UDC 550.36+622.24+550.832.6

HEAT EFFLUX ESTIMATION DURING A BOREHOLE DRILLING

V. I. ZUI [a], **Y. G. GRIBIK** [b], **A. L. SUSLENKO** [c]

[a]Belarusian State University, Nezavisimosti avenue, 4, 220030, Minsk, Republic of Belarus
[b]Institute for Nature Management, National Academy of Sciences of Belarus, F. Skoriny street, 10, 220114, Minsk, Republic of Belarus
[c]Republican Unitary Enterprise «Scientific-Production Center for Geology», Proletarskaya street, 77, 247760, Mozyr, Republic of Belarus

Corresponding author: zui@bsu.by

A field experiment to estimate the withdrawal of heat by a circulating mud was described on the basis of the borehole «Novo-Korenevskaya-13» located within the Pripyat Trough (Belarus) which was in a drilling process. A rock fragmentation process is accompanied by a heat release. Drilling of deep wells is fulfilled using a drilling mud (usually a clay mud). It cools the tool which frays and crushes rocks at the well bottom as well as removes detritus from a wellbore to the ground surface. The paper is devoted to calculation of the heat efflux by circulating drilling fluid during this well drilling. It was shown that this mud, circulating along the wellbore, evacuates to the ground surface not only detritus but provides the heat efflux as well. The experiment included the temperature monitoring of the drilling mud pumped into a drill string and its outflow from the well. We discuss the heat power delivered to the ground surface. It was confirmed that the heat efflux by the circulating fluid in a wellbore could attain hundreds of kilowatts or even slightly exceed 1 MW_{th} depending on the drilling depth, drillable rock types and the natural rock temperature at the considered depth. An assessment of heat withdrawal in the process of deep borehole drilling during oil exploration works within the Pripyat Trough represents both a scientific and practical interest. The heat release during the drilling process could be used for practical purposes.

Key words: borehole; borehole drilling; drilling mud; underground heat; borehole heat exchanger.

Acknowledgements. Authors acknowledge PhD M. D. Parkhomov for his help with calculations of the thermal power efflux from the drilled well «Novo-Korenevskaya-13» as well as for measurements of the volumetric heat capacity of a drilling mud sample.

ОЦЕНКА ВЫНОСА ТЕПЛА ПРИ БУРЕНИИ СКВАЖИНЫ

В. И. ЗУЙ [1)], **Я. Г. ГРИБИК** [2)], **А. Л. СУСЛЕНКО** [3)]

[1)]Белорусский государственный университет, пр. Независимости, 4, 220030, г. Минск, Республика Беларусь
[2)]Институт природопользования Национальной академии наук Беларуси, ул. Ф. Скорины, 10, 220114, г. Минск, Республика Беларусь
[3)]РУП «Научно-производственный центр по геологии», ул. Пролетарская, 77, 247760, г. Мозырь, Республика Беларусь

Описан полевой эксперимент по выносу тепла циркулирующим буровым раствором на базе скважины «Ново-Кореневская-13» Припятского прогиба (Беларусь). Доказывается, что буровой раствор, циркулирующий по стволу скважины, не только выносит на земную поверхность обломки разрушенной горной породы, но и обе-

Образец цитирования:
Зуй В. И., Грибик Я. Г., Сусленко А. Л. Оценка выноса тепла при бурении скважины // Журн. Белорус. гос. ун-та. География. Геология. 2017. № 1. С. 171–179.

For citation:
Zui V. I., Gribik Y. G., Suslenko A. L. Heat efflux estimation during a borehole drilling. *J. Belarus. State Univ. Geogr. Geol.* 2017. No. 1. P. 171–179.

Авторы:
Владимир Игнатьевич Зуй – доктор геолого-минералогических наук, профессор; доцент кафедры инженерной геологии и геофизики географического факультета.
Ярослав Гаврилович Грибик – кандидат геолого-минералогических наук, заведующий лабораторией геотектоники и геофизики.
Александр Лукич Сусленко – главный геолог Мозырской нефтеразведочной экспедиции глубокого бурения.

Authors:
Vladimir Zui, doctor of science (geology and mineralogy), full professor; associate professor at the department of engineering geology and geophysics, faculty of geography.
zui@bsu.by
Yaroslav Gribik, PhD (geology and mineralogy), head of the tectonics and geophysics laboratory.
yaroslavgribik@tut.by
Aleksandr Suslenko, chief geologist of the Mozyr Oil Exploration Expedition on Deep Drilling.
mozgeo@tut.by

спечивает вынос тепла. Исследование включало в себя мониторинг температуры бурового раствора: сначала – закачиваемого в бурильную колонну, затем – на выходе из скважины. Представлены расчеты выноса тепла циркулирующим буровым раствором в процессе бурения скважины. Оценивается тепловая мощность, доставляемая на земную поверхность. Подтверждено, что она может достигать сотен киловатт или даже незначительно превышать 1 МВт в зависимости от глубины бурения, типа разбуриваемых пород и их естественной температуры на рассматриваемой глубине. Показано, что оценка выноса тепла в процессе бурения глубокой нефтепоисковой скважины в пределах Припятского прогиба представляет как научный, так и практический интерес. Тепло, выделяющееся при бурении скважин, может быть использовано для практических нужд.

Ключевые слова: скважина; бурение скважины; буровой раствор; подземное тепло; скважинный теплообменник.

Благодарность. Авторы благодарят кандидата геолого-минералогических наук М. Д. Пархомова за помощь в проведении расчетов выноса тепла циркулирующим буровым раствором в процессе бурения скважины «Ново-Корневская-13» Припятского прогиба (Беларусь), а также за измерения объемной теплоемкости образца бурового раствора.

Introduction

An idea to use underground heat resources more than once was suggested in individual publications since the very beginning of geothermal investigations in Belarus (the end of fifties and early sixties of the past century). Neither detail nor preliminary estimates of geothermal potential in the country was done except the general statement of the idea, based on the practice of foreign countries.

For instance as far back as in 1959 the idea was put forward to use thermal waters of the Narovlya borehole [1], in particular using the natural flow of oil to recover a heat and produce the electricity from installed vertical turbine at its mouth. It is known that in general the period of natural well flowing has rather short duration followed by the operating cycle using in most cases sucker-rod pumps.

No justification of economic efficiency, technologic methods of the recovery, a life cycle of the turbine at the fountain regime of the well, as well as estimates how much electricity could be produced and how to put the axe in the helve related to the problem of very high mineralization of brines contained in productive horizons were discussed.

From geothermal point of view the well in the process of its drilling represents a borehole heat exchanger, created by a drilling string put into the circular hole, formed by the drilling tool in the process of its rotation and deepening the wellbore. The drilling process is accompanied by simultaneous pumping the drilling mud under pressure (usually a clay mud) into a drilling string. This fluid is used to cool the drill bit heated in the process of disintegration (fraying) of rocks at the well bottom. It also evacuates detritus from a wellbore to the ground surface during the drilling with a mud circulation in the wellbore, which is necessary to prevent the steel sticking by the accumulating detritus.

The temperature of rocks increases in the process of deepening the borehole. In result the circulating mud along the wellbore not only ensures the lifting of cuttings of crushed rocks to the ground surface but also provides the heat efflux. It results in the fluid temperature increasing at the wellbore mouth relatively to its temperature pumped into the drilling string both due to growing temperature of drilled rocks at the well bottom and due to the additional heat produced by the drill bit itself originating from the disintegration of rocks.

The temperature at the well bottom in deep holes of the Pripyat Trough varies in a wide range approximately from 30–50 to 115–140 ºC depending on geologic conditions. In this respect the location of the considered borehole within the trough plays an essential role. For instance, the temperature at comparable depths within the northern most warmed zone almost two times exceeds its values in the western and southern parts of this geologic unit.

Dozens of deep barren wells were drilled within the Pripyat Trough at studied structures outside the oil-water contacts which were later abandoned. They could be re-opened, repaired and used for a natural heat recovery [2]. Such an experiment to create the borehole heat exchanger was fulfilled in the deep abandoned well Berezinskaya-1, drilled at the end of sixties of the last century in the course of an oil exploration. It was plugged later. This experiment confirmed a possibility of the well utilization to create a borehole heat exchanger for recovery of the geothermal energy [3]. A task to produce the electricity then was not considered.

Drilling of deep boreholes is not practiced for scientific purposes to learn the recoverable resources of geothermal energy from hot horizons of the platform cover. We considered the possibility to study the heat efflux by drilling mud circulating in the drilled borehole which not only evacuated to the ground surface detritus but simultaneously provides the heat energy efflux. The drilling mud temperature data in the process of the borehole drilling is a primary source allowing estimating the heat efflux from the hole.

Exploratory procedure and source data

Testing technique. A test subject of the investigation was the deep borehole «Novo-Korenevskaya-13» located in the northern part of the Pripyat Trough. It was in the drilling process at the moment when the experiment was undertaken.

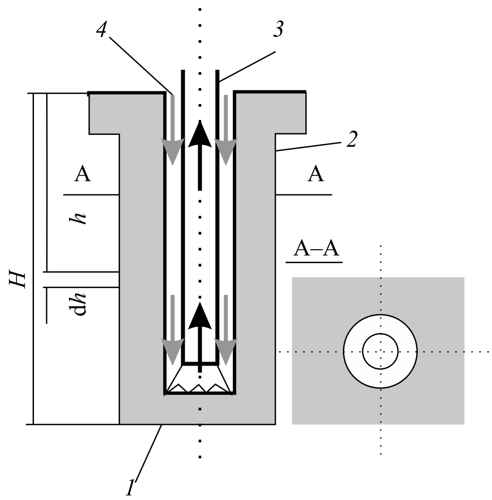

Fig. 1. Circulation diagram in a borehole heat exchanger [5 modified]:
1 – rocks; *2* – wellbore wall; *3* – drilling string; *4* – direction of a drilling mud circulation (could be reversed); *H* – total hole depth; *h* – current depth; d*h* – depth increment

The test technique included: 1) temperature monitoring of the drilling mud in the process the borehole drilling. The well actually represented a borehole heat exchanger where the drilling fluid was pumped into the annular space (hole clearance) in between the drilling string and walls with its outflow from the drilling string of the drilled wellbore taking into account its withdrawal rate (fig. 1). From geothermal point of view it is possible in general to consider the reverse direction of the mud circulation in such borehole heat exchangers. This part of the field work was organized by the Mozyr Oil Exploration Expedition of the Republican Unitary Enterprise «Belgeologiya» in December of 2008; 2) laboratory analytical works to process results, received in the course of the field experiment.

The final test objective was to estimate the heat efflux in the drilling process of the deep borehole «Novo-Korenevskaya-13» by means of the mud temperature monitoring at its input and output of the circulation loop in a drilled borehole (see fig. 1).

Previous investigations show that the central and southern zones of the Pripyat Trough are characterized by lower heat flow and temperature values at same depths as compared with the northern and northeastern parts of the structure. Similar tendency of the geothermal field intensity in the central, southern and western parts of the trough as compared to its northern zone is also reflected in temperature distribution maps. Discussed results show a high degree of the differentiation of the field geothermal parameters all over the Pripyat Trough territory [4].

In general case the heat removal from deep-seated rocks is usually realized by pumping out of mineral waters or brines contained in their pore space. A rapid grows of the mineralization with depth is a typical feature of underground fluids in deep horizons of the Pripyat Trough. For instance, it exceeds 200–300 g/dm^3 everywhere in the inter-salt deposits. It reaches up to 400–420 g/dm^3 in deep-seated sediments of the sub-salt complex. Pumping out of such brines from boreholes leads in their pressure and temperature reductions which results in a precipitation of salt crystals from brines and their sedimentation at walls of brine-raising pipes and shut-off-and-regulating elements which gradually plugs them.

Execution environment during field works

The heat removal from deep horizons of the platform cover within the Pripyat Trough could be fulfilled both by pumping out of warm brines and by creating borehole heat exchangers. The heat efflux with pumped out brines from productive horizons takes place in the first case. But these brines must be returned into underground horizons after their cooling due to high salinity. The heat in the second case is removed by means of a different fluid like fresh water or drilling mud circulating through the borehole heat exchanger where a hydraulic connection of the circulating fluid in the heat exchanger to underground horizons typically is small or absent. This approach also permits to remove the heat from impermeable rocks which don't contain fluids. For instance such as hot rocks of the crystalline basement, layers of rock salts, as well as other impermeable sediments could belong to them.

Situations with pumping out of highly mineralized brines for the terrestrial heat removal have a limited extent. For example, a warm brine with dissolved chemicals around 70 g/dm^3 and the temperature of 39 ºC at outlets of two producing wells at the Klaipeda geothermal station, Lithuania is pumped out and supplied to feed four absorption heat pumps. It was returned to the underground horizon after heat removal by heat pumps with the projected temperature of 11 ºC. A heat output at the moment of its commissioning was 35 MW$_{th}$ (of which geothermal part was 13.6 MW$_{th}$) [6]. After a few years of its exploitation an intake capacity of two absorption wells was reduced. The analysis showed that at the temperature of 11 ºC crystals of gypsum were precipitating and gradually mudding adjoining bottom hole regions of absorption wells. It resulted in decreasing of their productivity. After the problem was understood, the temperature of injected brines was increased to 18 ºC at which the gypsum doesn't precipitate of the brine and now the station operates only during the heating season. It resulted in the reduction of its heat power more than two times [6].

Another example of geothermal brines utilization is the geothermal station «Neustadt Glewe» located in between Berlin and Hamburg towns in Germany. Concentrated brines with the mineralization of 220 g/dm^3 are pumped out from a productive horizon. Their geothermal energy is recovered partly to support the temperature of a fluid returned to the original horizon around 50 ºC to prevent the precipitation of salt crystals from brines. In addition a small binary-cycle installation to produce electricity was also put into operation at this station. Its electric power is 230 kW$_e$ [7].

The second method of a heat removal, mentioned above, uses the scheme of a heat exchanger (annular tube system) at which into a casing pipe put without a filter till the well bottom, another water-raising pipe assembled, for instance of a tubing string. Fresh water is pumped into the annular space which reaches the well bottom and then it returns inside a water-raising pipe to the ground surface. Being warmed by the heat from rocks and raising inside the central pipe, it provides the heat efflux to the well mouth, which supplies this heat to the primary circulating contour of a heat pump. The reverse circulation scheme in the borehole heat exchanger is also acceptable.

Geothermal measurements in the Novo-Korenevskaya-13 borehole

The well was in a drilling process before the beginning of the experiment. Its drilling was stopped at the currents well bottom of 2895 m and during 7.5 days there was no a drilling mud circulation. Then the thermogram was recorded along the whole wellbore. It allowed calculating the geothermal gradient distribution. Results of the temperature measurements are shown in table 1. The average geothermal gradient within the depth interval of 550–2895 m was 13.4 mK/m.

Table 1

Temperature distribution along the wellbore of the Novo-Korenevskaya-13 borehole

Depth, m	Temperature, °C	Depth, m	Temperature, °C	Depth, m	Temperature, °C	Depth, m	Temperature, °C
50	9.38	800	25.1	1550	33.57	2300	43.11
100	13.93	850	26.41	1600	34.07	2350	43.58
150	16.1	900	27.27	1650	34.58	2400	43.92
200	17.04	950	27.32	1700	35.07	2450	44.23
250	17.18	1000	27.84	1750	35.82	2500	44.27
300	17.21	1050	28.31	1800	36.34	2550	45.2
350	18.57	1100	28.92	1850	37.11	2600	45.9
400	19.08	1150	29.84	1900	38.28	2650	46.25
450	19.08	1200	30.4	1950	39.09	2700	46.2
500	19.62	1250	30.75	2000	40.06	2750	46.89
550	20.34	1300	31.1	2050	40.9	2800	49.02
600	21.54	1350	31.73	2100	41.16	2850	49.63
650	22.43	1400	32.2	2150	41.75	2895	51.75
700	23.34	1450	32.55	2200	42.12	–	–
750	24.34	1500	33.12	2250	42.58	–	–

The thermogram recorded after 7.5 days of a quiescent mode of the well is shown in fig. 2. The diagram shape demonstrates that the quiescent time of the drill hole was not enough to buildup the thermal field of surrounding the wellbore rocks distorted by the drilling process after the drilling was stopped during 7.5 days only. For instance the curve itself is not smooth enough, there are wavy peaks not typical for other boreholes drilled within the same crustal block.

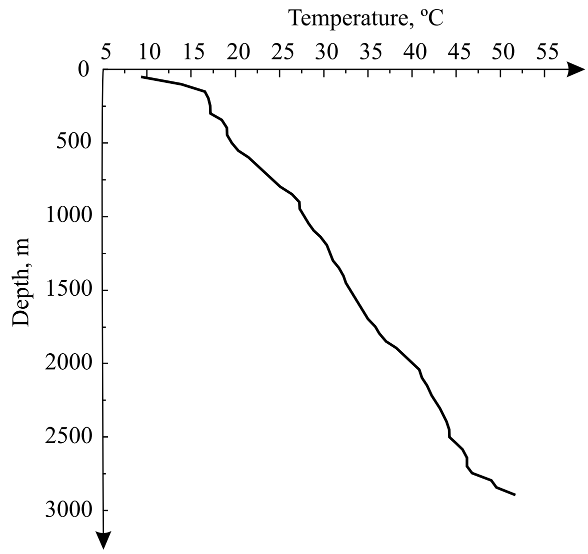

Fig. 2. Thermogram of the Novo-Korenevskaya-13 borehole after 7.5 days of a quiescent mode

A convolution of the diagram both in its upper and lower parts is an attribute typical for the thermal equilibrium absence between the wellbore and surrounding rocks. The thermogram extrapolation to the ground surface corresponds around 14–15 °C but it should approach approximately to the mean annual temperature of the local place which is 9–10 °C. In result it also confirms the fact that the thermal equilibrium in the borehole disturbed by the circulating drilling mud was not reached yet (fig. 2).

Results of the field experiment

The drilling process includes a number of alternate drilling and round-trips to lift the drill core or a well shutdown to fulfill borehole logging. A test to estimate the heat efflux from the Novo-Korenevskaya-13 well was fulfilled in the period from 22nd till 24th December, 2008. Periodic temperature measurements were organized at the inflow of a drill mud into the drilling string and its outflow from the borehole during the process of its circulation in the borehole (table 2). A special meter to record the circulation velocity of a drilling fluid was not used. Instead of it we accepted the discharge parameter from the pump delivery which was 18 dm^3/s. The air temperature was varying from –3 till –5 ºC. At the night time the drilling was stopped and a round-trip was fulfilled. The depth to the well bottom of the drilled hole was changed during the experiment time from 2790 to 2800.5 m. The maximal temperature of the drilling mud at its outflow from the annular space reached 28.5 ºC and the temperature of the fluid pumped into the drilling string was 3–5 ºC.

Table 2

Temperature variation of the drilling mud at the inflow into the drilling string and its outflow from the well

Data	Time, h and min	Drilling mud temperature at its inflow into the well, °C	Drilling mud temperature at its outflow from the well, °C	Current well bottom, m
22.12.2008	19^{00}	3	20	2790
	20^{00}	3	25	2790.4
	21^{00}	5	27	2790.8
	22^{00}	5	27.5	2791.4
	23^{00}	5.5	27.5	2791.6
	24^{00}	5.5	27.5	2792
23.12.2008	1^{00}	5.5	27.5	2792.5
	2^{00}	5.5	27.5	2793
	3^{00}	5.5	27.5	2793.6
	5^{00}	5.5	27.5	2794
	7^{00}	5	28	2795
	9^{00}	5	28	2796

Ending table 2

Data	Time, h and min	Drilling mud temperature at its inflow into the well, °C	Drilling mud temperature at its outflow from the well, °C	Current well bottom, m
Round-trip				
24.12.2008	1^{00}	5	12	2798
	2^{00}	5.5	23	2798.5
	4^{00}	5.5	27	2799
	6^{00}	6	27.5	2799.5
	8^{00}	5.5	28	2800
	10^{00}	5	28.5	2800.5

As it was mentioned, the process of the borehole deepening includes alternating actions on its drilling and interruption to lift core samples, organize borehole logging, round-trip operations, etc. The temperature variation diagrams at the inflow of the drilling mud into the drilling string and its outflow from the annular space is shown in fig. 3.

The drilling fluid temperature pumped into the borehole was changed during the experiment from 3 to 5.5 ºC and it varied at the outflow from 20 to 28.5 ºC. After 2 h of the drilling process the mud circulation, its temperature at the outflow from the annular space was stabilized and varied in a narrow interval of 27–28 ºC. After 14 h from of the experiment beginning of 23rd December 2008 the drilling was stopped and round-trip operations were started at night time (1^{00}). Temperature measurements were not fulfilled during this period of time. The drilling fluid temperature at 1^{00} (24.12.2008) dropped to 12 ºC, which is shown by a negative peak at the upper curve. After the drilling mud circulation was resumed, the temperature returned to its previous values of 27–28 ºC rather soon when the fluid temperature pumped into the drilling string was remaining practically same 5–6 ºC. This standing period in the well drilling was not taken into account in calculations of the thermal power efflux from the borehole.

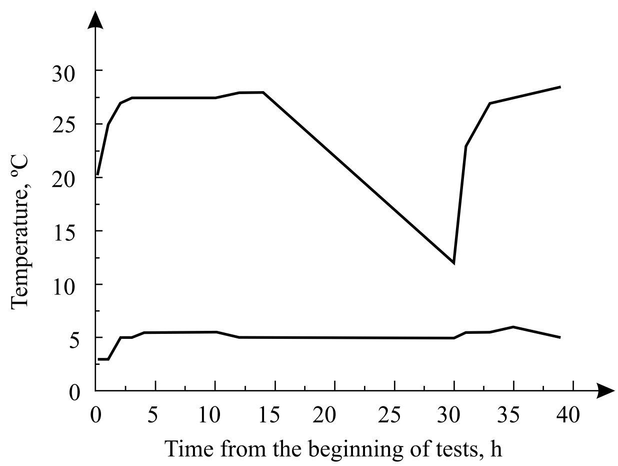

Fig. 3. Temperature variation diagrams at the inflow of the drilling mud into the drilling string (lower curve) and its outflow from the annular space (upper curve)

Heat efflux during the well drilling

Heat efflux at the time interval *i* between two temperature readings from thermometers for the drilling mud inflow into a borehole and its outflow Q_i [J], is a product of a volumetric heat capacity C_ρ [J/(m^3·K)], multiplied by the drilling mud volume V_i [m^3/s], pumped through the borehole heat exchanger (BHE) during the time unit, ΔT_i [K] – is the temperature difference between its values at the inflow of the fluid into the BHE and its outflow, t_i [s] – the pumping time interval.

$$Q_i = C_\rho \cdot \Delta T_i \cdot V_i \cdot t_i. \quad (1)$$

General heat efflux of the heat exchanger [J] during the test time *t* will be:

$$Q = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} \left(C_\rho \cdot \Delta T_i \cdot V_i \cdot t_i \right). \quad (2)$$

A specific heat capacity of a drilling mud was not measured during the well drilling. It is known that a heavy spar (barite) was used for weighting of the drilling mud. During calculations a simplified assumption was accepted that fresh water was circulating through the drilling string instead of a real drilling fluid, afterwards we shall apply a correction for a volumetric heat capacity of the clay drilling mud, it differs of the heat capacity of the fresh water.

The specific heat capacity of fresh water depends insignificantly of temperature [8] (fig. 4). Its minimal values at the fresh water density of 1000 kg/m^3 is in the range of 30–50 ºC and at a room temperature it is $4{,}18 \cdot 10^6$ J/(m^3 · ºC).

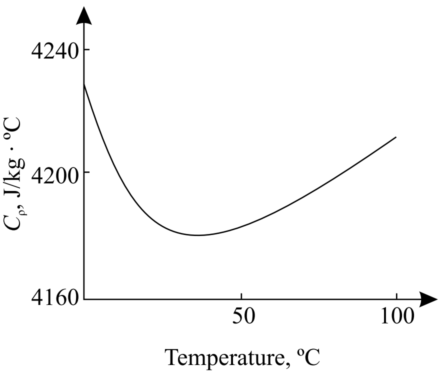

Fig. 4. Relationship of the specific heat of water from temperature

As indicated, during our experiment the fluid temperature at the outflow from the BHE reached 27–28,5 ºC. From fig. 4 it follows that for the considered temperature range we can accept the value of C_ρ = 4,18·10^6 [J/(m^3 · ºC)].

Results of calculations using relationships (1) and (2) are shown in table 3. Temperature values at the input of the borehole heat exchanger for each time interval are accepted as an arithmetic mean from their values at the beginning and the end of the considered time interval. The same approach was also used to determine the mean temperature at the fluid outflow from the drilled borehole.

It was assumed that the volumetric heat capacity of the fluid remains constant C_ρ = 4,18·10^6 [J/(m^3 · ºC)] during the experiment. Calculations were fulfilled for the first 14 hours since the beginning of the temperature registration during a process of continuing drilling of the borehole and the permanent rate of the hole washing by the drilling fluid equal to 18 dm^3/s.

Table 3

Estimation of the efflux of thermal power by drilling fluid during the well drilling process at C_ρ = 4,18 · 10^6 [J/(m^3 · ºC)]

Time intervals, *i*	Drilling mud temperature, ºC		ΔT, ºC	Pumping rate, m^3/s	Interval duration, s	Q_i, J
	At the BHE input	At the BHE output				
Drilling operations 22nd December, 2008 at the fluid pumping rate 18 dm^3/s (64,8 m^3/h)						
1 ($19^{00} – 20^{00}$)	3.0	22.5	19.5	0.018	3600	5 281 848 000
2 ($20^{00} – 21^{00}$)	4.0	26.0	22.0	0.018	3600	5 959 008 000
3 ($21^{00} – 22^{00}$)	5.0	27.25	22.25	0.018	3600	6 026 724 000
4 ($22^{00} – 23^{00}$)	5.25	27.5	22.25	0.018	3600	6 026 724 000
5 ($23^{00} – 24^{00}$)	5.5	27.5	22.0	0.018	3600	5 959 008 000
Drilling operations 23rd December, 2008 at the fluid pumping rate 18 dm^3/s (64,8 m^3/h)						
6 ($0^{00} – 1^{00}$)	5.5	27.5	22.0	0.018	3600	5 959 008 000
7 ($1^{00} – 2^{00}$)	5.5	27.5	22.0	0.018	3600	5 959 008 000
8 ($2^{00} – 3^{00}$)	5.5	27.5	22.0	0.018	3600	5 959 008 000
9 ($3^{00} – 5^{00}$)	5.5	27.5	22.0	0.018	7200	11 918 016 000
10 ($5^{00} – 7^{00}$)	5.25	28.0	22.75	0.018	7200	12 324 312 000
11 ($7^{00} – 9^{00}$)	5.0	28.0	23.0	0.018	7200	12 459 744 000
Total					50400	83 832 408 000
Average heat power of the heat exchanger				83 832 408 000 : 50 400 = 1 663 341.43 [J/s] = = 1, 66 [MW_{th}].		

Brief analysis of the operation of a borehole heat exchanger

A heat exchange between the rock massif and the wellbore has a complex character due to a number of factors: rock stratification of different mineralogical-and-lithologic section exposed by the well, different thermal and hydrodynamic properties (porosity, filtration factor, permeability, etc.), temperature and geothermal gradient for each depth interval, wellbore geometry, casing pipe and flow tubing designs, rate of the drilling fluid pumping, etc. Sometimes it is rather difficult to take all them into account.

A real borehole trajectory has the deviation both from the vertical and azimuth. Consequently, the wellbore represents a mine working described in three dimensions. In general case the analytical solution for heat transfer processes in such objects are absent. In general the problem is described by three dimensional partial differential equations. Their solution is possible by rather complex analytic expressions only for individual tasks under a number of simplifications.

The transitional regime takes place during a borehole drilling at which at least two mechanisms of heat transfer exist simultaneously. The prevailing mechanism is a convective one in the wellbore due to a drilling mud circulation. At the same time a conductive heat flow takes place into the wellbore from surrounding rocks or vice versa. When exposing the formation intervals of permeable rocks the problem is complicating by lateral convective heat exchange between the formation fluid and the wellbore due to the inflow of formation liquids into the well, or a drilling mud filtration into porous or fractured reservoirs in separate intervals of geologic section.

As it was shown in table 3, the heat power produced by a borehole heat exchanger, was calculated under the condition of a fresh water circulation inside it, which exceeds 1.66 MW_{th} with the flow rate of 18 dm^3/s (64.8 m^3/h). In addition it is necessary to mention that the contribution to heat recovery takes place due to three main components: 1) heat transfer by conduction into the wellbore from impermeable warm rocks and by conduction and convection from porous rocks; 2) heat generation produced by drill bit resulted from disintegration of rocks at the well bottom hole; 3) heat produced by a friction of the rotating drilling string at walls of the wellbore.

It is necessary to consider the calculated results on the heat efflux from the borehole in drilling only as a possible upper limit of the heat efflux from the BHE. Drilling mud sampling was not done during the time of the experiment and its volumetric capacity was not measured. Later a drilling fluid sample was taken from the different drilled borehole «Shatilki-15» with similar fluid density, but without using barite for weighting of the drilling mud. Laboratory measurements, fulfilled by PhD M. D. Parkhomov, showed that its volumetric heat capacity comprises 0.9 of the respective value for fresh water. It allowed applying a correction to the calculated heat power – 1.66 MW_{th}. Then the corrected value comprised $1{,}66 \cdot 0{,}9 = 1{,}49$ MW_{th}. It is assumed that taking into account of the barite influence could result in subsequent reduction of this heat power value to approximately 1.2–1.3 MW_{th}.

Results received during the experiment are in a good agreement with data of Russian researchers which used two or three times lower fluid circulation rates [9] when testing the Medyaginskaya well (heat power was 190 kW_{th} at the pumping rate of 23 m^3/h), the Danilovskaya-11 borehole (heat power was 290 kW_{th} at the circulation rate of 23 m^3/h) as well as the Tyrnauzskaya well – 600 kW_{th} at the rate of 33 m^3/h). When increasing the circulation rate to 64.8 m^3/h, which we had in the experiment, the heat power could reach or slightly exceed 1 MW_{th}. Then it will be purely comparable with the data received for the Novo-Korenevskaya-13 borehole. On the other hand, the authors in their paper [9] indicate that, when using a thermal insulating tubing, the heat power can also approach to 1 MW_{th}.

A field experiment was organized earlier in Belarus to create a borehole heat exchanger on the basis of the abandoned well Berezinskaya-1 located in the northern zone of the Pripyat Trough at the bank of the Berezina River [3]. Its wellbore was accessible till the depth of 1849 m, where the temperature raised to 55 ºC. Several tests were undertaken with different pumping rates through the borehole heat exchanger. A closed loop was used where fresh water was circulating through the BHE into a high-capacity tank vessel and returned again into the BHE. Other tests were organized where an open loop for water circulation was used (river – BHE – river). It was shown that when pumping the river water the thermal power of the BHE was approaching to 100 kW_{th} at much lower flow rate of 5–10 m^3/h. The inner pipe of the BHE in this test had no thermal insulation [3].

A number of other factors, which is difficult to take into account when drilling a well, influence a heat exchange within it such as periodic interruptions in drilling due to technology of these operations followed by resumed drilling mud circulation; heat exchange between circulating fluid in opposite directions inside the central pipe and in the annular space, as well as the surrounding the wellbore rocks of cased or uncased hole; its eccentricity, caused by features of a drilling string behavior in rocks, which results in its thermal contact with wellbore walls at separate intervals of the depth; variable heat dissipation along the wellbore walls and the drilling string; variable value along the depth of a heat transfer from rocks to the drilling mud due to design features of the well; pulling of drill string leads to the drilling mud agitation, which disturbs the temperature equilibrium inside the well; annular water circulation entering a well from exposed by drilling water-bearing layers, as well as other exothermal and endothermal processes. These processes lead to alternate directions of the heat flow between rocks and the drilling mud at different depth intervals.

The thermal power depends to different extent on a number of accountable factors in calculations such as: fluid temperature values at the input and output of the borehole heat exchanger, its pumping rate through the drilled well, as well as the circulation direction inside it (pumping into a central pipe, or into the annular space formed by the drilling string and the wellbore walls). The assessment of a heat production component resulted from the drilling string friction on walls of a wellbore leading in an increasing of the total thermal power, delivered by the drilling mud to the ground surface, is complicated due to variability of the actual wellbore geometry, hence the variable parameters of the string friction on walls within each of layers comprising the geologic section. The approaches for assessment of these components of the heat efflux require a separate thermal field consideration for each of drilled wells [10]. According to available information the final recovery of the geothermal state of rocks disturbed by drilling will require the period, exceeding 10–20 times the real drilling time [11].

Conclusions

The practical use of geothermal energy from interiors is based on the heat recovery from a rock massif or underground waters as a natural heat carrier. Temperature of sediments is the main key parameter which influences the resources of geothermal energy. An extraction of geothermal energy by means of pumping out of hot brines is complicated due to their high mineralization.

Results of the field experiment on heat efflux from the real drilled well «Novo-Korenevskaya-13» during the circulation of a drilling mud were processed and discussed in the paper. It was shown that the estimated thermal power of the BHE could exceed 1 MW_{th} at the pumping rate of 18 dm^3/s (64.8 m^3/h).

In principle it was shown a real possibility to recover the ground heat and its utilization by creating a geothermal installation on the basis of heat exchangers in those deep boreholes within the territory of the Pripyat Trough which didn't confirm the discovery of oil-fields. Produced heat could be used for heating and warm water supply for different consumers or used for other technologic processes.

Библиографические ссылки

1. *Богомолов Г. В.* Некоторые данные о геотермических условиях территории Белорусской ССР и прилегающих районов // Проблемы геотермии и практического использования тепла Земли : тр. Первого Всесоюзного совещ. по геотермал. исслед. (Москва, март 1956 г.) : в 2 т. / редкол.: В. И. Влодавец [и др.]. М., 1959. Т. 1. С. 240–243.
2. Подземные «котельные» / В. И. Зуй [и др.] // Народ. хоз-во Белоруссии. 1987. № 6. С. 13.
3. *Зуй В. И., Грибик Я. Г., Сусленко А. Л.* Опытные работы по созданию теплообменника в скважине Березинская-1 Припятского прогиба // Проблемы региональной геологии Беларуси : IV университет. геолог. чтения, посв. 15-летию кафедры динамич. геологии БГУ (Минск, 2–3 апр. 2010 г.). Минск, 2010. С. 69–70.
4. *Зуй В. И.* Тепловое поле платформенного чехла Беларуси. Минск, 2013.
5. *Kujawa T., Nowak W.* Thermal calculations of geothermal heat utilizing one-well systems with both injection and production // Proc. of the World Geotherm. Cong. 2000 (Kyushu – Tohoku, Japan, May 28 – June 10, 2000). Kyushu – Tohoku, 2000. P. 3483–3488.
6. Geothermal Energy Use in Lithuania / F. Zinevicius // Proc. of the World Geotherm Congr. 2015 (Melbourne, Australia, 19–25 April, 2015). P. 1–11 (CD-ROM).
7. *Sanner B.* Geothermal Power Generation // Renewable Energy Europe : Europ. Geotherm. Energy. Counc. (Madrid, June 26–28, 2007). Brussels, 2007. P. 1–12.
8. *Кошкин Н. И., Ширкевич М. Г.* Справочник по элементарной физике. М., 1976.
9. *Калинин М. И., Баранов А. В.* Метод расчета глубинных теплообменников для односкважинной технологии геотермального теплоснабжения // Разведка и охрана недр. 2003. № 6. С. 53–60.
10. *Проселков Ю. М.* Теплопередача в скважинах. М., 1975.
11. *Щербань А. Н., Черняк В. П.* Прогноз и регулирование теплового режима при бурении глубоких скважин. М., 1974.

References

1. Bogomolov G. V. Nekotorye dannye o geotermicheskikh usloviyakh territorii Belorusskoi SSR i prilegayushchikh raionov [Certain data on geothermal conditions within the territory of the Belarusian SSR and adjoining regions]. *Problemy geotermii i prakticheskogo ispolzovaniya tepla Zemli* : tr. Pervogo Vsesoyuznogo soveshch. po geoterm. issled. (Moscow, March, 1956) : in 2 vol. Mosc., 1959. Vol. 1. P. 240–243 (in Russ.).
2. Zui V. I., Tsalko P. B., Atroshchenko P. P., et al. Podzemnye «kotel'nye» [Underground «boiler-houses»]. *Nar. khoz-vo Beloruss*. 1987. No. 6. P. 13 (in Russ.).
3. Zui V. I., Gribik Y. G., Suslenko A. L. Opytnye raboty po sozdaniyu teploobmennika v skvazhine Berezinskaya-1 Pripyatskogo progiba [Experimental works on the creation of a heat exchanger in the Berezinskaya-1 well of the Pripyat Trough]. *Problemy regional'noi geologii Belarusi* : IV univ. geol. chteniya, posvyashchennye 15-letiyu kafedr. din. geol. BGU. (Minsk, 2–3 April, 2010). Minsk, 2010. P. 69–70 (in Russ.).
4. Zui V. I. Teplovoe pole platformennogo chekhla Belarusi [Geothermal field of the platform cover of Belarus]. Minsk, 2013 (in Russ.).
5. Kujawa T., Nowak W. Thermal calculations of geothermal heat utilizing one-well systems with both injection and production. *Proc. of the World Geotherm. Congr. 2000* (Kyushu – Tohoku, Japan, 28 May – 10 June, 2000). Kyushu – Tohoku, 2000. P. 3483–3488.
6. Zinevicius F., Sliaupa S., Mazintas A., et al. Geothermal Energy Use in Lithuania. *Proc. of the World Geotherm. Congr. 2015* (Melbourne, Australia, 19–25 April, 2015). P. 1–11 (CD-ROM).
7. Sanner B. Geothermal Power Generation. *Renewable Energy Europe*: Eur. Geotherm. Energ. Counc. (Madrid, 26–28 June, 2007). Brussels, 2007. P. 1–12.
8. Koshkin N. I., Shirkevich M. G. Spravochnik po elementarnoi fizike [Handbook on Elementary Physics.] Mosc., 1976 (in Russ.).
9. Kalinin M. I., Baranov A. V. Metod rascheta glubinnykh teploobmennikov dlya odnoskvazhinnoi tekhnologii geotermal'nogo teplosnabzheniya [Method to calculate deep heat exchangers for one-well technology of geothermal heat supply]. *Razved. i okhr. nedr*. 2003. No. 6. P. 53–60 (in Russ.).
10. Proselkov Y. M. Teploperedacha v skvazhinakh [Heat transfer in boreholes]. Mosc., 1975 (in Russ.).
11. Shcherban' A. N., Chernyak V. P. Prognoz i regulirovanie teplovogo rezhima pri burenii glubokikh skvazhin [Prognosis and management of thermal regime during drilling of deep boreholes]. Mosc., 1974 (in Russ.).

Статья поступила в редколлегию 22.11.2016.
Received by editorial board 22.11.2016.