3. Shepeta E. D., Samatova L. A., Voronova O. V. Promising trends in development of technologies for tungsten-containing ore and waste processing. *Gornyi Zhurnal*. 2018. No. 10. pp. 67–71. DOI: 10.17580/gzh.2018.10.13
4. Shepeta E. D., Samatova L. A., Alushkin I. V., Yushina T. I. Prospect of preliminary beneficiation use in the poor tungsten ores processing practice. *Non-Ferrous Metals*. 2016. Vol. 1. pp. 9–15. DOI: 10.17580/nfm.2016.01.02
5. TOMRA's mineral and ore sorting equipment for more profit. Available at: https://www.tomra.com/ru-ru/sorting/mining/ (accessed: 15.03.2020).
6. Available at: http://www.redwave.com/en/mining/ (accessed: 25.01.2019).
7. Efficiently optimise ore sorting. Available at: https://steinert-global.com/mining/ore-sorting/ (accessed: 25.01.2019).
8. Nadolski S., Samuels M., Klein B., Hart C. Evaluation of bulk and particle sensor-based sorting systems for the New Afton block caving operation. *Minerals Engineering*. 2018. Vol. 121. pp. 169–179.
9. Lessard J., Sweetser W., Bartram K. et al. Bridging the gap: Understanding the economic impact of ore sorting on a mineral processing circuit. *Minerals Engineering*. 2016. Vol. 91. pp. 92–99.
10. State-of-the-Art-Technology in Ore Mining. AT Mineral Processing. Available at: https://www.at-minerals.com/en/artikel/at_State-of-the-Art-Technology_in_Ore_Mining_1852781.html/ (accessed: 20.03.2020).
11. Separating impurities from quartz. AT Mineral Processing. Available at: https://www.at-minerals.com/en/artikel/at_Separating_impurities_from_quartz_1852565.html/ (accessed: 20.03.2020).
12. Konovalov G. N., Naumov M. E. Lump separation method. RF Patent No. RU2569528C1. MPK B03B 13/06(2006.01), B07C 5/34(2006.01). Applied:13.10.2014; published: 27.11.2015. *Byull. Izobret*. No. 33.
13. Wotruba H., Robben C. Sensor-based ore sorting in 2020. *Automatisierungstechnik*. 2020. Vol. 68(4). pp.231–238.
14. Kantsel V. A., Kantsel M. A., Mazurkevich P. A., Bogushevsky E. M. Loading-and-forming device for lump rock mass feed. RF Patent No. 2204517. MPK B65G47/19, B65G37/00. Applied: 13.07.2001; published : 20.05.2003.
15. Kantsel A. V., Danilov A. V., Tsuppinger A. A. et al. Ore separation modulus. RF Patent RU 2422210. MPK B03B 13/06, B07C 5/34. Applied: 19.03.2010; published: 27.06.2011.
16. Kantsel A. V., Mazurkevich P. A. Danilov A. V. et al. Multi-channel X-ray radiometric separator. RF Patent No. RU 2432206. MPK B03B 13/06. Applied: 29.04.2010; published: 27.10.2011, *Bulletin.* No. 30.
17. Tatarnikov A. P., Zvonarev V. N., Brodsky Yu. A. et al. Automatic ore dressing method and facility. RF Patent No. RU 2269380. MPL B03B13/00, B07C5/34. Applied: 25.05.2004; published: 10.02.2006. *Bulletin.* No. 4. EM

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IMPROVEMENT OF WELL FLUSHING TECHNOLOGY DURING DRILLING IN PERMAFROST

The article presents the research results on flushing of wells during drilling in permafrost. The most effective flushing method is the use of drill fluids added with various antifreeze agents. In order to reduce the time spent on the implementation of this method of well flushing, as well as to prevent thawing and collapse of rocks in unstable intervals of wells, before the addition of antifreeze agents, the drill fluid is cooled down to the desired temperature. To cool drill fluids in summer, a refrigeration machine is used. In winter period, natural cold accumulated by atmospheric air is used for cooling. The drill fluid is cooled by any known method, including simplified approaches without using of complex and energy-consuming compressor refrigeration machines, by air heat exchangers blown with cold air. The proposed method involves the negative temperature mode of flushing and can be used when drilling wells of any purpose, diameter and length in permafrost up to 600 m thick.

Keywords: *well drilling, heat transfer, permafrost, antifreeze additives, drill fluid, negative temperature flushing.*
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Drilling in permafrost is faced with specific difficulties at all stages of well construction [1–10]. These difficulties arise from the variation in thermal conditions in wells due to heat exchange between permafrost rocks and the flush fluid circulating in the wells. To prevent freezing problems when drilling in permafrost, heated process water or drill fluid are used, which often results in decohesion of permafrost, as well as in sloughing and caving-in of wells.

According to the accomplished studies, the most effective technique of well washing in such conditions is application of negative-temperature drill fluids added with antifreeze agents, including carbamide, potassium chloride KCl and sodium nitrate $NaNO_3$ which ensure the ice point depression in drill fluids down to values not higher than temperature of permafrost.

The change in the natural temperature conditions in permafrost during drilling with flush fluids is governed by the flush fluid temperature and generally exhibits three trends:

- partial or total thaw of rocks in the vicinity of wells as a result of the heat exchange with circulating flush fluid with positive temperature;
- total or partial preservation of natural negative temperature under the circulation of flush fluid cooled down to negative temperature and containing an additive agent meant to depress the point of congelation;
- partial or total recovery of negative temperature in the well vicinity during long-term operational shutdown or forced stopping of flush fluid circulation.

Thus, when drilling in permafrost, an extra parameter to characterize the well washing procedure should be assumed the flush fluid temperature. There can be the positive and negative service temperature of flushing. The choice of the flushing temperature is governed by the physical and mechanical properties of permafrost, by the ice content of frozen rocks, as well as by their thermophysical properties and natural temperature [11–15].

Aimed to reduce the time spent for implementation of this well flushing procedure, prior to adding an antifreeze agent, the drill fluid is cooled down to a temperature t_n found from the relation:

$$0 \le t_n \le t_k + \Delta t, \quad (1)$$

where t_k is the preset temperature of the drill fluid, °C; Δt is the decrease of the drill fluid temperature owing to heat of dilution of an antifreeze agent, °C.

The antifreeze additive is selected amidst water-soluble substances characterized with endothermal heat of dilution. In summer, the drill fluid is cooled using a refrigerator machine. In winter, cooling is executed under natural cold accumulated in air. The drill fluid is cooled using any known technique, including simple, without complex and energy-consuming vapor compression machines, owing to blowing of cool air by air cooling heat interchangers [16–22].

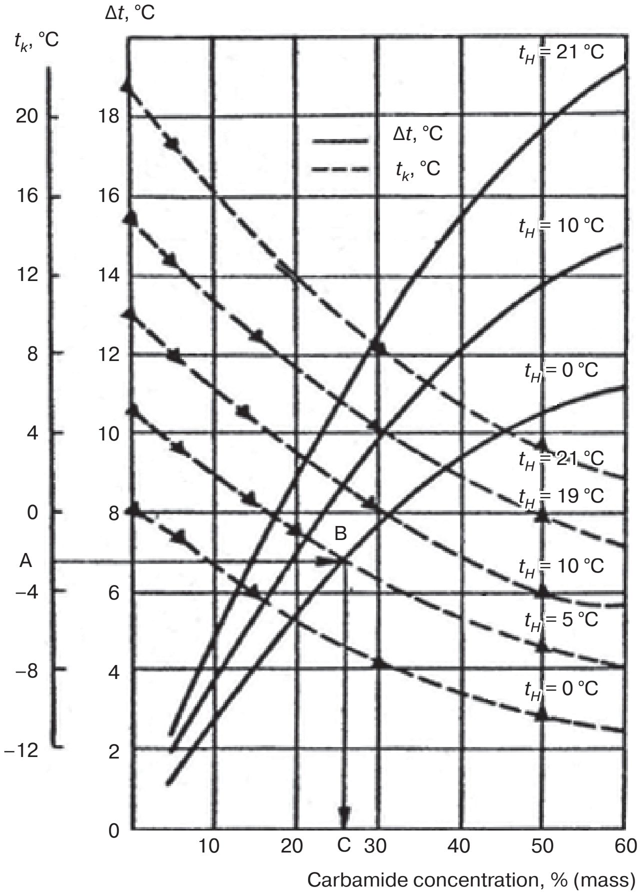
The proposed approach is a negative temperature washing technique applicable in drilling of any-purpose wells of any diameter and length in permafrost up to 600 m thick.

The figure shows the graph of the required concentration of an antifreeze additive (carbamide) in mass percent as function of the solution temperature t_k and the expected temperature decrease Δt_k owing to absorption of heat during dilution.

For example, 1 m^3 of drill fluid with initial temperature t_n = 5 °C is to be cooled down to the temperature t_k = –2.5 °C. Pre-cooling can only be done down to t_n = 0 °C; therefore, it is required to determine the antifreeze agent concentration such that to ensure the temperature decrease Δt = 2.5 °C. For instance, with carbamide, its concentration should be 25.5% (mass) (See the **Figure**). The required quantity of an antifreeze agent can be calculated from the known formula (without regard to heat exchange with the environment):

$$m = cm_s(t_n - t_k)/q, \quad (1)$$

where c is the specific heat per unit mass of drill fluid, J/kg·°C; m_s is the mass of drill fluid, kg; q is the specific heat of dilution of antifreeze agent, J/kg.



The required concentration of antifreeze agent (carbamide) versus the temperature of the solution ($T_H - t_n$, $T_K - t_k$)

Using this formula and laboratory test data, it is possible to plot graphs as in the figure for other antifreeze additives.

In this manner, the drill fluid is cooled down from 5 to 0 °C, with measuring duration of this operation; then, the drill fluid is added with 25.5 % (mass) of carbamide; 2.2 min later the drill fluid acquires the temperature of –2.5 °C. In accord with the described procedure, test cooling of drill fluids was undertaken using the known methods and the newly proposed approach. The test results are compiled in **Table 1**.

As follows from Table 1, the proposed method ensures essential reduction in cooling time as compared with the known techniques. For example, cooling of drill fluid from 20 to –5°C takes 176 min in the known method and 126 min with the proposed procedure. On the whole, the cooling time consumption is reduced by 45–28%. At the same time, the energy input of cooling is decreased within the same ranges due to shortened operating time of a refrigerating machine with an input up to 26 kW.

To the sufficient engineering accuracy, the cooling time T (preliminary cooling by the proposed procedure, or total time by the known method), given the known thermophysical properties of a drill fluid and cooling capacity of a refrigerating machine, can be calculated from the known expression:

$$T = cm_s \Delta t / kq, \quad (1)$$

where c is the specific heat per unit mass of drill fluid, J/kg·°C; m_s is the mass of drill fluid, kg; Δt is the required reduction in

Table 1. Experimentation results

Drill fluid composition, mass %	Antifreeze additive, mass %	Drill fluid temperature, °C			Cooling time, min	
		Initial	After pre-cooling	Final (preset)	Pre-cooling	Total time to final temperature
1. Cooling of salt solution by refrigerating machine KHM-FU-40-1						
1. Process water	KC1-23.5 KC1-15.0 KC1-10.0	20 20 20	- - -	0 –2.5 –5.0	- - -	128 160 188
2. Palygorskite –5.0, CMC-600–0.5, Water	KC1-22.4 KC1-14.2 KC1-9.5	20 20 20	- - -	0 –2.5 5	- - -	126 147 176
2. Proposed procedure						
2.1. Pre-cooling by refrigerating machine KHM-FU-40-1 and cooling owing to endothermal heat of dilution of antifreeze agent						
1. Process water	KC1-23.5 KC1-15.0 KC1-10.0	20 20 20	10 5 0	0 –2.5 –5	67 91 126	71 95 129
2. Palygorskite–5, CMC-600–5, Water	$NaNO_3$-22.4 $NaNO_3$-14.2 $NaNO_3$-9.5	20 20 20	10 5 0	0 –2.5 –5	66 88 123	70 91 126
3. Bentonite–5; PAA–0.2; Water	Carbamide-28.4 Carbamide-24.0 Carbamide-18.0	20 20 20	10 5 0	0 –2.5 –5	67 92 124	73 94 131
2.2. Pre-cooling owing to natural heat exchange with atmospheric air in winter (air temperature –5 °C) and cooling owing to endothermal heat of dilution of antifreeze agent						
4. Process water	$NaNO_3$-32.0 $NaNO_3$-15.0	20 20	10 0	0 –5	35 85	38 87
2.3. Pre-cooling by air cooling heat interchangers in autumn and spring seasons under air temperature of °C and cooling owing to endothermal heat of dilution of antifreeze agent						
5. Bentonite–5; PAA–0.2; Water	Carbamide-28.2 Carbamide-18.0	20 20	10 0	0 –5	20 45	26 52
Note: CMC – carboxyl methyl cellulose.						

temperature, °C; k is the efficiency of refrigerating machine in heat exchange with an intermediate heat source (0.55).

Refrigerating machines are used for cooling drill fluids only in summer when the air temperature is higher. In winter, or in autumn and spring, featuring lower or negative air temperatures in the permafrost areas, as well as longer duration of cooling as compared with summer, it is efficient to carry out pre-cooling of drill fluids using natural cold accumulated in air. In this respect, Table 1 describes additionally two approaches to pre-cooling of drill fluids. These data prove that with the proposed procedure, pre-cooling is feasible by any known method, including simplified, without involvement of complex and energy-consuming refrigerating machines.

The tests were carried out in thermally insulated reservoirs filled with the same quantities of drill fluids (3 m^3). Both the known and proposed methods used the series-produced refrigerating machine KHM-FU-40-1 with rated cooling capacity of 48846 kcal/h (56.72 kJ/s). The thermophysical properties and process properties of the tested drill fluids are described in **Tables 2 and 3**, respectively.

It follows from Table 3 that drill fluids after addition of antifreeze agents (carbamide, potassium chloride KCl and sodium nitrate $NaNO_3$) have acceptable parameters for drilling technology. In this connection, the proposed procedure of drilling in permafrost with negative temperature of flushing is applicable in any-purpose borehole drilling.

Table 2. Thermophysical properties of resultant drill fluids

Composition, % (mass)	Specific heat per unit mass, kJ/kg °C	Thermal diffusivity, $m^2/s \cdot 10^6$
Fresh water (at 0 and 20°C)	4.2119–4.1809	0.131–0.143
Clayey solutions with clay content of: 11.0 20.0 30.7 40.5 40.0	 3.82 3.57 3.20 2.88 2.55	 0.147 0.155 0.165 0.174 0.183
Thin clay drill fluids: Bentonite–5; PAA – 0.2; water Palygorskite–5, CMC-600 – 0.5, water	 3.99 3.98	 0.142 0.142
Emulsion solution EN-4-3, water	2.28	0.190
Surfactant solution Sulfanol – 0.5, water	3.02	0.162
Solid components in drill fluids: Clay Sodium chloride Sodium nitrate Sodium carbonate Potassium chloride Carbamide	 0.92 0.85 1.09 1.03 0.11 1.56	 - - - - - -

Table 3. Process properties of resultant drill fluids

Composition, % (mass)	Temperature, °C	Antifreeze additive, % (mass)	Properties				
			Density, kg/m^3	Relative viscosity, °C	Water loss, cm^3	Static shear stress, Pa	Settling out, %
Bentonite (5.0) PAA (0.2) Water	20.0 5.0 –2.5 20.0	– – Carbamide 25.5 Carbamide 25.5	1030 1030 1120 1120	30 34 36 34	10.5 10,0 7.0 9.5	0.44/0.64 0.70/0.612 1.34/2.34 0.80/1.48	0 0 0 0
Process water	5.0 –2.5	– $NANO_3$ 18.5	1000 1140	15 15	– –	– –	– –
Palygorskite 5.0 CMC-600 (0.5) Water	20.0 5.0 20.0 –2.5	– – KCl 15.0 KCl 15.0	1030 1030 1150 1150	20 25 32 48	7.0 6.0 22.0 11.0	0/0 0/0 0/0 0/0	0 0 0 0

Conclusions

1. Thaw of permafrost in the vicinity of holes is eliminated as the temperature of flush fluid with antifreeze additive is not higher than the temperature of permafrost in the borehole environment.

2. Natural negative temperature of permafrost is preserved.

3. Time spent for well flushing under negative temperature owing to cooling of drill fluid down to the temperature calculated from formula (1) before adding an antifreeze agent is reduced.

References

1. Kudryashov B. B., Yakovlev A. M. Drilling of wells in permafrost. Moscow : Nedra, 1983. 286 p.
2. Maramzin A.V., Ryazanov A. A. Drilling of exploration wells in the areas of permafrost. Moscow : Nedra, 1971. 148 p.
3. Trubetskoy K. N., Myaskov A. V., Galchenko Yu. P., Eremenko V. A. Creation and justification of convergent technologies for underground mining of thick solid mineral deposits. *Gornyi Zhurnal*. 2019. No. 5. pp. 6–13. DOI: 10.17580/gzh.2019.05.01
4. Galchenko Yu. P., Eremenko V. A. Model representation of anthropogenically modified subsoil as a new object in lithosphere. *Eurasian Mining*. 2019. No. 2. pp. 3–8. DOI: 10.17580/em.2019.02.01
5. Vysotin M. G., Kosyreva M. A., Leizer V. I., Aksenov Z. V. Design rationale for engineering multipurpose bench for physical simulation of geomechanical processes in secondary stress fields under conditions of mining with convergent geotechnologies. *GIAB*. 2019. No.10. pp. 131–145.
6. Eremenko V. A., Myaskov A. V., Galchenko Yu. P., Barrenechea R., Esaú M. et. al. Substantiation of convergent technology data for the Ilets rock salt deposit. *J. Fundament. Appl. Min. Sci.*. 2018. Vol. 5. pp 37–48.
7. Galchenko Yu. P., Eremenko V. A., Myaskov A. V., Kosyreva M. A. Solution of geoecological problems in underground mining of deep iron ore deposits. *Eurasian Mining*. 2018. No.1. pp. 35–40. DOI: 10.17580/em.2018.01.08
8. Eremenko V. A., Barnov V. G., Kondratenko A. S., Timonin V. V. Method for mining steeply dipping thin lodes. *Gornyi Zhurnal*. 2016. No. 12. pp. 45–50. DOI: 10.17580/gzh.2016.12.10
9. Barnov N. G., Eremenko V. A., Kondratenko A. S. Blasting of hydrofracturing-preconditioned blocks with decoupled explosive charges. *GIAB*. 2016. No.3. pp. 200–209.
10. Barnov V. G., Eremenko V. A., Kondratenko A. S., Timonin V. V. Substantiation of parameters of geotechnology for mining primary corundum deposits in difficult working conditions in upland areas. *Gornyi Zhurnal*. 2015. No. 11. pp. 42–47. DOI: 10.17580/gzh.2015.01.09
11. Rzepka A. V., Figurak A. A., Lepekhin A. N., Yarantsev V. A., Klimenko V. N. et. al. Guidelines for the preparation and use of low-temperature-resistant washing liquid when drilling permafrost. Leningrad : VITR. 1986. 36 p.
12. Gritsenko A. A., Kuligin A. V., Ivankin R. A., Griguletsky V. G. Urgent problems of well drilling technologies applied at fields of JSC "Gazprom". PART 2. Stroitelstvo neftyanykh i gazovykh skvazhin na sushe i na more. 2014. No. 4. pp. 7–18.
13. Shryock S. H., George C. R. Method for cementing wells in low temperature formations. U. S. Patent No. 3937282, IPC E21b33/13. Halliburton Company. Published: 10.02.1976.
14. Marques C., Castanier L. M., Kovscek A. R. Super insulated wells to protect permafrost during thermal oil recovery. *International Journal of Oil, Gas and Coal Technology*. 2011. No. 4. pp. 4–33.
15. Sedov V. T. Heat transfer during drilling of frozen rocks. Leningrad : Nedra. 1990. 126 p.
16. Features of construction and operation of wells in conditions of long-term frost. ERTA Group: E-Journal. 2004. Available at: http://gasforum.ru/obzory-i-issledovaniya/885/ (accessed 15.09.2017).
17. Figurak A. A., Rzepka A. V., Batalov N. I., Sklyanov V. I., Serebrennikov G. P. Method wash the wells when drilling in permafrost. USSR copyrigt certificate No. 1378443. Published: 01.11.1987.
18. Kuznetsov V. N. et al. Improvement of drilling technology in permafrost areas. Express Information. *Ser. Equipment and Technology of Exploration, Production Organization*. Moscow : *VIEMS*. 1982.
19. Timofeev N. G., Skryabin R. M., Atlas R. A., Nikolaev M. V., Ivanov A. G. Temperature during drilling in permafrost. *Nedropolzovanie XXI vek.* 2017. No. 5 (68). pp. 46–53.
20. Research of interaction of wells with permafrost and improvement of their fastening. Available at: http://earthpapers.net/-2015 (accessed: 22.10.2020).
21. Doinikov Yu. A. Improving the technology of drilling blastholes in the kimberlite deposits in Yakutia. Dissertation ... of Candidate of Engineering Sciences. Irkutsk, 2012. 128 p.
22. Polozkov A. V. Development of methods for monitoring the technical condition of wells in the cryolithozone. Dissertation ... of Candidate of Engineering Sciences . Moscow, 2009. 161 p. EM