Energy Assessment of the State of Pipe Column in the Deep Well Drilling

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Abstract

The paper studies the technological features of drilling and the compressed air expulsion, and a generalized assessment of the heat balance of pipe column in drilling well. An algorithm of the non-equilibrium thermodynamics with the linear regimes of energy loading of the pipe column during a well drilling is considered. A computational analysis is performed with the following initial data: D=0.28 m; d=0.155 m; t_p=48°C; t_1=23.6°C; t_2=35.3°C; thermal conductivity coefficients: rocks λ_1=2.56 W/(m·°C); and steel pipe of the column λ_2 and λ_3 = 60 W/(m ·°C); the heat transfer coefficient from the ascending and outgoing flows of the washing liquid are 175 W/(m·°C) and 256 W/(m·°C). In this case, the average linear heat transfer coefficient is 220 W/(m_2·°C). An algorithm for estimating the heat balance of the drill column and its annulus during their interaction with humidified compressed air is proposed. When the well is purged with compressed air, the average linear heat transfer coefficient is 95 W/(m_2·°C); the bulk temperature gradient for mud at the bottom of a 100 m long drill string was 0.03 °C/m. From the above parameters, the ratios are formed that are equal to the Onsager and Saxen ratios, which makes it possible to determine the parameters by calculation.

Keywords: borehole, drill column, drilling fluid, compressed air, inter-tubular volume.

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Dərin qazıma quyusunda borunun vəziyyətinin enerji qiymətləndirilməsi

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Xülasə

Məqalədə, quyunun sıxılmış hava ilə qazılması və üfürülməsinin texnoloji xüsusiyyətləri və qazıma quyusunda boru kəmərinin istilik balansının ümumiləşdirilmiş qiymətləndirilməsi məsələləri nəzərdən keçirilib. Quyuların qazılması zamanı boru kəmərinin enerji yüklənməsinin xətti rejimli qeyri-müvazinat termodinamikasının alqoritmi işlənilib. Verilmiş ilkin məlumatlarla hesablama təhlili aparılıb: D=0,28 m; d=0,155 m; t_p=48°S; t_1=23,6°S; t_2=35,3°S; istilikkeçiricilik əmsalları: qayalar λ_1=2,56Vt/(m·°S); və polad boru kəməri λ_2 və λ_3 = 60 Vt/(m·°S); yuyucu mayenin yüksələn və çıxan axınlarından istilikötürmə əmsalı: 175 Vt/(m·°S) və 256 Vt/(m·°S) təşkil edib. Bu halda, orta xətti istilikötürmə əmsalı 220 Vt/(m^2·°S)-dir. Nəmlənmiş sıxılmış hava ilə qarşılıqlı əlaqə zamanı borunun istilik balansının və borulararası həcmin qiymətləndirilməsi alqoritmi təklif edilib. Onsager və Saksen nisbətləri parametrlərin hesablama yolu ilə müəyyənləşdirilməsinə imkan verir.

Açar sözlər: qazıma quyusu, qazıma borusu, gilli məhlul, sıxılmış hava, borulararası həcm.

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Энергетическая оценка состояния колонны труб в бурящейся глубокой скважине

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Аннотация

В работе рассмотрены технологические особенности бурения и продувки сжатым воздухом скважины и обобщенная оценка теплового баланса колонны труб в бурящейся скважине. Рассмотрен алгоритм неравновесной термодинамики с линейными режимами энергонагруженности колонны труб при бурении скважины. Выполнен расчетный анализ при следующих исходных данных: D = 0,28 м; d = 0,155 м; tп = 48°C; t1 = 23,6°C; t2 = 35,3°C; коэффициенты теплопроводности: горных пород λ1=2,56 Вт/(м·°C); и стальной трубы колонны λ2 и λ3 = 60 Вт/(м·°C); коэффициент теплоотдачи от восходящего и исходящего потоков промывочной жидкости составили 175 Вт/(м·°C) и 256 Вт/(м·°C). При этом средний линейный коэффициент теплоотдачи составляет 220 Вт/(м2·°C). Предложен алгоритм оценки теплового баланса бурильной колонны и ее межтрубного объема при их взаимодействии с увлажненным сжатым воздухом. Соотношения Онзагера и Саксена позволяют определить параметры расчетным путем.

Ключевые слова: буровая скважина; колонна бурильных труб; глинистый раствор; сжатый воздух; межтрубный объем.

Introduction

The existing methods for designing drill strings do not fully take into account the specific conditions of their operation when drilling deep wells, in particular, the weakening of the material of drill pipes and the decrease in their performance characteristics with an eccentric location of the drill string in the well and elevated volumetric operating temperatures, and a number of other factors also affect factors. In most geological regions of near and far abroad, the volume temperature of mountain rocks at a depth of 5-10 km reaches 200-400°C, which requires the creation of heat-resistant drilling fluids, supported by a forecast of the energy assessment of the state of the pipe string in a deep well being drilled.

Analysis of literary sources and the state of the problem

A well-known classical scheme for determining the heat transfer coefficient through a cylindrical wall [1]. This coefficient characterizes the intensity of heat transfer from one liquid to another through the wall separating them.

The work [2] outlines the scientific foundations and practical methods for calculating the temperature inside a drilling well for various technological processes and stages of drilling, highlights the role of the temperature factor in the occurrence of complications during drilling, summarizes and analyzes the results of domestic and foreign experimental and theoretical studies on the study of the temperature regime of drilling wells. wells, the methodology and results of studying the temperature fields of the near-wellbore and bottom-hole zones and the working part of the drilling tool and pipes in turbine and rotary drilling are given. However, this material did not propose a multilayer structure in relation to the drill string to determine the heat transfer coefficient through its wall.

In [3], it is noted that the temperature field of the well is formed under the influence of the heat exchange process between the circulating flushing fluid and the rocks that make up the well. The temperature of the rock mass can be tentatively estimated using a geometric gradient that determines the temperature increments per 1 m of the well depth:

$$T_3 = t_0 + n^\circ L, \tag{1}$$

where T_3 is the temperature of rocks; t_0 is the temperature of the neutral layer; n°- geometric gradient; L - the current well depth.

The neutral layer is understood as the layer of constant annual temperature. The depth of its occurrence is determined by the temperature conditions on the earth's surface, the thermophysical properties of rocks, and the rheological and geomorphological features of the given region. For most areas, the depth of the neutral layer is 20-40 m, and its temperature is considered to be usually equal to the average annual air or soil temperature (in the range from 0 to 15°C). It is obvious that the neutral temperature layer is heat-insulating, which does not allow heat flow to penetrate deep into the well.

To determine the heat transfer coefficients from the outer and inner surface of the drill pipe, which are constituent dependencies for determining the heat transfer coefficient. The complex apparatus of the theory of similarity is applied. In the latter, from the base pipe with certain geometric parameters, from which they switch to other pipe sizes, which leads to inaccuracies in the calculated results [1].

Let us dwell briefly on the basic principles that take place in thermal problems. Reciprocity is used in solving some problems of heat conduction; this means that if the heat source Is located at point 1 causes a temperature change $\Delta t = f(\tau)$ at point 2, then if the source is moved to point 2, the same temperature change will occur at point 1 [4].

It should be emphasized that at mutual points the rates of temperature change are the same, but the temperature gradients are different, so it must be remembered that the transition to an equivalent problem - the temperature fields turn out to be different. The importance of applying the reciprocity principle in problems of heat conduction is known [4].

These include under the action of a heat source: in a semi-limited body or in an unlimited plate; a plate covered with a layer of turbulent fluid, as well as in a plate in the presence of a fluid layer and an adiabatic level on one boundary, and a type III boundary condition on the other. Symmetry - proportionality, proportionality of the parts of the product located on both sides of the middle of the center.

The problem is to generalize the energy assessment of the state of a pipe string in a deep well being drilled by applying non-equilibrium thermodynamics with linear thermal loading.

In this publication, the following issues are considered: technological features of drilling and blowing a well with compressed air; a generalized assessment of the heat balance of the pipe string in the drilling well; the discussion of the results.

The purpose of the work is to substantiate the possibility of using non-equilibrium thermodynamics with linear thermal regimes as applied to a pipe string in a drilling well.

Technological features of drilling and blowing compressed air wells

Let us consider the technological features of drilling when a clay solution is used as a medium.

<u>Drilling period.</u> When the fluid moves in the drill string, the work of the flow is in the field of gravitational forces, the polytropic expansion of the liquid passes without the return of external work and with the release of heat through the walls of the drill string. In the bottomhole volume, an adiabatic outflow from the bit channels occurs with friction and heating due to heat generation that occurs when the drilling tool crown rubs against the rock being destroyed when the mud moves in the annulus. In this case, schemes of direct and reverse flushing with a solution of a drilling well are used (Fig. 1 a, b).

The heat exchange processes of the drill pipe string depend on its location in relation to the borehole walls (Fig. 1 c, d). With one amount of fluid flow rate, with a symmetrical arrangement of the drill string, we have a quasi-stable temperature field, and with an eccentric arrangement, it is non-stationary.

<u>From the point of view</u> of the thermal regime, the period of blowing the well before drilling differs from the period of drilling the well by the absence of heat release on the contact surface between the bit and the array, since the destruction of the array does not occur during this period. The air jet at the bottom of the well is heated as a result of heat exchange with the rock mass.

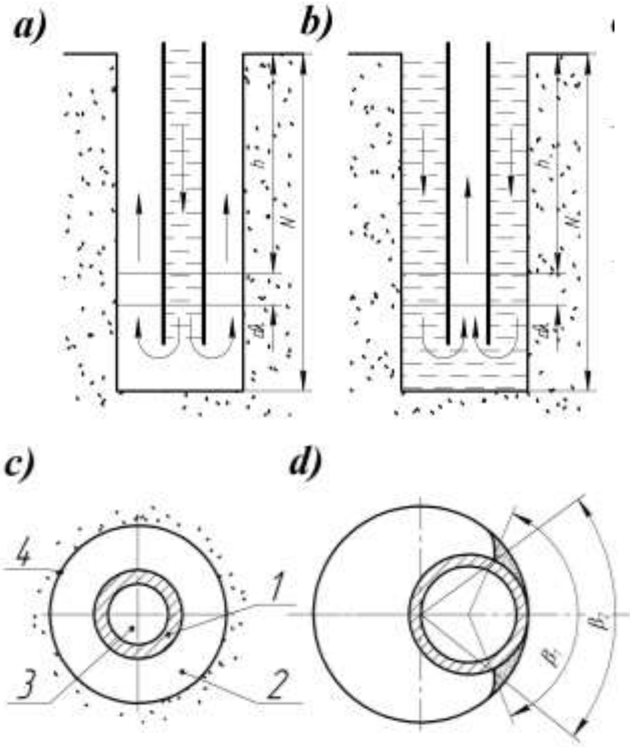

Figure 1 a, b, c, d – Schemes of direct (a) and reverse (b) flushing with a solution of a drilling well and its cross sections with a symmetrical (c) and eccentric (d) arrangement of the drill string: 1 – drill string; 2 - annulus volume; 3 - solution with rock being carried out; 4 – rock

On fig. 2 shows the algorithm for estimating the heat balance of the drill string and its annulus during their interaction with humidified compressed air.

During the downtime of the well due to tripping operations, the non-stationary temperature field in the rock mass around the well is restored and the air filling the well is heated, which is accompanied by free convective heat transfer inside the well and moistening the air as a result of evaporation of moisture from the uncased part of the well walls.

In this case, a scheme of direct and reverse blowing of the well with compressed air is implemented (Fig. 3 a, b) to remove the clay solution with the products of destruction of rocks.

Generalized energy estimation of the heat balance of a pipe string in a drilling well

The importance of applying the reciprocity principle in problems of heat conduction is known [4]. These include under the action of a heat source: in a semi-limited body or in an unlimited cylindrical tube; a pipe covered with a layer of turbulent fluid, as well as in a pipe in the presence of a fluid layer and an adiabatic condition on one boundary, and a type III boundary condition on the other.

Symmetry - proportionality, proportion-nality of the parts of the product located on both sides of the middle of the center. On fig. 4 shows the algorithm of non-equilibrium thermodynamics with linear regimes of energy loading of the pipe string during well drilling.

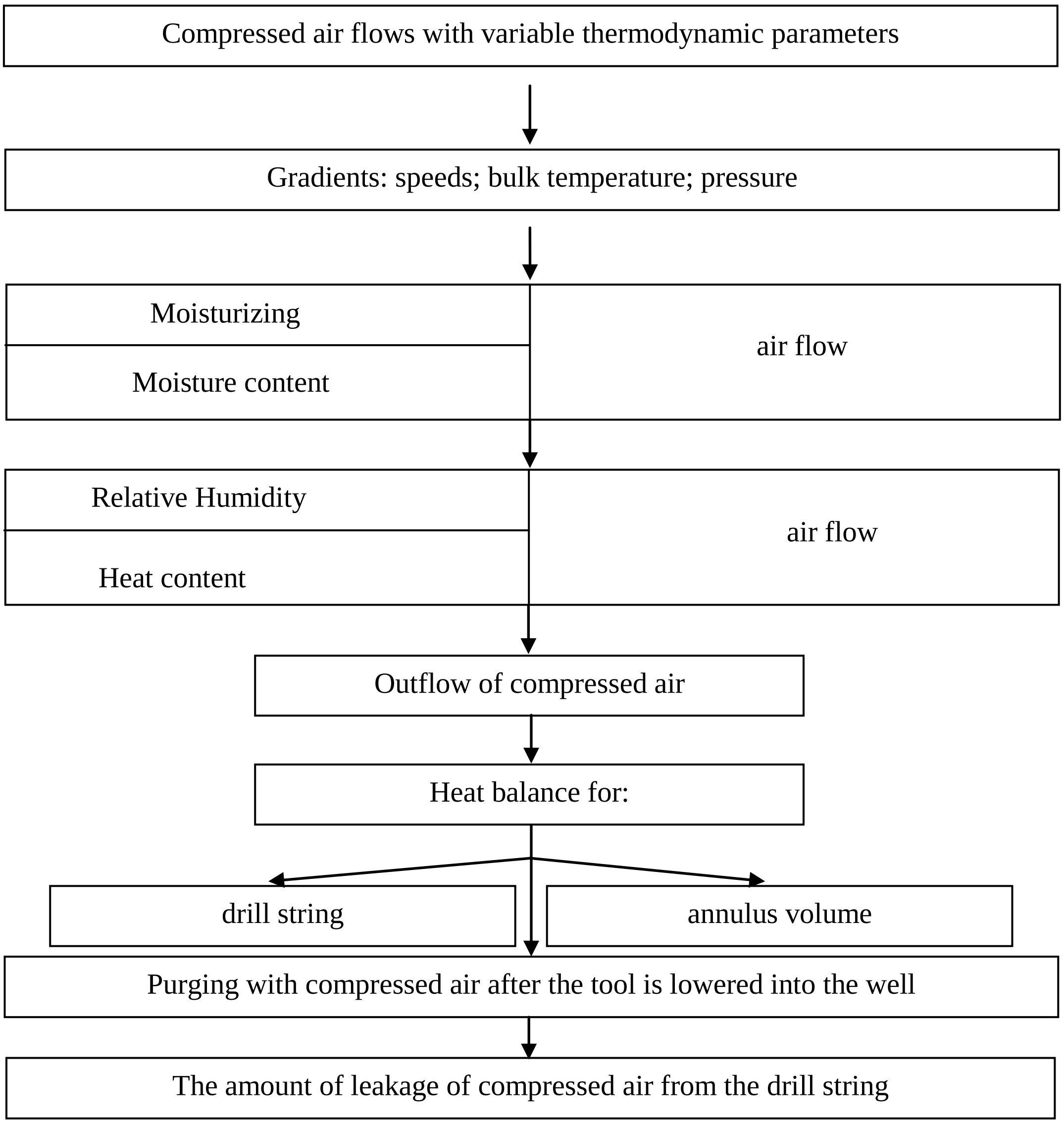

Figure 2 – Algorithm for estimating the heat balance of the drill string and its annular volume during their interaction with humidification by compressed air

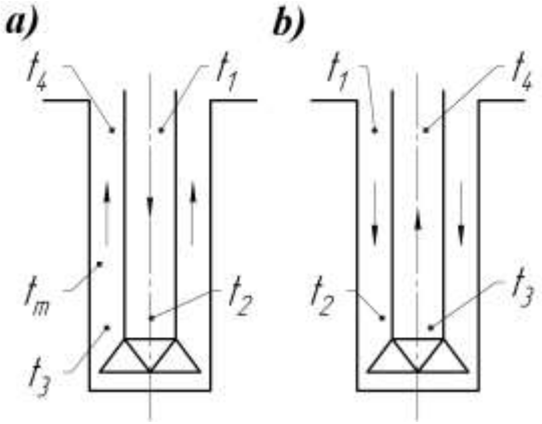

Figure 3 a, b – Schemes of direct (a) and reverse (b) blowing of the well with compressed air, taking into account its leakage: tm is the temperature of the air mixture in the annulus, resulting from the displacement of air coming from the bottom of the well in the amount of G_2, with air entering into annular volume directly from the drill string due to leakage through threaded connections in the amount of G_1 - G_2; $t_{1\ -4}$ - air temperature, respectively, at the inlet to the drill string, in front of the drilling tool, at the exit from the bottomhole and at the exit from their well; d_4 - moisture-containing jets at the exit of their well; $t_{p.sr}$ - average temperature of rocks along the depth of the well

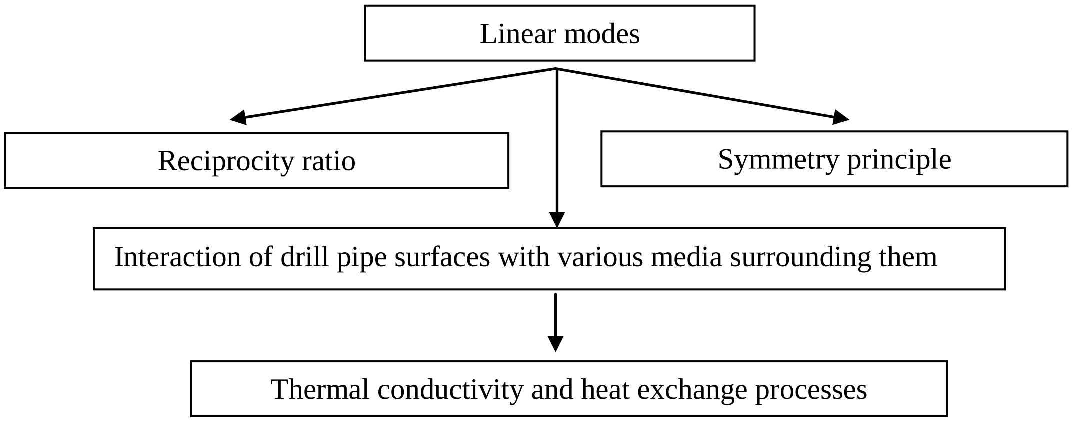

Figure 4 – Algorithm of non-equilibrium thermodynamics with linear regimes of energy loading of the pipe string during well drilling

Table 1 – Linear heat transfer coefficients in a multilayer structure of a drilling well

Heat exchange processes:	Estimated dependencies
«rock - annulus with mud»:	$K_1 = \dfrac{1}{\dfrac{\delta_1}{\lambda_1} + \dfrac{\lambda}{\alpha_1 d_1}}$; (1)
«annulus with mud – the outer surface of the column wall»:	$K_2 = \dfrac{1}{\dfrac{1}{\lambda_1 d_1} + \dfrac{\delta_2}{\lambda_2}}$; (2)
«the inner surface of the column wall - clay solution with rock»:	$K_3 = \dfrac{1}{\dfrac{\delta_2}{\lambda_2} + \dfrac{1}{\lambda_2 d_2}}$; (3)
Total heat transfer coefficient	$K = \dfrac{1}{\dfrac{1}{\lambda_1 d_1} + \dfrac{1}{2\lambda}\ln\dfrac{d_2}{d_1} + \dfrac{1}{\lambda_2 d_2}}$. (4)

Symbols: δ_i, λ_i, α_i – thicknesses, thermal conductivity and heat transfer coefficients of the corresponding layers of the multihierarchical structure of the drilling well.

Let us dwell on the determination of the linear heat transfer coefficients in the multi-layer structure of a drilling well (Table 1).

Dependence (1) is not completely included in expression (4), since it almost does not affect the numerical value of K [5].

The components included in dependence (4) are the thermal resistances of thermal conductivity (δ_i / λ_i) and heat transfer (1/ $\lambda_i d_i$).

The value of K_i is called the linear heat transfer coefficient; it characterizes the intensity of heat transfer from the fluid solution in the annulus to another fluid with rock through the drill string wall separating them.

The reciprocal of the linear heat transfer coefficient is called the linear thermal resistance to heat transfer:

$R_i = 1/k_l = 1/\alpha_1 d_1 + (1/2\lambda)\ln d_2/d_1 + 1/\alpha_2 d_2 = R_{ж1} + R_с + R_{ж2}$; (5)

R_l = measured in (m·K)/W.

The computational analysis [6] was performed with the following initial data: D = 0.28 m; d = 0.155 m; t_p = 48°C; t_1 = 23.6°C; t_2 = 35,3°C; thermal conductivity coefficients: rocks λ_1=2.56 W/(m ·°C); and steel pipe of the column λ_2 and λ_3 = 60 W/(m · °C); the heat transfer coefficient from the ascending and outgoing flows of the washing liquid was 175 W/(m·°C) and 256 W/(m·°C). In this case, the average linear heat transfer coefficient is 220 W/(m^2 ·°C).

In metal cylindrical pipes, the heat flux may differ in direction from the temperature gradient; a temperature gradient in one direction can cause heat flow in the other direction. Entropy production is determined by the expression [7]:

$$\sigma = \sum_{i=1}^{k} J_{qi} \frac{\partial}{\partial x_i}\left(\frac{1}{T}\right), \tag{6}$$

where J_{qi}–heat flow; x_i – cartesian coordinates; T – ambient volumetric temperature.

The heat flux for a discrete system of tribocoupling is determined from the expression

$$J_{qi} = \sum_k L_{ik} \frac{\partial}{\partial x_k}\left(\frac{1}{T}\right) = \sum_k \left(\frac{-L_{ik}}{T^2}\right)\frac{\partial T}{\partial x_k}, \tag{7}$$

where L_{ik} – Onsager's reciprocity.

For anisotropic solids, the thermal conductivity is a second rank tensor.

Fourier's law in this case is written as

$$J_{qi} = -\sum_k k_{ik} \frac{\partial T}{\partial x_k}, \tag{8}$$

Based on comparison (7) with (8), we obtain the equality

$$L_{ik} = T^2 k_{ik}. \tag{9}$$

The reciprocity relation $k_{ik} = k_{ki}$ then means that

$$k_{ik} = k_{ki}, \tag{10}$$

i.e., thermal conductivity is a symmetrical tensor. For many metal cylindrical pipes, their symmetry and their crystal structure imply that $k_{ik} = k_{ki}$.

However, this does not at all mean confirmation of the reciprocity relations, since it follows from the trigonal, tetragonal, and hexagonal symmetry of crystals that [8]

$$k_{12} = -k_{21}. \tag{11}$$

If the reciprocity relations are valid, then

$$k_{12} = k_{21} = 0. \tag{12}$$

Equation (12) implies that a temperature gradient in the x direction causes a heat flow in the positive y direction, but a gradient in the y direction causes a heat flow in the negative x direction. It follows from Onsager's reciprocity relation that the validity of the reciprocity relation is confirmed [10-12].

In table 2 and 3 show the quantitative ratios of velocity gradients, volumetric temperature and pressure during forward and reverse flushing of a drilled well with mud, as well as purging the annulus with compressed air after the tool is lowered into the well. The minimum ratio in both cases was observed for the pressure gradient, and the maximum for the velocity gradient.

The discussion of the results

Studies of non-equilibrium thermodynamics with linear regimes of parameter changes during the interaction of the surfaces of a drilling string of pipes based on the reciprocity relation and symmetry principles made it possible to establish the following [9]:

Table 2 – Parameters and their ratios during forward and reverse flushing of a drilling well

Gradients and ratios		Estimated dependencies
Onsager relations	Flow potential Gradients:	$\left(\frac{\Delta\phi}{\Delta p}\right)_{I=0} = -\frac{L_{12}}{L_{11}} = 0,95;$ (13)
	speed	$\left(\frac{V_1}{V_2}\right) = \frac{L_{12}}{L_{11}} = 0,97;$ (14)
	bulk temperature	$\left(\frac{T_1}{T_2}\right) = -\frac{L_{12}}{L_{22}} = 0,9;$ (15)
	pressure	$\left(\frac{p_1}{p_2}\right) = \frac{L_{12}}{L_{22}} = 0,89;$ (16)
Saxene ratios		$\left(\frac{\Delta\phi}{\Delta p}\right)_{I=0} = -\left(\frac{J_1}{J_2}\right)_{\Delta p=0} = 0,9;$ (17) $\left(\frac{\Delta p}{\Delta\phi}\right)_{J=0} = -\left(\frac{J_2}{J_1}\right)_{\Delta\phi=0} = 0,98.$ (18)

Table 3 - Parameters and their ratios when blowing with compressed air after the tool is lowered

Parameters and ratios		Estimated dependencies
Onsager relations	Flow potential Gradients:	$\left(\frac{\Delta\phi}{\Delta p}\right)_{I=0} = -\frac{L_{12}}{L_{11}} = 0,9;$ (19)
	speed	$\left(\frac{V_1}{V_2}\right) = \frac{L_{12}}{L_{11}} = 0,95;$ (20)
	bulk temperature	$\left(\frac{T_1}{T_2}\right) = -\frac{L_{12}}{L_{22}} = 0,92;$ (21)
	pressure	$\left(\frac{p_1}{p_2}\right) = \frac{L_{12}}{L_{22}} = 0,9;$ (22)
Saxene ratios		$\left(\frac{\Delta\phi}{\Delta p}\right)_{I=0} = -\left(\frac{J_1}{J_2}\right)_{\Delta p=0} = 0,9;$ (23) $\left(\frac{\Delta p}{\Delta\phi}\right)_{J=0} = -\left(\frac{J_2}{J_1}\right)_{\Delta\phi=0} = 0,92.$ (24)

An algorithm for estimating the heat balance of the drill string and its annulus during their interaction with humidified compressed air is proposed. An algorithm of non-equilibrium thermodynamics with linear regimes of energy loading of a pipe string during well drilling is considered. Carried out computational analysis with the following initial data: D = 0.28 m; d = 0.155 m; t_p=48°C; t_1 = 23.6°C; t_2 = 35.3°C; thermal conductivity coefficients: rocks λ_1=2.56 W/(m·°C); and steel pipe of the column λ_2 and λ_3=60 W/(m·°C); the heat transfer coefficient from the ascending and outgoing flows of the washing liquid was 175 W/(m·°C) and 256 W/(m·°C). In this case, the average linear heat transfer coefficient is 220 W/(m^2·°C); when the well is purged with compressed air, the average linear heat transfer coefficient is 95 W/(m^2·°C); the bulk temperature gradient for mud at the bottom of a 100 m long drill string was 0,03 °C/m. From the above parameters, ratios are formed that are equal to the Onsager and Saxen ratios, which makes it possible to determine the parameters by calculation.

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