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Simulation of Thermal Power on Bottomhole on the Basis of Experimental Studies of Drilling Tool Operation

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ABSTRACT

This work analyzes analytical dependences used for determination of power on bottomhole, the influence of negative temperatures on rock destruction tool is estimated. The experimental study of power on bottomhole is described including its influence on the temperature of borehole. On the basis of experimental results, the conclusion is made of strong correlation between power on bottomhole and volumetric rock destruction, mathematical model of this dependence has been developed. The proposed model can be applied for optimization of hole drilling modes.

Key words: Geological prospecting, hole drilling, experimental studies of power on bottomhole.

1. INTRODUCTION

During drilling of prospective holes, the power on bottomhole is one of the most important parameters determining both the energy intensity of production process and the efficiency of rock destruction. Precise determination of power level at the designing stage of drilling makes it possible to determine rational modes and to provide its economic efficiency [1-4].
The power during core drilling [5] is comprised of three main constituents:

$$Ndr = Nbh + Nrot + Nst; \qquad (1)$$

where Nbh is the power consumed on bottomhole, W; Nrot is the power consumed for rotation of drilling pipe string in the hole, W; Nst is the power consumed by transmission and other units of drilling rig, W.
Let us consider the power on bottomhole (Nbh). The power for rock destruction during drilling depends on the type of rock destruction tool and drilling mode parameters [2, 6].
During drilling by hard alloy bits, the power on bottomhole is determined as follows:

$$Nbh = 5.3 \cdot Cax \cdot n \cdot Dbit \cdot (0.137 + \mu fr); \qquad (2)$$

where Cax is the axial load, N; n is the RPM, min-1; Dbit is the bit average diameter, m; µfr is the coefficient of friction of bit cutters against bottomhole rock [2].
The power on bottomhole upon diamond drilling is:

$$Nbh = 0.2 \cdot Cax \cdot n \cdot Dbit; \qquad (3)$$

and upon noncore drilling:

$$Nbh = 0.35 \cdot Cax \cdot n \cdot Dbd; \qquad (4)$$

where Dbd is the boring bit diameter, m.
The aforementioned equations of power on bottomhole are theoretical. Predictions of power on bottomhole using these equations can differ from practical results. Certain amount of heat is released during rock destruction, which is consumed for heating of borehole zone and drilling bit.
High bottomhole temperatures affect negatively the operation of rock destruction tool due to high contact temperatures accompanied by various irreversible consequences. This exerts negative impact on the structure of rock destruction tool, which loses its initial strength. Destruction of hard rocks by diamond bits is accompanied by the temperatures of 600-800°C and higher, decreasing abrasive properties of diamonds by 30-60% regarding the initial values [7]. Hence, peculiar attention is attracted to thermal flow released on bottomhole during operation of rock destruction tool.
The studies on this field were carried out by Kozlovskii, Kudryashov, Zakhar'ev, Kurochkin, Onoshka, Skryabin, and Gorshkov.
Since the temperature determined by the power dissipated on bottomhole is one of the main factors influencing the operation efficiency of rock destruction tool during drilling of prospective holes, then it is required to estimate experimentally the power on bottomhole and the amount of heat released on bottomhole as a function of drilling parameters [8-11].

2. EXPERIMENTAL PROCEDURE OF TEST DRILLING WITH BLOWING

The experimental studies during test drilling with air blowing were aimed at determination of thermal power on bottomhole, which determined the increase in blowing air temperature.
The main tasks of the experimental studies are as follows:
- direct measurements of power on bottomhole;
- determination of thermal power during drilling with heavily worn cutters;
- measurement of heat released during drilling.

Solution to the formulated problems will allow to determine the flow rate of cleaning agent, required not only for discharge of drilled rock but also to maintain the required temperature mode of hole drilling.
The experimental drilling with air blowing [10] was performed with the following tools and assemblies:
- electric meter to measure total energy consumption;
- electric drill (rotation mode, Status MPR-70: rated power 1,200 W, 600 rpm);
- vortex tube, grade 50008N (for air cooling) [11];
- swivel and hard-alloy bits;
- artificial drilled block (rock sample);
- multichannel temperature meter (IRT-4);
- anemometer for measurement of air flow rate, (smart sensor AR816);
- tachometer for measurement of drilling bit RPM (SEM. AT-8);
- electronic scales for measurement of axial load;
- torque wrench, A90039, for measurements up to 110 Nm;
- piston compressor (PKSD-5,25DM(R));
- reducing valve with pressure gage to control air pressure supplied to vortex tube.

Figure 1 illustrates the flowchart of experimental rig for drilling with blowing.

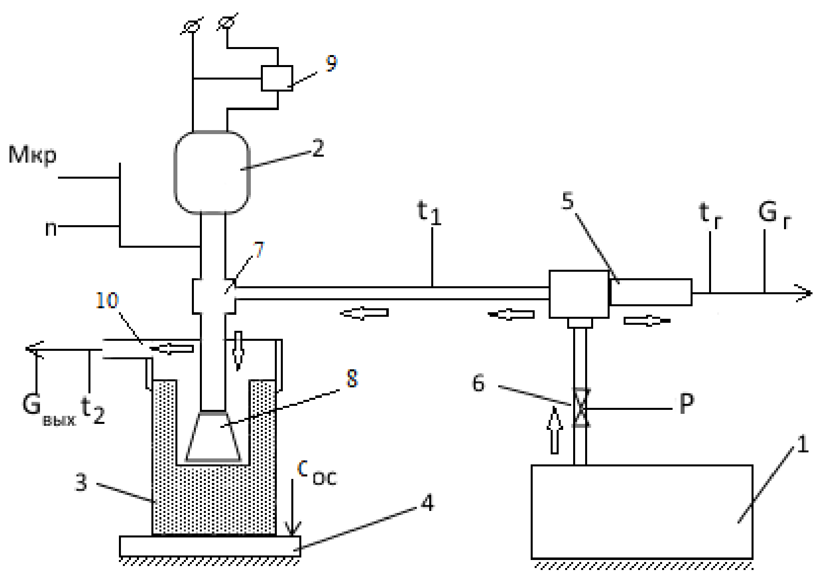

Figure 1: Flowchart of experimental facility of drilling with air blowing. 1 - compressor, 2 - electric drill, 3 - drilled rock, 4 - scales, 5 - vortex tube, 6 - pressure control, 7 - swivel, 8 - drilling bit, 9 - electric meter, 10 - sealer.

The measurement points are shown in the flowchart: t_h – the temperature of hot flow at outlet of vortex tube, °C; t_1 – the temperature of cold air at outlet of vortex tube, °C; t_2 – the temperature at outlet of the sealer, °C; G_h – hot air flow rate, m/s; G_{out} – the air flow rate at outlet of the sealer, m/s; C_{ax} – the axial load, N; P – the air pressure, MPa; n - the measurements of RPM.

The experiments were carried out as follows: the generator of cold fraction 8N was installed in the vortex tube 5, the vortex tube was connected to the receiver of the compressor 1, the pressure control 6 was installed in the connecting hoses between the receiver and the vortex tube. The cold outlet of the vortex tube was connected via hose to the swivel 7. The electric drill 2 was connected to the rock destruction tool via the swivel, the scales 4 were installed under the drilled rock 3. The electric drill was connected to power supply via the electric meter 9 and activated in the mode of rotation and blowing. The pressure was adjusted to 0.8 MPa by means of the holder, the axial load of 10 kg was applied to the drill, the axial load was determined using the scales 4. Current time, readings of the electric meter (Wh), and axial load (C_{ax}) were detected, the RPM readings (n) in rock destruction tool were detected using tachometer.

Preliminary, using torque wrench and tachometer, the RPM readings as a function of torque on drill shaft were determined.

After temperature stabilization, the multichannel meter (IRT-4) was used for measurement of ambient temperature (t_{amb}), the temperature of hot air flow (t_h), cold outlet of vortex tube (t_1), and flow from the sealer 10 (t_2).

The smart sensor AR816 was used to measure the air flow rate at the hot outlet of the vortex tube and at the sealer outlet.

Knowing the air flow rates in expansion tubes, air flow rate (G_h) and (G_{out}) was calculated as follows:

$$G = v \cdot \frac{\pi d^2}{4} \cdot \rho, \text{ kg/s}; \quad (5)$$

where v was the air flow rate, m/s; d was the tube diameter at the measurement point, m; ρ was the air density, kg/m^3.

After deactivation of the dill, the readings of electric meter and time were recorded, the depth and the diameter of bore hole were measured.

Then all measurements were repeated at the air pressure of 0.7; 0.6; 0.5; 0.4; 0.3 and 0.2 MPa. The same was performed with the axial loads C_{ax} = 300 and 500 N.

In order to determine the highest heat flow, all procedures were repeated at the same partakers with significantly worn cutters of the drilling bit.

The experimental data were recorded as the average of three measurements. The number of tests was determined on the basis of the preset error of 10% and initial dispersion. The parameters were predicted and the data were processed using Microsoft Office Excel and Mathcad.

3. EXPERIMENTAL RESULTS OF TEST DRILLING WITH BLOWING

On the basis of experimental results during drilling with blowing, the following parameters were determined:

1. Power transferred to bottomhole during drilling:

$$N = Mtr 2\pi n/60, \text{ W}; \quad (6)$$

where Mtr was the shaft torque, N·m; n was the shaft rpm;

2. Thermal power released at bottomhole, i.e. the power consumed for heating of borehole zone and drilling bit [12]:

$$Ptherm = c \cdot G \cdot (t2 - t1), \text{ W}; \quad (7)$$

where c was the air thermal capacity, J/kg·°C; G was the air flow rate, G=v kg/s;

3. Power consumed for rock destruction:

$$Ndest = N - Ptherm, \text{ W}; \quad (8)$$

where N was the power on bottomhole; Ptherm was the thermal power on bottomhole.

4. nrpm of drilling pipe as a function of axial load Cax on boring pipe (Fig. 2).

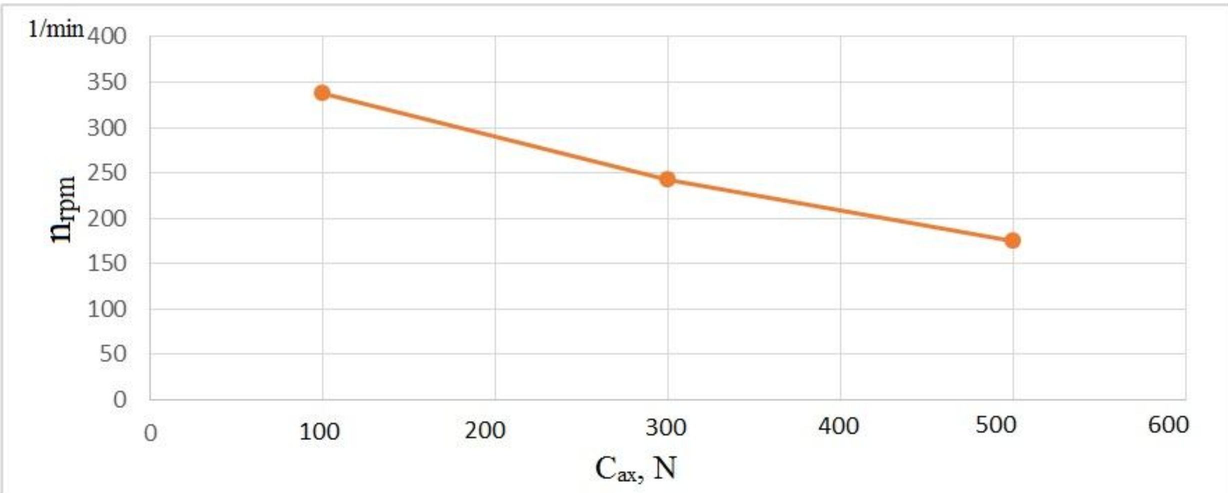

Figure 2: Drilling pipe RPM (nrpm) as a function of axial load (Cax) on boring pipe

The curve of drilling pipe RPM as a function of axial load on boring pipe (Fig. 2) demonstrated decrease in the drilling pipe RPM by 75-80 with the increase in the axial load on boring pipe (Cax) by 200 N.

5. Bottomhole temperature as a function of axial load.

During the experiments it was detected that the bottomhole temperature (t2out) depended on the axial load on boring pipe. Figure 3 shows that with the increase in the axial load by each 200 N, the air temperature at bottomhole outlet increases by 4-5°C.

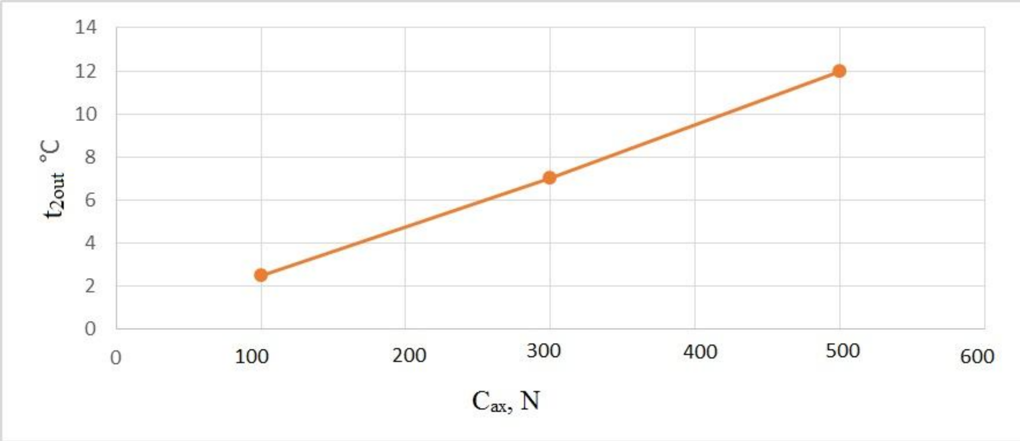

Figure 3: Air temperature from bottomhole (t2out) as a function of axial load Cax at input air temperature t1in = –28°C

Such temperature increase can be attributed to the fact that with increase in the axial load, the power on bottomhole also increases, hence, increases the heat for heating of borehole zone and drilling bit.

6. Air temperature from bottomhole t2out as a function of temperature of blowing air supplied to bottomhole t1in. Figure 4 illustrates air temperature from bottomhole as a function of temperature of blowing air at the axial load on boring pipe equaling to 500 N.

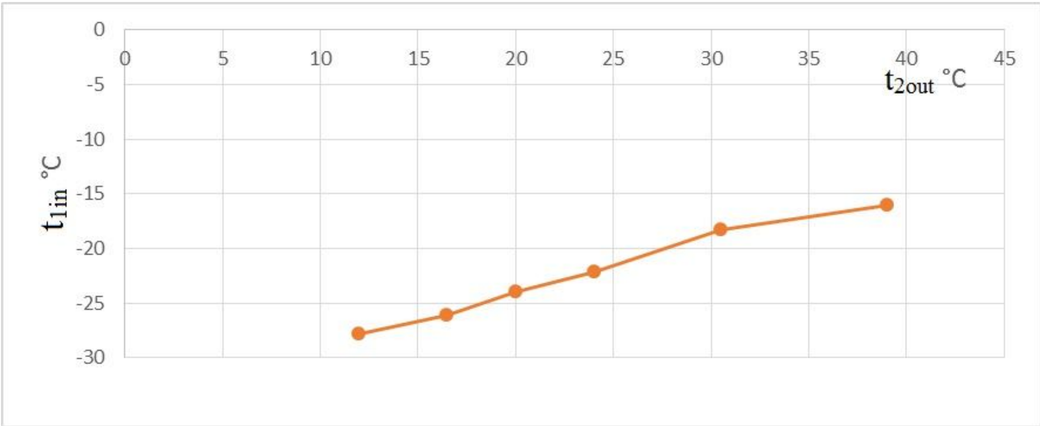

Figure 4: Air temperature from bottomhole (t2out) as a function of input air temperature (t1in) at Cax=500 N

It can be seen in Fig. 4 that the air temperature at bottomhole outlet decreases by 4-8°C with the increase in the negative temperature of blowing air by 2-3°C.

When the experiments are performed with the axial load of 300 and 100 N, the air temperature from bottomhole also decreases by 4-5°C with the increase in the negative temperature of blowing air.

7. Air temperature from bottomhole as a function of flow rate of blowing air.

During the experiments, when the flow rate of blowing air increased by 0.0018-0.002 kg/s, the temperature at cold outlet of the vortex tube decreased by 2-4°C, (Fig. 5), and the air temperature on bottomhole decreased by 4-5°C. Since the air heat capacity is low, higher air flow rate is required for more intensive cooling. Therefore, air temperature on bottomhole as a function of air flow rate has been determined in the preset range of drilling parameters.

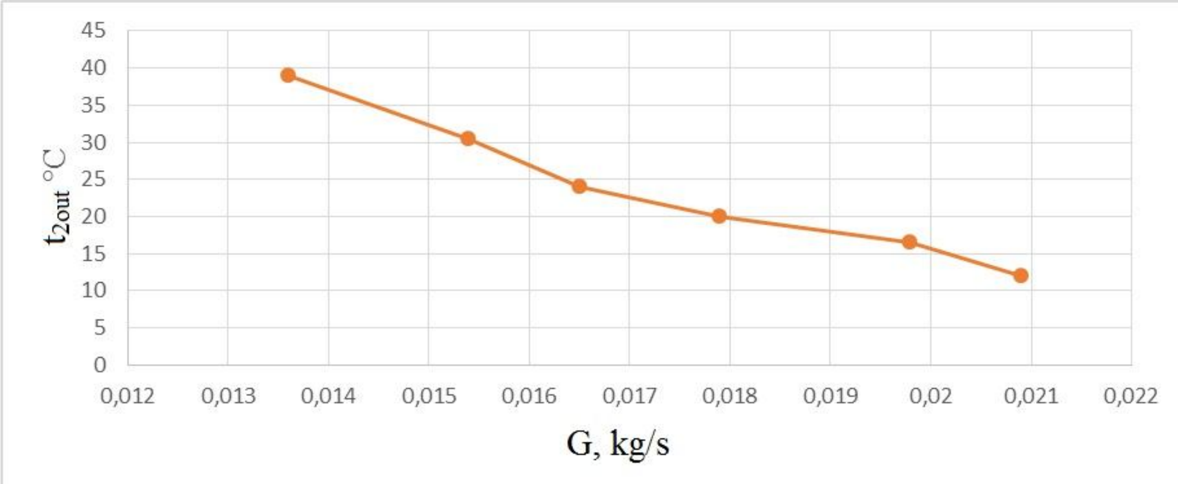

Figure 5: Air temperature at bottomhole as a function of blowing air flow rate.

8. Thermal power on bottomhole as a function of axial load on boring pipe.
The thermal power on bottomhole depends on the axial load.

It can be seen in Fig. 6 that with the increase in the axial load by 200 N, the thermal power increases by 90–100 W.

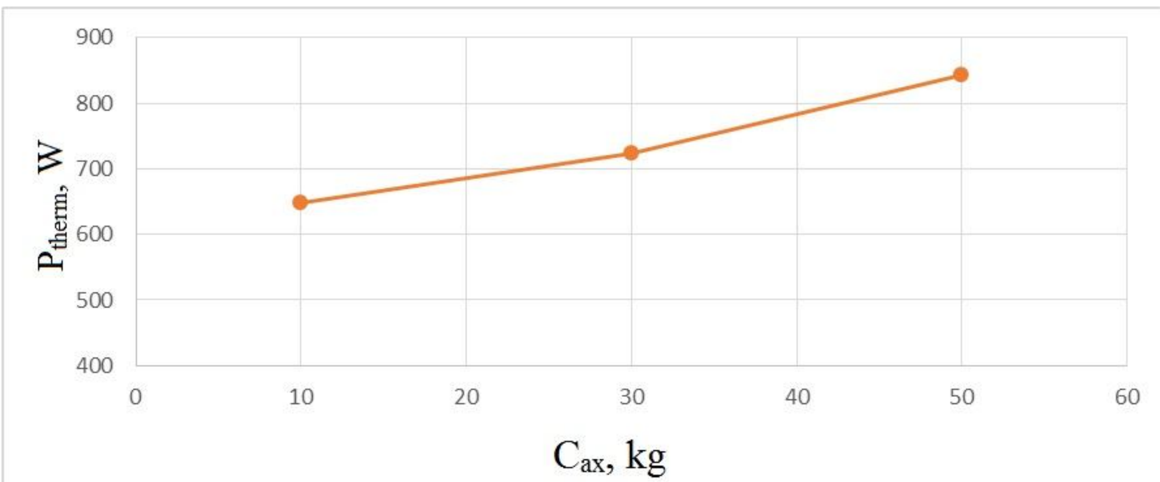

Figure 6: Thermal power on bottomhole (Ptherm) as a function of axial load (Cax) on boring pipe

9. Thermal power as a function of volumetric drilling rate.
During the experiments it was revealed that the thermal power on bottomhole depended more stable on the rate of volumetric rock destruction. The rate of volumetric destruction is a generalizing factor accounting for such drilling parameters as axial load (Cax) and RPM (nrpm).
On the basis of experimental results, the thermal power (Ptherm) as a function of rate of volumetric destruction (vvd) was determined, which is illustrated in Fig. 7.

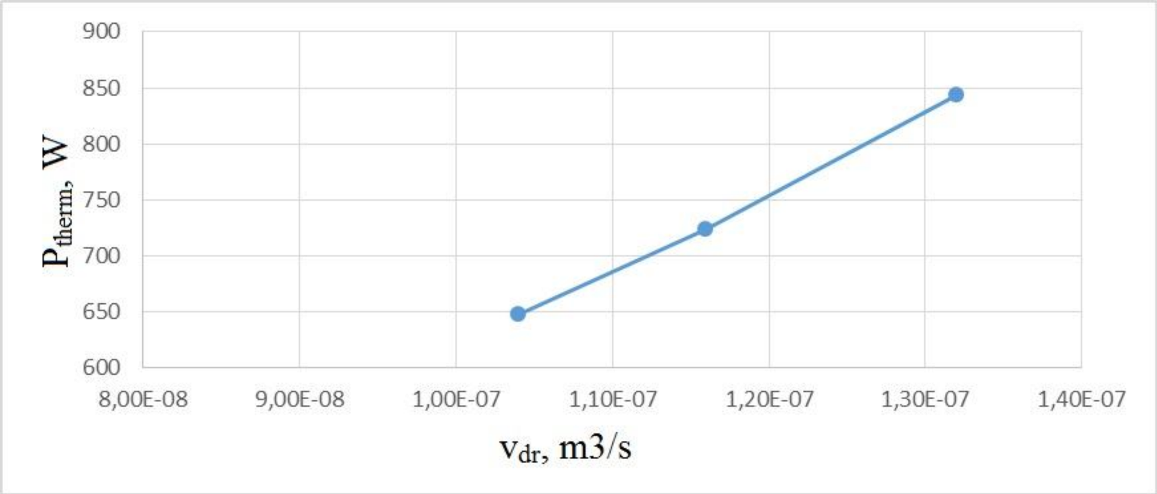

Figure 7: Thermal efficiency as a function of volumetric drilling rate

On the basis of experimental results, the thermal power on bottomhole as a function of volumetric drilling rate was determined. Good agreement between these parameters is confirmed by high correlation coefficient.

The regression analysis [13], based on fthe experimental data, determined the thermal power as a function of volumetric drilling rate:

Ptherm = 7·109·vvd – 83.82, W (9)

where vvd was the rate of volumetric drilling, m3/s.

The obtained equation can be used to determine the increase in temperature of blowing air:

$$\Delta t_3 = \frac{P_{therm}}{Gc} = \frac{7 \cdot 10^9 \cdot v_{vd} - 83.82}{Gc} \quad (10)$$

where Ptherm is the thermal power released on bottom hole during drilling, W; c is the air thermal capacity, J/kg·°C; G is the air flow rate, kg/s; vvd is the rate of volumetric drilling, m3/s.

The accuracy of this model is verified by comparison of the experimental data and those obtained by Eq. (9). The predicted data are summarized in Table 1. The following notations are used in the table: n is the number of test series; Ptherm is the average value of experimentally determined thermal power released on bottomhole, W; vvd is the rate of volumetric drilling, m3/s; P*therm is the thermal power released on bottomhole obtained by the regression equation, W.

Table 1: Predicted parameters based on experimental data

n	$P_{therm.}$ W	$V_{vd,}$ m^3/s	$P^*_{therm.}$ W	P_{therm} - $P^*_{therm.}$ W	($P_{therm.}$ - $P^*_{therm.}$)^2, W
1	648	$1.04\cdot10^{-07}$	644.18	3.82	14.5924
2	724	$1.16\cdot10^{-07}$	728.18	-4.18	17.4724
3	843.5	$1.32\cdot10^{-07}$	840.18	3.32	11.0224
	$\sum P_{therm}$ = 2215.5				$\sum(P_{therm.} - P^*_{therm.})^2$ = 43.0872

The dispersion of experimental data is as follows:

σ2 = [∑(Ptherm – P*therm)2]/n = 14.36;

at average thermal power Pst

Pst = (∑Ptherm)/n = 738.5 W.

The accuracy can be estimated by relative error:

A= (σ · 100%)/ Pst = 0.51%.

Root mean square error is 0.51% of arithmetic mean value, hence, it is possible to state that Eq. (9) with sufficient accuracy describes empirical dependence of the thermal power on the rate of volumetric drilling and can be used as the mathematical model of this dependence [14, 15].

Equation (9) allows to predict the air temperature at the bottomhole outlet and to determine ultimate values of temperature and air flow rate supplied to the bottomhole using Eq. (10). Hence, it is possible to predict temperature mode of hole drilling and to optimize its parameters under specific geological conditions. The flow rate of blowing air supplied to the hole should be predicted by the suspension velocity and carrying out drill rock particles. Herewith, it is necessary to consider for provision of preset temperature on bottomhole.

5. CONCLUSION

1. Analysis of theoretical dependences has demonstrated that they do not account for all factors and do not allow to

determine correctly the heat amount for heating of borehole zone and tools.
2. The experimental studies upon test drilling with blowing has allowed to determine thermal power on bottomhole, that is, capacity used for heating of borehole zone and rock destruction tool.
3. Drilling pipe RPM as a function of axial load on boring pipe has been determined during the tests.
4. Bottom hole temperature as a function of axial load has been determined (Fig. 3). The temperature of blowing air from bottom hole increases with axial load.
5. Thermal power on bottomhole as a function of axial load on boring pipe has been determined (Fig. 6).
6. Thermal power on bottomhole as a function of volumetric drilling rate has been determined.
7. Empirical analytical dependence of thermal efficiency on volumetric drilling rate is proposed, which can be used to predict temperature mode in bottomhole upon hole drilling.
8. The air flow rate to hole should be determined by output of slurry and verified with consideration for required temperature on bottomhole.

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