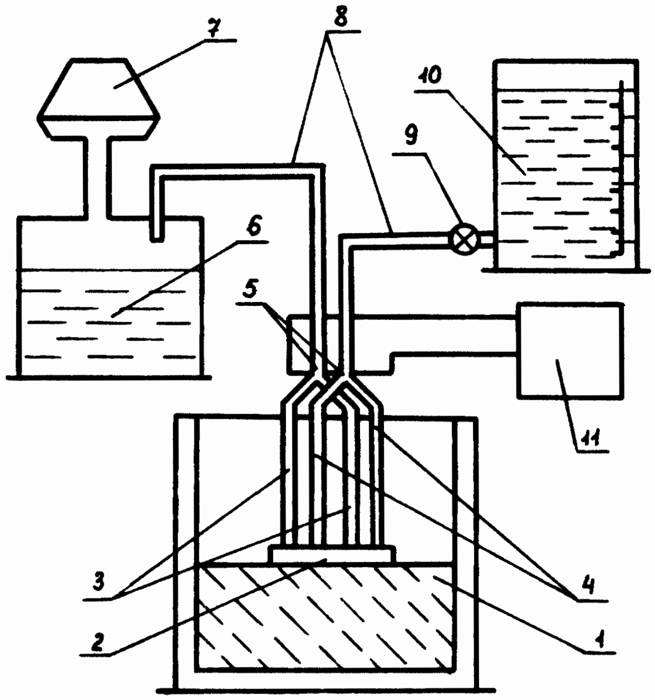

Fig. 2. Scheme of experimental hot-fluid stand.
1: ice block, 2: hot-fluid drill head, 3: forcing tubes, 4: draining tubes, 5: thermal detecting elements, 6: water-collection tank, 7: turbocompressor, 8: hoses, 9: valve, 10: hot fluid, 11: thermal measuring device.

Table 1. Tests results of ice core hot-fluid drilling.

Volume flow (*l*/h)	Primary temperature (°C)	Final temperature (°C)	Hole diameter (mm)	Core diameter (mm)	Drilling rate (m/h)
25.0	95	22	124	61	0.95
152.5	97	46	118-120	68	2.55
77.7	95	44	120	62	1.64
82.8	95	45	119	65	2.00
94.1	95	46	121	65	1.83
30.4	97	28	122	63	1.13
53.4	97	33	121	64	1.57

opposite forcing tubes; larger volume flow of hot water formed deeper hollows. As the turbocompressor did not clean the ice face out carefully, on the walls of boreholes and ice cores cavities were formed with depth about 11-15 mm. Difference of drill head cross section did not influence the drilling rate.

The experimental and theoretical data of drilling rate depend on volume flow of hot fluid as shown in Fig. 3. We see satisfactory agreement between our theory and the experiment.

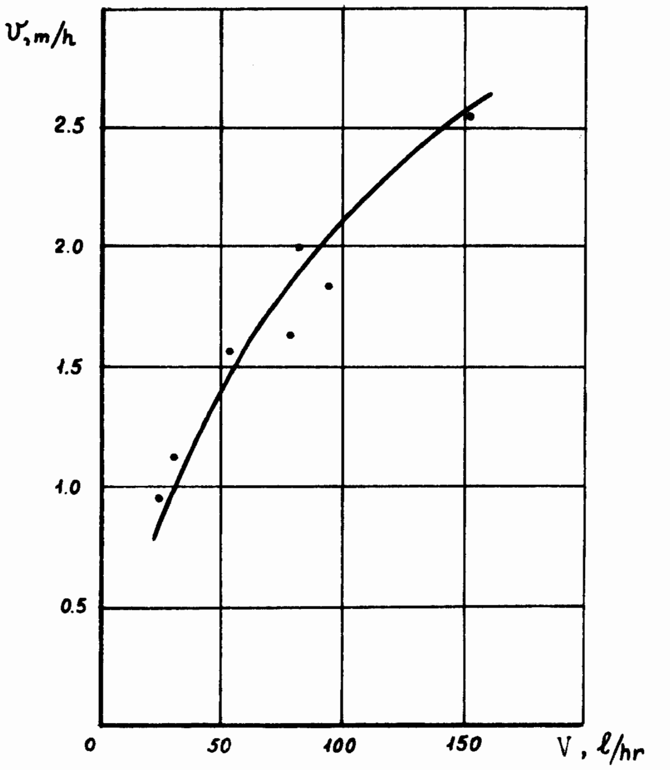

Fig. 3. Drilling rate v versus volume flow of hot fluid V (experimental points and theoretical curve).

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