MUD-PUMP PRESSURE IN GEOTHERMAL WELLS

TLAK IZPLAČNE ČRPALKE PRI GEOTERMALNIH VRTINAH

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Ključne besede

hidravlika vrtanja, tlak črpalke, izplaka, reološki modeli, geotermalna energija

Abstract

Rotary drilling is a mining method for the extraction and exploration of mineral resources. A significant pressure drop occurs during deep-well rotary drilling. This paper presents a procedure and a theoretical background of the working-pump-pressure determination for exploration geothermal borehole Sob-4g, located in Murska Sobota, NE Slovenia. We determined all the partial pressure drops in the mud-circulation system when drilling the final section of a 1201.15-m-deep borehole. For this, it is important to choose the correct rheological model that follows the behaviour of the drilling fluid. In the presented case, the Bingham plastic model was used. The aim of the paper's hydraulic analysis is to provide the optimal drilling parameters and therefore the maximum effects in deep-well drilling. We show that most of the drilling mud-pressure energy is consumed within the drill string and through the bit. The fluid-flow regime in the drill pipes, collars and drill bit is turbulent, while it is laminar in the annulus.

Izvleček

Rotacijsko vrtanje je rudarska metoda za pridobivanje in raziskovanje mineralnih surovin. Med rotacijskim vrtanjem globokih vrtin prihaja do občutnega padca tlaka. V prispevku je predstavljen postopek in teoretično ozadje določanja delovnega tlaka črpalke za raziskovalno geotermalno vrtino Sob-4g, ki se nahaja v Murski Soboti, SV Slovenija. Določili smo vse delne padce tlaka v izplačnem sistemu pri vrtanju končnega odseka 1201,15 m globoke vrtine. Za to je pomembno izbrati pravilen reološki model, ki sledi obnašanju izplačnega fluida. V predstavljenem primeru je bil uporabljen Binghamov plastični model. Cilj hidravlične analize prispevka je zagotoviti optimalne parametre vrtanja in s tem največje učinke pri vrtanju globokih vrtin. Večina tlačne energije izplake se porabi znotraj drogovja in preko dleta. Režim pretoka izplačnega fluida v vrtalnem drogovju, težkem drogovju in dletu je turbulenten, medtem ko je v medprostoru laminaren.

1 INTRODUCTION

Deep wells are most commonly drilled for oil and gas extraction or the use of geothermal energy. One of the most important elements in the drilling process is the drilling mud. It is a fluid that performs numerous functions, including carrying the rock fragments to the surface, providing hydrostatic pressure in the well and cooling the drill bit. The mud circulation is provided by mud pumps via a suitable working pressure and flow rate. The pump pressure provides sufficient energy for the mud circulation, while the flow rate enables the transport of the drilled cuttings to the surface.

The drilling fluid circulates in the mud system. It starts at the surface and runs downwards through the drill string and the drill bit and upwards in the annulus between the drill string and the borehole wall, back to the surface. The pressure energy from mud pump is mostly consumed in overcoming the internal friction in the drill string and for the fluid acceleration through the bit nozzles. There is a significant local reduction of the diameter in the bit nozzles, which leads to a large increase in the fluid kinetic energy and, therefore, the fluid velocity. Consequently, the bit nozzles are areas with a drastic pressure drop. Increasing the kinetic energy at the drill bit means a higher hydraulic power, which reflects in a better cutting action and a more efficient cleaning of the drilled particles beneath the bit.

Determining the working pump pressure (WPP) is an important element of the drilling hydraulics and represents an indispensable part of the deep-well design. The WPP is defined as the sum of all the partial pressure drops. Therefore, all the pressure drops in the mud circulating system have to be known. The WPP increases with an increasing drilling depth.

2 DRILLING PROCESS TECHNOLOGY

A borehole is drilled using a drilling rig, which is a set of machines, devices and elements that are necessary for the drilling process. The drilling process is a sequence of the following operations:

1) Connecting the drill pipes, drill collars and the drill bit.
2) Lengthening the drill pipes and lowering the drill bit into the borehole bottom.
3) Drilling bit action (drilling) with the simultaneous carrying of drill cuttings to the surface.
4) Connecting additional drill pipes due to the bit progress in depth.
5) Rising of the drill string from the borehole (for example, due to the wear of the drill bit).

The rock at the borehole bottom is cut using the rotation of the roller cone bit, which is attached to the end of the drill collars and affected by its load. The roller cone bit rotates together with the drill string, cutting the rock beneath it. The transport of the drilled cuttings from the borehole bottom to the surface goes via the mud fluid [1].

Three main components of the deep well drilling are:

1) Weight on the bit.
2) Bit rotation.
3) Circulation of the drilling fluid.

3 DRILLING FLUID

The mud or the drilling fluid is a liquid used in the drilling process that continuously circulates from the surface downwards through the drill pipes and bit nozzles and upwards to the surface through the annular space between the drill pipes and the borehole wall.

We can distinguish between the major and minor functions of the drilling fluids. The major functions are, in general, the removal of the drilled cuttings, the containment of the subsurface formation fluid pressures and the borehole stabilization. Minor functions, including the cooling and lubricating of the drill string and drill bit, preventing particle sedimentation at the mud-circulation stop, and reducing the weight during the drill string operations (buoyancy), aid in the formation evaluation and cleaning of the drill bit [2].

Removing the cuttings beneath the drill bit is necessary for progress in the drilling process. This is achieved by the flow of drilling fluid through the annular space between the borehole wall and the drill string. Removal of the cutting particles depends on the annular mud velocity, the mud rheological properties, the borehole deviation, the rotation of the drill string, the borehole eccentricity, the drilling rate and the size and shape of the drilled cuttings [2].

A sufficient mud density prevents the intrusion of the formation fluids into the borehole. The mud density is achieved with additives (for example, barite). Clay is added, for example, for a higher viscosity of the mud. The drilling regime is, in most cases, over-pressured, which means that the pressure gradient is greater than 9.8 kPa per meter of well depth.

4 MUD PUMPS

A mud pump provides enough energy for the pressure of the fluid across the circulating system. Mud-pump engines can produce around 1600 kW of power with flow rates of up to 5000 l/min and pressures of up to $600 \cdot 10^5$ Pa. Generally, there are two types of reciprocating mud pumps: duplex and triplex.

4.1 Duplex pump

The principle of a double-acting, two-cylinder (duplex) pump is schematically shown in Fig. 1. As the piston moves forward (to the right-hand side in Fig. 1), it discharges fluid through the open discharge valve. At same time, the intake valve is opened, allowing fluid to enter the chamber behind the piston. There is a reversible principle as the piston returns (see Fig. 2) [3].

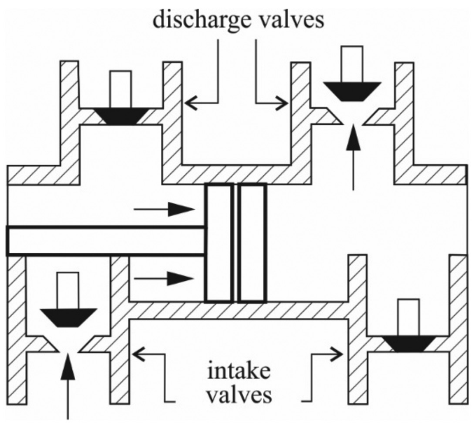

Figure 1. Duplex pump (piston moves forward).

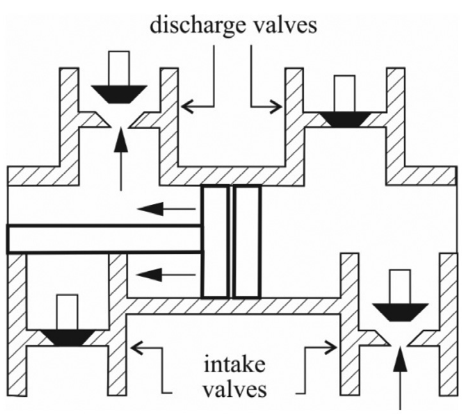

Figure 2. Duplex pump (piston moves backward).

Theoretical volume when the piston moves forward:

$$V_1 = \frac{\pi d^2 L}{4} \qquad (1)$$

where V_1 is the volume of the discharged fluid when the piston moves forward (m^3), d is the inner diameter of the piston cylinder (m) and L is the piston stroke (m).

When the piston returns, the theoretical volume of the discharged fluid is:

$$V_2 = \frac{\pi (d^2 - d_r^2) L}{4} \qquad (2)$$

where V_2 is the volume of the discharged fluid when the piston moves backwards (m^3) and d_r is the piston-rod diameter (m).

The total volume of discharged fluid in one crankshaft stroke is:

$$V = 2(V_1 + V_2)\,\eta_v = \frac{2\pi (2d^2 - d_r^2) L \eta_v}{4} \qquad (3)$$

where η_v is the volumetric efficiency of the pump (/).

4.2 Triplex pump

The principle of a single-acting, three-cylinder (triplex) pump is schematically shown in Fig. 3. With this pump the piston discharges fluid in only one direction.

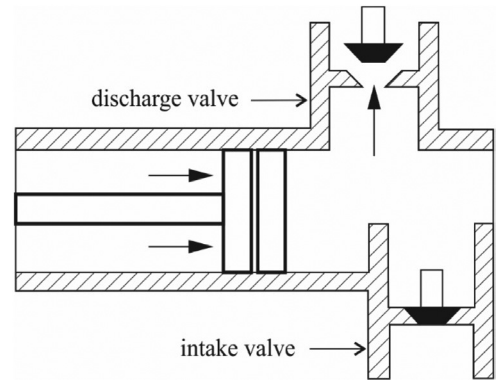

Figure 3. Triplex pump (piston moves forwards).

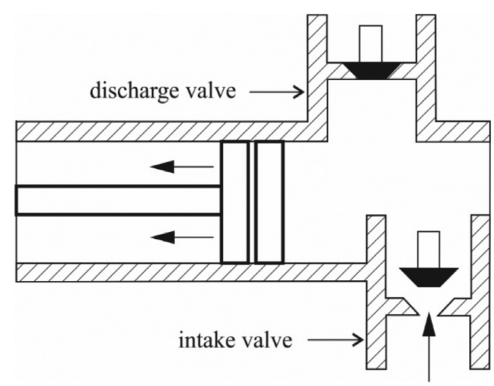

Figure 4. Triplex pump (piston moves backwards).

The total volume of discharged fluid in one crankshaft stroke is:

$$V = \frac{3\pi d^2 L \eta_v}{4} \qquad (4)$$

5 RHEOLOGICAL MODELS

There are significant resistance forces to overcome in a mud-circulation system. Rheological models, used as an approximation for the fluid behaviour, are in general Newtonian (linear) and non-Newtonian (non-linear). These models are used to derive the pressure-drop equations.

5.1 Newtonian model

A Newtonian fluid is ideally viscous. It follows a linear relation between the shear stress (τ) and the speed of the shear deformation-shear rate ($\dot{\gamma}$).

$$\tau = \mu\dot{\gamma} \qquad (5)$$

where τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}) and μ is the Newtonian viscosity (Pa s).

Examples of a Newtonian fluid are water, oil and gas.

The linear relationship between the shear stress and the shear rate is valid only as long as the fluid moves in layers or laminae. This is true only at relatively low rates of shear. When turbulent flow occurs, pressure drops have to be determined with empirical correlations [4].

5.2 Non-Newtonian models

Non-Newtonian fluids are real. They do not exhibit a direct proportionality between the shear stress and the shear rate [4]. Shear-dependent non-Newtonian fluids are pseudoplastic (shear thinning) if the apparent viscosity decreases with an increasing shear stress and dilatant (shear thickening) if the apparent viscosity increases with an increasing shear stress. Drilling fluids and cement slurries are generally thixotropic, which means that they are pseudoplastic and have a time-dependent viscosity [4].

Fluids with plastic flow behaviour (Bingham fluids) start to flow when the limit shear stress is exceeded. When the shear flow is established, fluids with plastic flow behaviour show a linear dependence of the shear stress and the shear rate. In this case the Newtonian model is valid.

The Bingham model represents a rigid matter that starts to flow as a viscous fluid when the yield strength is exceeded. After this, it behaves as a Newtonian fluid. A Bingham fluid is typical for bentonite muds. The rheological model is defined by:

$$\tau = \mu_{pl}\dot{\gamma} + \tau_0 \qquad (6)$$

where μ_{pl} is the plastic viscosity (Pa s) and τ_0 is the yield strength (Pa).

The Ostwald-de Waele model is defined as a power law:

$$\tau = K|\dot{\gamma}|^{n-1}\dot{\gamma} \qquad (7)$$

where K is the flow-consistency index (Pa s) and n is the flow-behavior index (/).

Like in the Bingham model, the equation consists of two parameters: K and n. A higher K means a higher viscosity of the fluid. The deviation of parameter n from 1 is a criterion for the fluid deviation from a Newtonian fluid. In the case when n=1, the fluid follows the Newtonian law, if K=μ. It behaves pseudoplastically (viscosity decreases with increasing shear stress) when n<1 and dilatantly (viscosity increases with increasing shear stress) when n>1. The equation is valid in the laminar-flow region.

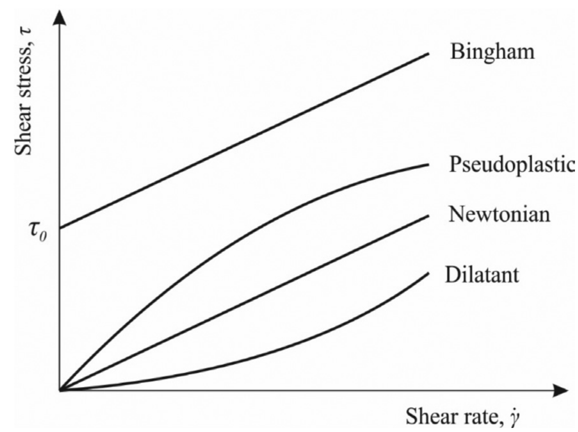

Figure 5. Rheological models.

6 PRESSURE DROPS

6.1 Generally about pressure drops

When flowing in a pipe, a fluid losses part of its energy due to the friction/resistance forces. These forces are internal friction due to the viscosity and external friction due to pipe roughness [5].

A circulating drilling mud has an initial energy represented by the pump-discharge pressure. This energy is totally lost in the mud circuit. The mud pressure is zero when it returns to the pits. In this case, the pump-discharge pressure represents the total pressure losses in the mud circuit [5].

When drilling, pressure drops occur in the following areas: surface equipment, drill pipes and drill collars, drill bit and annulus between the well bore and the drill string. Pressure drops in the drill string and annulus do not directly contribute to the drilling process, but cannot be avoided if the fluid is to be circulated around the system. Pressure drops in drill bit, on the other hand, do perform a useful function, since it helps to cut rock and clean the drilled cuttings from the face of the bit.

It is, therefore, desirable to optimize the pressure drops through the nozzles (and therefore the cleaning of the bit face) and minimize the drops in the drill string and annulus [3].

The pump pressure (p_p) is expended by: frictional pressure losses in the surface equipment (p_s), frictional pressure losses in the drill pipes (p_{dp}), frictional pressure losses in the drill collars (p_{dc}), pressure losses through the bit nozzles (p_b), frictional pressure losses in the drill-collar annulus (p_{dca}) and frictional pressure losses in the drill-pipe annulus (p_{dpa}) [4].

$$p_p = \Delta p_s + \Delta p_{dp} + \Delta p_{dc} + \Delta p_b + \Delta p_{dca} + \Delta p_{dpa} \qquad (8)$$

The total frictional pressure loss can be represented as p_f:

$$p_p = p_b + p_f \qquad (9)$$

It is evident from the equation that the working pump pressure is consumed for the fluid acceleration in the bit nozzles and overcoming the flow resistance in drill pipes and the annulus.

Pressure drops depend on the rheological properties of the mud, the flow type (laminar or turbulent) and the geometry of the pipes and the well bore.

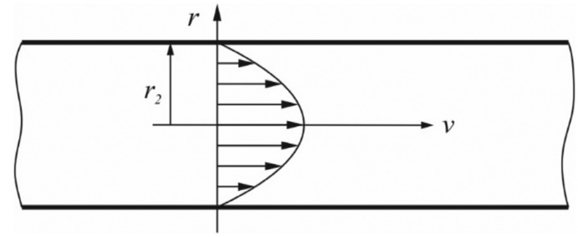

Figure 6. Mud-velocity profile for flow in a pipe (r_2 is the radius of the pipe).

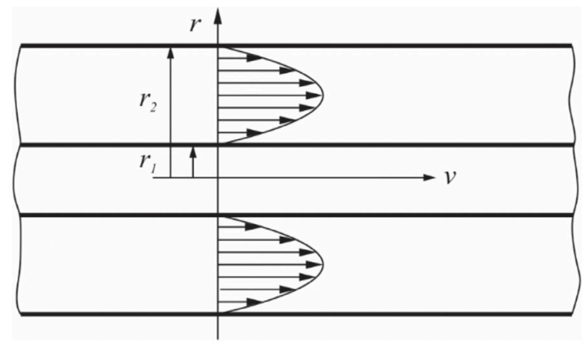

Figure 7. Mud-velocity profile for the flow in an annulus (r_1 is the radius of the pipe, r_2 is the radius of the borehole).

6.2 Laminar flow in the drill string and annulus

The flow type, within which the fluid flows in the drill string or annulus, depends on the Reynolds number (N_{Re}). It is defined as (for pipe flow):

$$N_{Re_p} = \frac{\rho \bar{v} d_i}{\mu} \qquad (10)$$

where ρ is the mud fluid density (kg/m^3), $\bar{v}$ is the fluid average velocity (m/s) and d_i is the pipe inner diameter (m).

For annular flow:

$$N_{Re_a} = \frac{\rho \bar{v}(d_b - d_o)}{\mu} \qquad (11)$$

where d_b is the borehole diameter (m) and d_0 is the pipe outer diameter (m).

In the case when the density and viscosity of the drilling mud are constant, the Reynolds number depends only on the pipe diameter and the mud velocity. If the flow rate is constant, the Reynolds number depends only on the pipe diameter. The value of the Reynolds number is not constant across the whole mud system, but it changes. Thus, the mud flow can be laminar at one point and turbulent at another.

The Newtonian fluid flow is laminar if N_{Re} is less than 2100 and turbulent if N_{Re} is more than 2100. Actually, when N_{Re} values are in region 2000–4000, the flow is in a transition between laminar and turbulent flow.

Fluid flow in the drill string or annulus do not have a uniform velocity. In the case of laminar flow, the fluid velocity by the wall pipe equals zero. The velocity is the highest at the maximum distance from the pipe wall, which is in the center of the pipe.

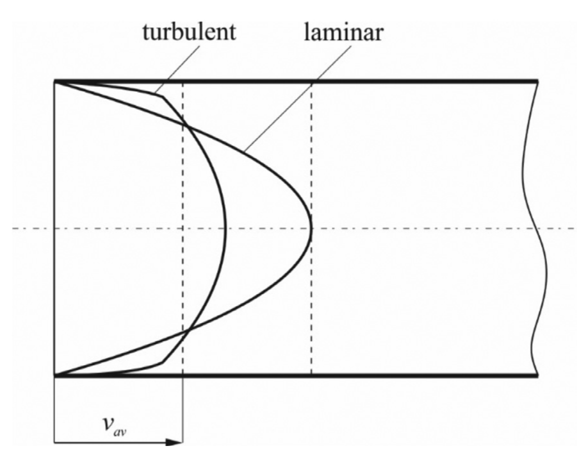

Figure 8. Laminar and turbulent velocity profiles.

Velocity profiles for laminar flow in the pipe annulus are shown in Fig. 6 and Fig. 7. Pipe flow represents the flow from the surface to the bit and annular flow represents the flow from the drill bit back to the surface.

Fig. 8 shows the velocity profile of a circular pipe (laminar and turbulent flow). The maximum velocity in the case of turbulent flow is $v_{max,t} = (1.15\ldots1.25)v_{av}$ and in the case of laminar flow $v_{max,l} = 2v_{av}$, where v_{av} represents the average velocity [6].

6.3 Turbulent flow in the drill string and annulus

High velocities of flow rates mean that the fluid does not flow in layers, but in a chaotic way. Turbulent flow can be divided into three regions: the laminar flow, the transition between laminar and turbulent flow and the turbulent core.

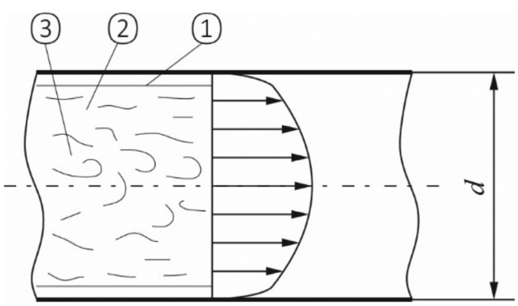

Figure 9. Turbulent flow in a pipe (1 thin layer of laminar flow, 2 transition layer, 3 turbulent core; *d* is the diameter of the pipe).

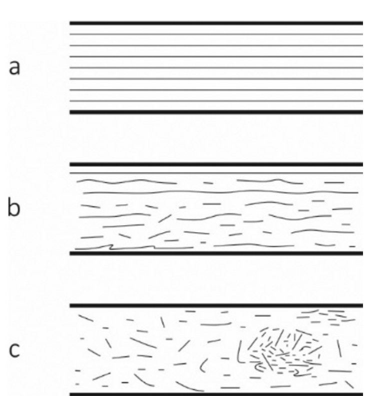

Figure 10. Laminar and turbulent flow patterns in a circular pipe (a - laminar flow, b - transition between laminar and turbulent flow, c - turbulent flow).

When calculating pressure drops in drill pipes and annulus, the type of fluid must be known (Newtonian, non-Newtonian). The flow type is determined with a calculation of the critical velocity, which depends on the rheological parameters of the mud.

There are some assumptions in calculating the pressure drops. These are: drill pipes are placed into the well concentric, drill pipes do not rotate, well bore is circular in shape with known diameter, mud fluid is incompressible, the flow is isothermal and the pipes are smooth. For this reason, the equations contain some experimentally determined factors.

6.4 Pressure drop in drill string and annulus

The equations for the pressure-drop calculation in the pipe and the annular space are given as follows, according to the Fanning equations [7].

For pipe flow:

$$\Delta p_i = \frac{2f\rho L v^2}{d_i} \qquad (12)$$

where Δp_i is the pipe pressure drop (Pa), f is the hydraulic friction factor (/) and v is the flow rate (m/s).

For annular flow:

$$\Delta p_a = \frac{2f\rho L v^2}{d_b - d_o} \qquad (13)$$

where Δp_a is the annular pressure drop (Pa).

6.5 Pressure drop in bit nozzles

The purpose of bit nozzles is a better cleaning action of the drilling fluid at the bottom of the hole. Because of the small diameter of the bit nozzles, fluids reach high velocities inside the nozzle [8]. The nozzle velocity is defined as:

$$v_n = \frac{q}{A_t} \qquad (14)$$

where v_n is the nozzle velocity (m/s), q is the mud flow rate (m^3/s) and A_t is the total nozzle area (m^2).

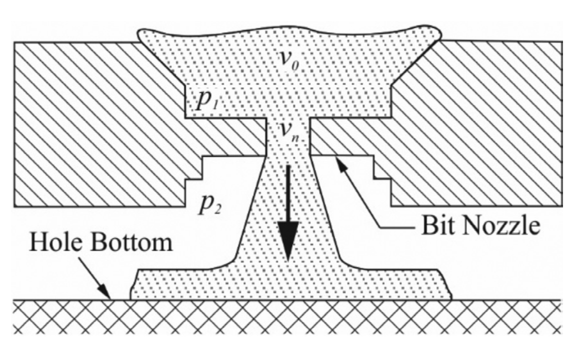

Figure 11. Drill bit nozzle (v_0 and p_1 are the mud fluid input velocity and pressure, v_n and p_2 are the mud fluid output velocity and pressure).

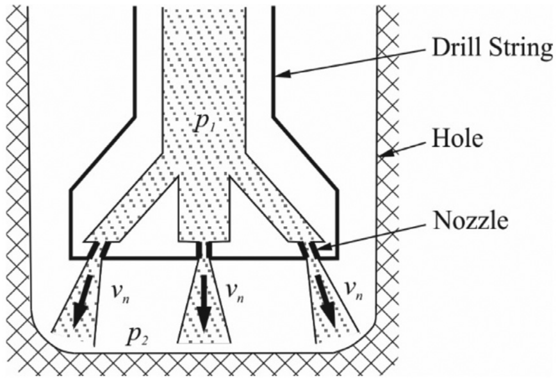

Figure 12. Drill bit with three nozzles.

Fluid flow through bit nozzles is shown in Fig. 11. The input velocity v_0 is negligible compared to the output velocity v_n. Fluid acceleration occurs due to the local reduction of the diameter in the nozzles. Kinetic energy increases, while the pressure energy decreases. Consequently, a pressure drop occurs at the bit nozzles. The pressure drop is defined by [8]:

$$\Delta p_b = \frac{\rho q^2}{2C^2 A_t^2} \qquad (15)$$

where *C* is the nozzle-discharge coefficient (/).

7 EXPERIMENTAL

An exploratory geothermal borehole (EGB) Sob-4g was constructed with the aim of exploring potential geothermal aquifers for the reinjection of cooled thermo-mineral water from the Sob-3g borehole back into the production aquifers.

A reinjection system, which consist of a geothermal reinjection well and the surface reinjection unit, is a necessary part for returning the water to the production aquifer [9].

EGB Sob-4g is located in Murska Sobota close to the existing geothermal boreholes Sob-1 and Sob-2, which exploit the thermo-mineral water for district heating and balneology.

In general, geothermal energy in Slovenia is utilized for individual space heating, district heating, cooling, greenhouse heating, bathing, swimming and snow melting [10].

EGB Sob-4g is 1201.15 m deep. Drilling has been made through geological formations of Mura and Lendava. Drilling has stopped at the upper part of the Murska Sobota formation. In the first section (0–580.73 m) bentonite drilling mud and in second section (580.73–1201.15 m) polymer drilling mud were used.

The EGB Sob-4g location belongs to one of six regional numerical models of groundwater flow in Slovenia [11].

7.1 Borehole construction

The borehole is constructed in two stages. The first stage consists of drilling the first section (from 0.00 m to 580.73 m) and the casing. The second stage consists of drilling the second section (from 580.73 m to 1201.15 m).

Table 1. Drilled intervals.

Section	Drilled interval (m)	Bit diameter (mm)
1	0.00–580.73	444.50
2	580.73–1201.15	311.20

Table 2. Casing intervals.

Section	Casing interval (m)	Casing diameter (mm)
1	0.00–578.25	339.70
2	530.30–1201.00	177.80

Table 3. Drilling equipment for second stage drilling.

Drilling Equipment		Length (m)
drill bit	311.15 mm HUGES, IADC 135 GTX-G3; nozzles 3×10.32 mm	0.30
1. stabilizer	Ø 311.15 mm	1.21
drill collar	Ø 165.1 mm	8.47
2. stabilizer	Ø 311.15 mm	1.49
drill collar	Ø 165.1 mm	8.90
3. stabilizer	Ø 311.15 mm	1.39
drill collar	Ø 165.1 mm	78.98
transition pipe	101.6 mm IF (male) × 101.6 mm IF (female)	0.28
drill pipe	Ø 127.00 mm, 29 kg/m, 114.3 mm IF	524.49
transition pipe	114.3 mm IF (male) × 101.6 mm FH (female)	0.61
drill pipe	Ø 101.60 mm, 22.6 kg/m, 101.6 mm FH	568.83
kelly	hexagonal; thread 88.9 mm IF (male)	8.2

All the pressure drops during drilling at the final depth (1201.15 m) are determined. At the final depth the maximum pressure drop that the mud pump has to overcome is expected.

In Table 3 the drilling equipment in the borehole is listed. Individual tools are described from the borehole bottom to the top. It means that the drill bit is located at the borehole bottom, followed by sections of stabilizers and drill collars, a transition pipe, drill pipes and a kelly at the borehole surface.

Table 4. Calculation input data – borehole construction.

Section	Length (m)	Hole/ Casing diameter (m)	Drill String type	Drill String – outer diameter (m)	Drill String – inner diameter (m)
1	525	0.318	drill pipe	0.127	0.109
2	53	0.318	drill pipe	0.102	0.085
3	516	0.311	drill pipe	0.102	0.085
4	97	0.311	drill collar	0.165	0.076

Table 4 represents the input data for calculation of the pressure drops. The borehole is divided into four sections. The first three sections are equipped with drill pipes and the fourth section with drill collars.

Table 5. Calculation input data – mud properties.

ρ (kg/m^3)	1150
τ_0 (Pa)	13
μ_{pl} (10^{-3} Pa s)	22
q (m^3/s)	0.0183

For the working pump pressure determination, all the partial pressure drops have to be calculated.

The pressure drop in the surface equipment is estimated to be $3{\cdot}10^5$ Pa (from Drilling Data Handbook).

The calculation of all the other pressure drops is made relating to the calculation input data, shown in Table 4 and Table 5. Equations for the Bingham rheological model are used.

8 RESULTS

The pressure drop in the drill string (drill pipes and drill collars) is $18.741{\cdot}10^5$ Pa, in the annular space $3.239{\cdot}10^5$ Pa, in the drill bit $38.427{\cdot}10^5$ Pa and in the surface equipment $3{\cdot}10^5$ Pa. The total pressure drop is $63.4{\cdot}10^5$ Pa. The mud pump has to provide a minimum of $63.4{\cdot}10^5$ kPa of pressure at a flow rate of 0.0183 m^3/s (1100 l/min).

Fig. 13 shows the dependency of the pressure drop versus the well bore depth and the type of equipment.

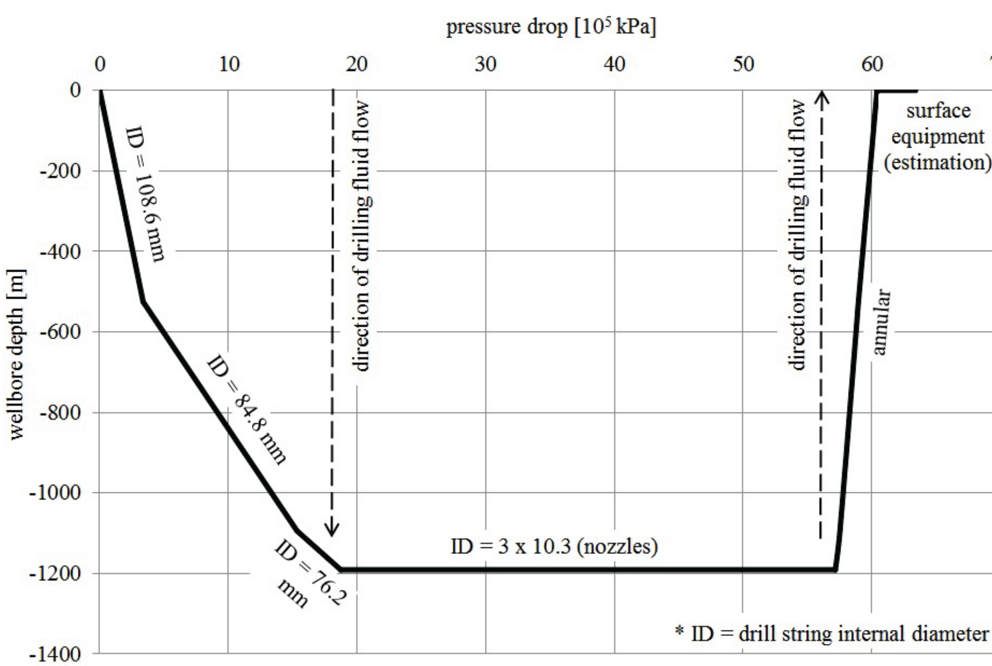

Figure 13. Pressure drop versus well bore depth. The direction of the drilling fluid flow follows the black line from the left- to the right-hand side of the diagram.

Table 6. Pressure drop in drill pipes and drill collars (mud fluid moves in the downwards direction).

Section	Fluid velocity (m/s)	Critical velocity (m/s)	Fluid flow type	Pressure drop (10^5 Pa)
1	1.978	1.913	turbulent	3.371
2	3.242	1.971	turbulent	1.114
3	3.242	1.971	turbulent	10.844
4	4.019	2.002	turbulent	3.413

Table 7. Pressure drop in annular space (mud fluid moves in upwards direction).

Section	Fluid velocity (m/s)	Critical velocity (m/s)	Fluid flow type	Pressure drop (10^5 Pa)
1	0.270	1.686	laminar	1.444
2	0.253	1.670	laminar	0.128
3	0.270	1.676	laminar	1.307
4	0.336	1.731	laminar	0.360

Table 8. Pressure drop at drill bit (mud fluid moves in downwards direction).

Nozzle number	Nozzle diameter (mm)	Fluid velocity (m/s)	Pressure drop (10^5 Pa)
1	10.32	73.113	38.427
2	10.32		
3	10.32		

The fluid actual and critical velocities in the drill string are shown in Table 6. It is evident that in all four sections of the borehole, the fluid flow type is turbulent because the actual velocity exceeds the critical velocity. In contrast, actual fluid velocities in the annular space are significantly lower than the critical velocities. Consequently, the fluid flow type is laminar, as shown in Table 7.

The maximum pressure drop occurs in the drill pipes and the drill-bit nozzles. In the shown experimental case, the pressure drop in the drill bit equals 61 % and the pressure drop in the drill pipes equals 29 % of all the pressure drops. Other pressure drops arise in the surface equipment and the annular space. They are negligible.

Fluid-flow type through the drill pipes (drill string and drill collars) and the drill bit nozzles is turbulent. The fluid flow type in the annular space is laminar. Fluid velocities in the drill pipes are in range 1 m/s to 5 m/s, depending on the inner diameter of the drill pipe. The drill bit nozzle output velocity exceeds 70 m/s. The drill bit pressure drop (61 % of all the pressure drops) is in range of hydraulics optimization and therefore suitable.

9 CONCLUSIONS

In this article, deep drilling hydraulics and pressure drops have been studied in order to determine the working pressure of a mud pump. Based on the governing equations of Bingham non-Newtonian fluid flow, a numerical method has been used to calculate all the pressure drops while drilling the final section of the exploratory geothermal borehole Sob-4g, located in Murska Sobota, NE Slovenia.

The results of the numerical analysis shows where the areas of maximum pressure drops in the deep well drilling are to be expected.

The majority of the pressure drop occurs in the drill bit nozzles and the drill pipes. The fluid flow is turbulent in both of these regions. The pressure drops in the annular space and the surface equipment is minimal. They are negligible in comparison with the pressure drops in the pipes and the drill bit.

The contribution of this article can be placed in the wider context of geothermal energy usage development. With the use of the described model for determining the pressure drops in a deep geothermal borehole, it is shown how we can predict the hydraulic state within the borehole during the process of drilling.

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