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Forecast of Thermal Behaviour Dynamics at Interface of Borehole 5 and Subglacial Lake Vostok (Antarctica)

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Abstract

This research covers deep-hole ice drilling techniques and bore-hole surveying as well as environmentally clean technology of subglacial Lake Vostok penetration in Antarctica.

Borehole 5G at the Vostok Russian Antarctic Research Station was made using a drilling technology developed at the St. Petersburg Mining University that helped to penetrate Subglacial Lake Vostok while securing environmental safety of this relict lake.

The objective of further research activities is to develop a technology to maintain the borehole-lake interface zone in the working condition during the lake survey execution.

The paper reviews results of freezing time calculations for the lake water with 'positive' temperature entering the borehole upon penetration into the subglacial lake. These results were obtained using independent calculation methods.

Issues concerned with the borehole thermal behaviour at the borehole-lake interface are also examined.

Keywords: Antarctica, deep-hole drilling, ice, ice core, borehole, lake water, heat exchange, Subglacial Lake Vostok

INTRODUCTION

Penetration into Subglacial Lake Vostok in Antarctica that took place in February 2012 has aroused keen interest in the world's academic community [3, 5]. This penetration was preceded by research activities to develop an ice drilling technique for conditions close to the phase-transition point [4, 6, 7].

The final stage of activities carried out in Borehole 5G upon its penetration into Subglacial Lake Vostok is freezing of the lake water that entered the borehole to a particular depth, which is part of the assumed drilling technology, with subsequent drilling in order to recover an ice core sample of the lake water [8].

FORECASTING THE DYNAMICS OF FREEZING OF LAKE WATER IN THE WELL

For successful implementation of the developed technology to penetrate into Subglacial Lake Vostok it is required to forecast the dynamics of lake water freezing in the borehole. Considering the difficulties concerned with experimental studies of the formulated problem, it seems reasonable to carry out a theoretical investigation of the water freezing process in the borehole-lake interface zone.

Let us forecast the lake water freezing dynamics in the borehole. Let the frost line (see Figure 1) be expressed as a circumference with radius R_f for the instant of time τ_f, counting the time from the frost penetration onset. Then, due to $d\tau_f$ the frost line will advance by the value equal to dR_f. It is obvious that the internal part of the borehole radial section will be divided into two zones, i.e. *Zone 2* where the liquid is not frozen and *Zone 1* where it has already frozen up.

The position of the melt water frost line in the borehole is determined by the distance from this R_f line to the axis of the thermal drilling assembly. The correlation between this position and the time elapsed from freezing onset τ_f is roughly described by the expression introduced by L.S. Leibenzon [1]:

$$\frac{R_f^2}{2}\ln\left(\frac{R}{R_f}\right)-\frac{R^2-R_f^2}{4}=\frac{\lambda_w\left(t_{ice}-t_{melt}\right)}{\Psi\rho_{ice}}\tau_f , \qquad (1)$$

where: λ_w is water thermal conductivity factor, 0.597 W/m·°C; Ψ is latent heat of ice melting, $3.35\cdot10^5$ J/kg; ρ_{ice} is ice density, 923 kg/m^3; t_{ice} is ice temperature, -2.8 °C; t_{melt} is ice melting temperature, -2.5°C; R is the borehole radius, 0.0685 m.

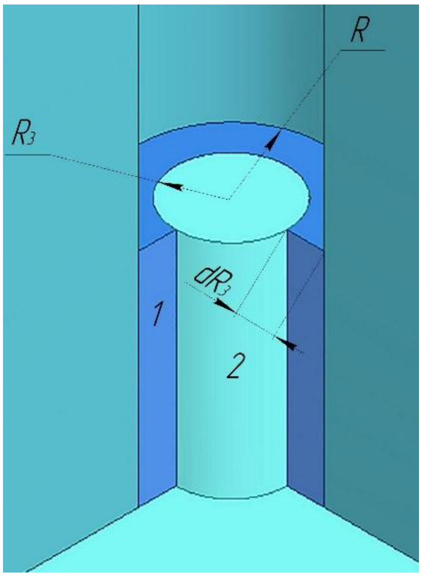

Figure 1. Radial section of melt water frost line in the borehole

Let us determine the time needed for complete freezing of the liquid. For this purpose, we introduce the following equation (1): $R_f=0$, which gives us

$$\tau_f = \frac{\Psi \rho_{ice} R^2}{4\lambda_w (t_{melt} - t_{ice})} \qquad (2)$$

Results of the liquid freezing time calculations at various frost line positions in the borehole radial section are given in Table I and are illustrated by Figure 2.

TABLE I
Calculation Results of Melt Water Freezing Time in the Borehole

R_f, m	τ_f, hours	τ_f, days
0.0685	0	0
0.065	2.66	0.11
0.050	73.84	3.07
0.035	218	9.09
0.020	396.4	16.52
0.010	504.2	21
0	562.6	23.44

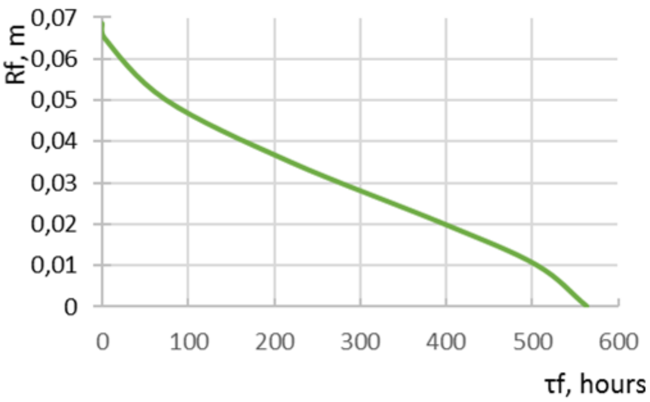

Figure 2. Calculated dependence of melt water freezing time versus frost line positions in the borehole

In order to assess the freezing time for water that entered the borehole as a function of the distance to the lake surface, let us introduce value t_{ice} as a function of this distance to Equation (2). Then Equation (2) will look in the following way:

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$$\tau_f = \frac{\Psi \rho_{ice} R^2}{4\lambda_w \left(t_{melt} - t_{ice}(h^*)\right)} \qquad (3)$$

where: $t_{ice}(h^*)$ is relationship of ice temperature t_{ice} throughout the borehole-lake interface zone (~ *30 m*) versus distance h^* to the lake surface which is calculated using the following evident expression:

$$t_{ice}(h^*) = -2.8 - \eta h^* = -2.8 - 0.0208h^*$$

where: $\eta = 0.0208$ ˚*C/m* is the temperature gradient; *–2.8* is ice temperature near the borehole bottom, ˚*C*.

Calculation results are provided in Table II and their graphical representation is given in Figure 3.

As a comparison, let us take the methodology of time assessment for water freezing inside the borehole as the result of long-term convection. Current calculation methodologies of heat exchange due to natural convection use empirical dependences of the Nusselt number (*Nu*) mainly on the product of the Grashof and Prandtl numbers.

TABLE II
Calculation Results of Water Freezing Time Versus Distances Between Interface Zone of Borehole 5G and Lake Surface

h^*, m	τ_f, hours	τ_f, days
0	562.6	23.5
5	417.8	17.5
10	332.2	13.9
15	275.8	11.5
20	235.7	9.8
25	205.8	8.6
30	182.4	7.5

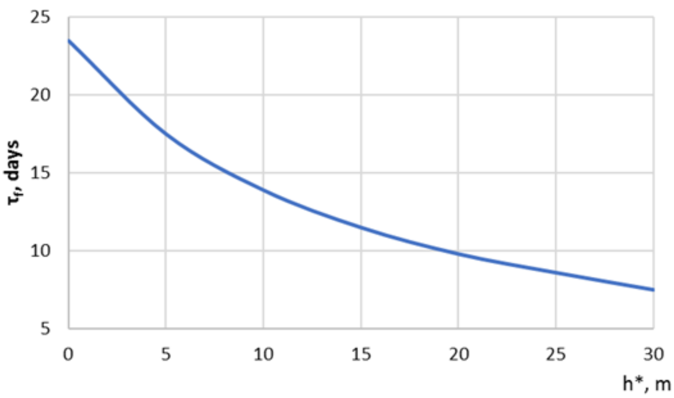

Figure 3. Relationship of lake water freezing time inside borehole versus distance to subglacial lake surface

Comparison of methods for estimating the freezing time of water in a well

Lake water entering the borehole and mixing up with the melt water, which was formed during thermal drilling, will have a slightly positive temperature. Thermal motion of the liquid medium along the ice wall of the borehole is a classical example of free convection that is characterized with a laminar flow during the initial stage of heat transfer and with a turbulent flow afterwards. When this happens, the heat-transfer coefficient α initially goes down, then increases and remains constant. The temperature differential Δ between the ice wall and the lake water will be varying both along the height of the borehole and in time. Let us consider the temperature differential as a parameter and calculate the dependence of time required for water freezing on this parameter.

As in the course of water freezing over the borehole walls the value of temperature differential will be decreasing and the heat-transfer coefficient α will finally equal to zero, let us ake the half-value of α to approximately account for these circumstances in our calculations. The following balance equation will be true for such conditions of lake water freezing in the borehole:

$$Q = \frac{\alpha}{2}\pi DHt\tau, \qquad (4)$$

From which we obtain the equation below to define the duration (time) of the freezing process τ:

$$\tau = \frac{2Q}{\alpha\pi DHt}, \qquad (5)$$

Calculation results of the borehole freezing time versus the temperature difference between the lake water and the surrounding ice mass are given in Table III and are graphically illustrated in Figure 4, where the values in brackets indicate the distance to the lake surface corresponding to the given temperature differential Δ, *°C*.

TABLE III

Calculation Results of Lake Water Freezing Time in the Borehole

Δ, °C	***Nu***	***α, W/m·ºC***	***τ, hours***	***τ, days***
3	135.15	17.64	14.69	0.61
2.5	129.13	15.86	19.61	0.82
2.0	122.12	13.93	27.90	1.16
1.5	113.65	11.76	44.07	1.84
1.0	102.69	9.29	83.69	3.49
0.5	86.35	6.20	250.79	10.45
0.25	72.61	4.14	756.16	31.30

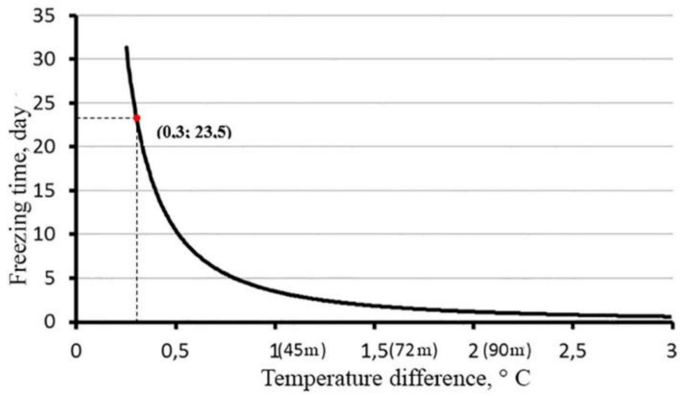

Figure 4. Dependence diagram of lake water freezing time versus ice mass temperature.

CONCLUSIONS

Despite all the conditionality of the used calculation techniques, the results seem realistic especially for low values of the temperature differential. The data obtained using two independent methods are characterized with a close quantitative match at the temperature differential of Δ=*0.3 °C*, which proves reliability of the developed calculation methodology.

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