Selection of parameters for mud pumps used for HDD Systems

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Výber parametrov kalových výplachových čerpadiel používaných pre HDD systémy

Design solutions of rigs used for HDD are presented in the paper. HDD devices are classified on the basis of presented criteria, and then a division of rigs was proposed. The principles of determining technological parameters of piston mud pumps for HDD are presented. The principles of determining volume flow rate for an arbitrary rheological model of drilling mud are discussed. The dependences enabling a calculation of resistance of drilling fluid flow in a circulation system are also presented.

Key words: *Horizontal directional drilling, drilling rigs, mud pumps selection*

Introduction

Trenchless techniques and technologies are more and more frequently applied for underground gas-, water-, sewage-, heating-, electric power- and telecommunications pipelines constructions. HDD technologies occupy a prominent position among the trenchless construction methods. Constant technical advancement enables construing modern, fully automized and miniaturized rigs for drilling boreholes of changing trajectory [4,5,6]. At the stage of design and performance of a well it is important to properly select subassemblies of the HDD rig.

Drilling rigs used for HDD technologies

The presently applied World's drilling design solutions for HDD are a result of years of theoretical and practical development in the directional drilling. The rig designs differ in the transport, drive of the drilling head's stem, the power and the drilling mud system.

Among the most important technological technical parameters of HDD equipments are: the kind of drive, available power, the hoist and push force, the torque, the maximal rotary speed of stem, the pressure and pumping rate of a mud pump, geometrical dimensions and the design properties of drilling rods.

Having analyzed the design solutions of HDD rigs produced over the world, as well as the personal experience, we propose the following classification of rigs (Tab. 1):

Tab. 1. Division of HDD rigs.

Category of rig	Type of rig	pull/push force [kN]	Torque [Nm]	Power of equipment [kW]	Max. pumping rate of mud pump [L/min]	Diameter of pipes [Mm]
1.	very low	< 100	< 2500	< 75	100	< 60
2.	low	100 ÷ 250	<2500 ÷ 15000	75 ÷ 150	500	60 ÷ 89
3.	average	250 ÷ 500	15000 ÷ 25000	150 ÷ 300	1000	89 ÷ 127
4.	high	500 ÷ 1000	25000 ÷ 50000	300 ÷ 600	1500	127 ÷ 140
5.	very high	> 1000	> 50000	> 600	>1500	127 ÷ 168

Selection methodics of mechanical parameters of HDD equipment

To provide a reliable realization of horizontal drilling processes, it is crucial to have a rig with appropriate technical parameters.

At the Department of Drilling and Geoengineering, Faculty of Drilling, Oil and Gas AGH-UST, recommendations for the HDD equipment selection have been worked out. The proposed methodics encompasses the determination of minimal technical-technological requirements which should be met by a HDD rig and the string to minimize the risk of a failure or complications when drilling a horizontal borehole.

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The following parameters are determined at the stage of analyses:

- minimal hoist force, torque and power of the rig,
- geometric and material parameters of mud pipes,
- minimal drilling mud rate and pressure of mud pumps.

The hoist force, torque and the power of the rig are presented in the paper [7]. The selection of geometric and material parameters of mud pipes, accounting for the expected intensity of spatial deflection of a HDD axis trajectory was described in [3].

The selection principles of technical parameters of piston mud pumps for HDD are presented in this paper. The minimal value of the drilling mud rate and minimal pressure of mud pumps should be determined at each stage of realization of the HDD, i.e. when drilling a pilot borehole, reaming, accounting for the removal of the casing pipe.

Determination of the drilling mud pumping rate

In a majority of cases, HDD are performed in loose ground and rocks (Quaternary strata). To provide a reliable drilling and maximal protection for the open wall of the borehole against the erosive activity of drilling mud, three conditions should be met:

a. clearing the borehole from the cuttings
b. providing laminar flow of re-pumped fluids in the annular space
c. maintaining suitable pressure in the annular space, less than the pressure of the overburden ground and rocks.

On the condition of cleaning the borehole from the cutting it is possible to determine minimal mud flow rate enabling removal of the cuttings at each stage of the borehole performance.

Conditions: laminar character and maintaining appropriate pressure values in the annular space between the rods and the borehole's walls.

Cleaning the borehole from the cuttings

The drilling mud pumped to a horizontal HDD should enable a removal of cuttings from the borehole. Its flow rate depends on the drilling technology and the amount of the cuttings. The minimal value of the drilling mud flow rate should be determined from the formula:

$$Q_{\min} = a \cdot F \cdot v_w \tag{1}$$

Providing laminar flow of pumped fluids in the annular space

To determine the admissible value of admissible flow rate of drilling mud, the Reynolds critical number has to be determined [1]. Depending on the rheological model of drilling mud, various algorithms can be applied.

For the Newtonian fluid, having the rheological model $\tau = \eta \cdot (-\frac{dv}{dr})$, the Reynolds critical number is established in the form:

$$\mathrm{Re}_{kr} = 2100 \tag{2}$$

For the Bingham model, $\tau = \tau_0 + \eta \cdot (-\frac{dv}{dr})$, the Hedstrom number has to be established for determining the Reynolds critical number in the annular space [1]:

$$He = \frac{\rho \cdot \tau_0 \cdot (D_0 - d_z)^2}{\eta^2} \tag{3}$$

The Reynolds critical number is obtained from a nomogram (Fig. 1) presenting the dependence of the Reynolds critical number on the Hedstrom number.

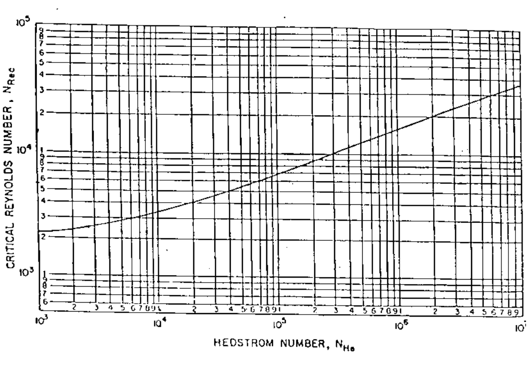

Fig. 1. Dependence of the Reynolds critical number for the Bingham fluid on the Hedstrom number.

The generalized Reynolds number can be also used for hydraulic calculations of Bingham fluid. The critical value is:

$$\overline{\mathrm{Re}}_{kr} = 2100 \tag{4}$$

When considering the drilling mud as the Ostwald de Waele fluid rheological model $\tau = k \cdot (-\frac{dv}{dr})^n$, the generalized Reynolds critical value should be determined from the formula:

$$\overline{\mathrm{Re}}_{kr} = 3470 - 1370 \cdot n \tag{5}$$

The admissible fluid flow rate which does not create a turbulence in the annular space between the borehole's walls of diameter D_o and the mud pipes of outer diameter d_z is determined from the formulae:

- for the Newtonian fluid:

$$Q_{\max} = \frac{525 \cdot \pi \cdot \eta \cdot (D_o + d_z)}{\rho} \tag{6}$$

- for the Bingham fluid:

$$Q_{\max} = \pi \cdot (D_o + d_z) \cdot \frac{1050 \cdot \eta + \sqrt{1{,}1 \cdot 10^6 \cdot \eta^2 + 350 \cdot \rho \cdot (D_o - d_z)^2 \cdot \tau_0}}{4 \cdot \rho} \tag{7}$$

- for the Ostwald de Waele fluid:

$$Q_{\max} = \frac{\pi}{4} \cdot \left(D_0^2 - d_z^2\right) \cdot \sqrt[2-n]{\frac{k \cdot \overline{\mathrm{Re}}_{kr} \cdot \left(\frac{6n+2}{n}\right)^n}{8 \cdot (D_0 - d_z)^n \cdot \rho}} \tag{8}$$

Maintaining appropriate pressure values in the annular space, lower than the overburden ground and the rock pressure

For the drilling mud flow it is crucial to know the pressure values in the annular space between the open wall of a horizontal borehole and the casing pipes. Too high pressure values may result in the loss of drilling mud into the surrounding ground and rocks. It may also cause permanent deformation of the existing landscape morphology owing to the densification, delamination, fracturing or displacement of ground and rocks of the overburden.

The pressure value in the annular space during the successive stages of HDD realization should be calculated from the formula:

$$\mathrm{p_p} = \mathrm{p_h} + \mathrm{p_r} \tag{9}$$

The hydrostatic pressure p_h is defined from:

$$\mathrm{p_h} = \rho \cdot \mathrm{g} \cdot \mathrm{h} \tag{10}$$

The dynamic component p_r in equation (9) is related to the movement of drilling mud in the annular space.

Its value is defined as a sum of drilling mud flow resistances calculated from a given place in the annular space to the point in which the drilling fluid outflows from the borehole.

The pressure losses of the drilling mud laminar flow in the annular space L long is determined for:

- Newtonian fluid from a transformed Hagen-Poiseuill formula:

$$p_r = \frac{128 \cdot \eta \cdot L \cdot Q}{\pi^2 \cdot (D_0 - d_z)^3 \cdot (D_0 + d_z)^2} \tag{11}$$

- Bingham fluid:

$$p_r = \frac{128 \cdot \eta \cdot L \cdot Q}{\pi^2 \cdot (D_0 - d_z)^3 \cdot (D_0 + d_z)^2} + \frac{16 \cdot \tau_0 \cdot L}{3 \cdot (D_0 - d_z)} \tag{12}$$

- Ostwald de Waele fluid:

$$p_r = \frac{4 \cdot k \cdot L}{(D_0 - d_z)} \cdot \left[\frac{8 \cdot (3 \cdot n + 1) \cdot Q}{n \cdot \pi \cdot (D_0 - d_z)^2 \cdot (D_0 + d_z)}\right]^n \tag{13}$$

During HDD reaming operations, an additional piston effect should be accounted for.

Theoretical considerations (analysis of continuity equation) lead to a conclusion that the drilling mud flow rate in the annular space of constant geometry (when the string is in motion) can be calculated from the formula:

$$v_T = v_{r\max}\left(\frac{d_z^2}{D_0^2 - d_z^2}\right) \tag{14}$$

It follows from analyses [2] that the rate value is higher in real conditions than the theoretical v_T value. The drilling mud flow in the annular space in the course of piston effect should be calculated from the formula:

$$v_T = v_{r\max}\left(\frac{d_z^2}{D_0^2 - d_z^2} + b\right) \tag{15}$$

The value of parameter a can be calculated from the quotient d_z/D_0 and the flow conditions [2]

The change of drilling mud flow rate in the annular space, being a result of the piston effect, should be determined from the formula:

$$\Delta Q_T = \frac{\pi}{4}\cdot\left(v_{r\max}\cdot d_z^2 + \left(D_0^2 - d_z^2\right)\cdot b\right) \tag{16}$$

The pressure value losses for the drilling mud flow in the annular space should be defined from the following relations:

- for the Newtonian fluid:

$$p_r = \frac{128\cdot\eta\cdot L\cdot\left(Q \pm \frac{\pi}{4}\left(v_{r\max}\cdot d_z^2 + \left(D_0^2 - d_z^2\right)\cdot b\right)\right)}{\pi^2\cdot\left(D_0 - d_z\right)^3\cdot\left(D_0 + d_z\right)^2} \tag{17}$$

- for the Bingham fluid:

$$p_r = \frac{128\cdot\eta\cdot L\cdot\left(Q \pm \frac{\pi}{4}\left(v_{r\max}\cdot d_z^2 + \left(D_0^2 - d_z^2\right)\cdot b\right)\right)}{\pi^2\cdot\left(D_0 - d_z\right)^3\cdot\left(D_0 + d_z\right)^2} + \frac{16\cdot\tau_0\cdot L}{3\cdot\left(D_0 - d_z\right)} \tag{18}$$

- for the Ostwald de Waele fluid:

$$p_r = \frac{4\cdot k\cdot L}{\left(D_0 - d_z\right)}\cdot\left[\frac{8\cdot(3\cdot n+1)\cdot\left(Q \pm \frac{\pi}{4}\left(v_{r\max}\cdot d_z^2 + \left(D_0^2 - d_z^2\right)\cdot b\right)\right)}{n\cdot\pi\cdot\left(D_0 - d_z\right)^2\cdot\left(D_0 + d_z\right)}\right]^n \tag{19}$$

The sign „+" in equations (17 to 19) are applicable when the reaming direction is congruent with the direction of the flow in the annular space, whereas „-" is used otherwise. During performing a pilot HDD, the k and v_{rmax} values should be assumed to be zero.

The pressure in the annular space should be lower than the geostatic pressure of ground and rocks of the overburden.

$$p_P < p_G, \tag{20}$$

Knowing the thickness of the overburden h_n and its average density ρ_n in any point of the trajectory, the following formulae are obtained:

- for the Newtonian fluid:

$$\rho + \frac{128\cdot\eta\cdot L\cdot\left(Q \pm \frac{\pi}{4}\left(v_{r\max}\cdot d_z^2 + \left(D_0^2 - d_z^2\right)\cdot b\right)\right)}{\pi^2\cdot\left(D_0 - d_z\right)^3\cdot\left(D_0 + d_z\right)^2\cdot g\cdot h} \le \rho_n\cdot\frac{h_n}{h} \tag{21}$$

- for the Bingham fluid:

$$\rho + \frac{128\cdot\eta\cdot L\cdot\left(Q \pm \frac{\pi}{4}\left(v_{r\max}\cdot d_z^2 + \left(D_0^2 - d_z^2\right)\cdot b\right)\right)}{\pi^2\cdot\left(D_0 - d_z\right)^3\cdot\left(D_0 + d_z\right)^2\cdot g\cdot h} + \frac{16\cdot\tau_0\cdot L}{3\cdot\left(D_0 - d_z\right)\cdot g\cdot h} \le \rho_n\cdot\frac{h_n}{h} \tag{22}$$

- for the Ostwald de Waele fluid:

$$\rho + \frac{4 \cdot k \cdot L}{(D_0 - d_z) \cdot g \cdot h} \cdot \left[\frac{8 \cdot (3 \cdot n + 1) \cdot \left(Q \pm \frac{\pi}{4} \left(v_{r\max} \cdot d_z^2 + \left(D_0^2 - d_z^2 \right) \cdot b \right) \right)}{n \cdot \pi \cdot (D_0 - d_z)^2 \cdot (D_0 + d_z)} \right]^n \leq \rho_n \cdot \frac{h_n}{h} \qquad (23)$$

The admissible value of flow rate does not result in the rock destruction, and can be calculated from the formula:

- for the Newtonian fluid:

$$Q_{\max} = \left(\rho_n \cdot \frac{h_n}{h} - \rho \right) \cdot \frac{\pi^2 \cdot (D_0 - d_z)^3 \cdot (D_0 + d_z)^2 \cdot g \cdot h}{128 \cdot \eta \cdot L_1} \mp \frac{\pi}{4} \left(v_{r\max} \cdot d_z^2 + \left(D_0^2 - d_z^2 \right) \cdot b \right) \qquad (24)$$

- for the Bingham fluid

$$Q_{\max} = \left(\left(\rho_n \cdot \frac{h_n}{h} - \rho \right) - \frac{16 \cdot \tau_0 \cdot L_1}{3 \cdot (D_0 - d_z) \cdot g \cdot h} \right) \cdot \frac{\pi^2 \cdot (D_0 - d_z)^3 \cdot (D_0 + d_z)^2 \cdot g \cdot h}{128 \cdot \eta \cdot L_1} \mp \frac{\pi}{4} \left(v_{r\max} \cdot d_z^2 + \left(D_0^2 - d_z^2 \right) \cdot b \right) \qquad (25)$$

- for the Ostwald de Waele fluid

$$Q_{\max} = \frac{n \cdot \pi \cdot (D_0 - d_z)^2 \cdot (D_0 + d_z)}{8 \cdot (3 \cdot n + 1)} \cdot \sqrt[n]{\left(\rho_n \cdot \frac{h_n}{h} - \rho \right) \cdot \frac{(D_0 - d_z) \cdot g \cdot h}{4 \cdot k \cdot L_1}} \mp \frac{\pi}{4} \left(v_{r\max} \cdot d_z^2 + \left(D_0^2 - d_z^2 \right) \cdot b \right) \qquad (26)$$

Selection of mud pump parameters

Accounting for the introduced dependences, the minimal flow rate of drilling mud can be determined for the assumed rheological model. It is a conjunction of the following dependences:

- for the Newtonian fluid:

$$\begin{cases} Q_{pomp} \geq a \cdot F \cdot v_w \\ \wedge \\ Q_{pomp} \geq \dfrac{525 \cdot \pi \cdot \eta \cdot (D_0 + d_z)}{\rho} \\ \wedge \\ Q_{pomp} \geq \left(\rho_n \cdot \dfrac{h_n}{h} - \rho \right) \cdot \dfrac{\pi^2 \cdot (D_0 - d_z)^3 \cdot (D_0 + d_z)^2 \cdot g \cdot h}{128 \cdot \eta \cdot L_1} \mp \dfrac{\pi}{4} \left(v_{r\max} \cdot d_z^2 + \left(D_0^2 - d_z^2 \right) \cdot b \right) \end{cases} \qquad (27)$$

- for the Bingham fluid:

$$\begin{cases} Q_{pomp} \geq a \cdot F \cdot v_w \\ \wedge \\ Q_{pomp} \geq \pi \cdot (D_0 + d_z) \cdot \dfrac{1050 \cdot \eta + \sqrt{1{,}1 \cdot 10^6 \cdot \eta^2 + 350 \cdot \rho \cdot (D_o - d_z)^2 \cdot \tau_0}}{4 \cdot \rho} \\ \wedge \\ Q_{pomp} \geq \left(\left(\rho_n \cdot \dfrac{h_n}{h} - \rho \right) - \dfrac{16 \cdot \tau_0 \cdot L_1}{3 \cdot (D_0 - d_z) \cdot g \cdot h} \right) \cdot \dfrac{\pi^2 \cdot (D_0 - d_z)^3 \cdot (D_0 + d_z)^2 \cdot g \cdot h}{128 \cdot \eta \cdot L_1} \mp \dfrac{\pi}{4} \left(v_{r\max} \cdot d_z^2 + \left(D_0^2 - d_z^2 \right) \cdot b \right) \end{cases} \qquad (28)$$

- for the Ostwald de Waele fluid

$$\begin{cases} Q_{pomp} \geq a \cdot F \cdot v_w \\ \wedge \\ Q_{pomp} \geq \frac{\pi}{4} \cdot \left(D_0^2 - d_z^2\right) \cdot \sqrt[2-n]{\frac{k \cdot (3470 - 1370 \cdot n) \cdot \left(\frac{6n+2}{n}\right)^n}{8 \cdot \left(D_0 - d_z\right)^n \cdot \rho}} \\ \wedge \\ Q_{pomp} \geq \frac{n \cdot \pi \cdot \left(D_0 - d_z\right)^2 \cdot \left(D_0 + d_z\right)}{8 \cdot (3 \cdot n + 1)} \cdot \sqrt[n]{\left(\rho_n \cdot \frac{h_n}{h} - \rho\right) \cdot \frac{\left(D_0 - d_z\right) \cdot g \cdot h}{4 \cdot k \cdot L_1}} \mp \frac{\pi}{4}\left(v_{r\max} \cdot d_z^2 + \left(D_0^2 - d_z^2\right) \cdot b\right) \end{cases} \tag{29}$$

The minimal value of mud pump pressure can be defined by calculating resistances of mud flow in the circulation system. The pump pressure should be higher than the total resistance of flow.

$$\mathrm{p}_{\mathrm{pomp}} > \sum \mathrm{p}_{\mathrm{r}} \tag{30}$$

The total resistance of flow $\sum \mathrm{p}_{\mathrm{r}}$ of drilling mud in the circulation system is a sum of pressure losses inside the mud pipes, in the annular space between the open wall of a horizontal borehole and the mud pipes or casing pipes, and also the bit or reamer nozzles.

The resistance of flow in the string and annular space should be determined depending on the assumed rheological model of drilling mud from the formulae (11) to (13). These mathematical dependences enable to determine the resistances of the mud flow inside the mud pipes are are listed in Tab. 2.

Tab. 2 Mathematical dependences enabling the calculation of resistance of thedrilling mud flow in a circulation system.

Model of fluid	Laminar flow	Turbulent flow
Newtonian	$p_r = \frac{128 \cdot \eta \cdot L \cdot Q}{\pi^2 \cdot \left(d_w\right)^5} + \frac{16 \cdot \tau_0 \cdot L}{3 \cdot d_w}$	$p_r = 0.145 \cdot \frac{L \cdot \rho^{0.79} \cdot Q^{1.79}}{\cdot \left(d_w\right)^{4.79}}$
Bingham	$p_r = \frac{128 \cdot \eta \cdot L \cdot Q}{\pi^2 \cdot \left(d_w\right)^5} + \frac{16 \cdot \tau_0 \cdot L}{3 \cdot d_w}$	$p_r = 0.145 \cdot \frac{L \cdot \rho^{0.79} \cdot Q^{1.79}}{\cdot \left(d_w\right)^{4.79}}$
Ostwald de Waele	$p_r = \frac{4 \cdot k \cdot L}{d_w} \cdot \left[\frac{8 \cdot (3 \cdot n + 1) \cdot Q}{n \cdot \pi \cdot \left(d_w\right)^3}\right]$	$p_r = \frac{\frac{3.93 + \ln n}{1.5625} \cdot L \cdot \rho \cdot Q^2 \cdot \left(\frac{8 \cdot 4^{2-n} \cdot \rho \cdot Q^{2-n}}{\pi^{2-n} \cdot d_w^{4-3 \cdot n} \cdot k \cdot \left(\frac{6 \cdot n + 2}{n}\right)^n}\right)^{-\frac{1.75 - \ln n}{7}}}{\pi^2 \cdot \left(d_w\right)^5}$

Pressure losses in bit nozzles should be calculated from the formula:

$$p_r = \frac{0.898 \cdot \rho \cdot Q^2}{\left(\sum_{i=1}^{m} d_i^2\right)^2} \tag{31}$$

Summing up

A continuous technical progress enables to make new and fully automized miniaturized and compact rigs for HDD with a spatially variable trajectory.

In changeable morphological, hydrogeological and geological-drilling conditions it is very important that the rig subassemblies were properly selected. Mud pump parameters are especially significant.

The needed technical parameters of mud pipes should be determined for each stage of HDD realization, i.e. the drilling of pilot borehole, reaming and the dragging of the casing pipe.

All the presented equations and formulae are recommended for relevant calculations.

Denotations

a. coefficient of mud volume excess in reference to the produced cuttings [-]. It is assumed on the basis of practical experience that the well is cleaned correctly if 4 units of mud per 1 unit of mud are introduced in a unit of time.
b. coefficient accounting for the influence of floating of fluid particles through the walls of the string on the fluid flow rate in the annular space, [-].

D_0 – borehole's diameter, [m];
d_i – diameter of the i–th nozzle, [m];
d_z – outer diameter of drilling rods, [m];
d_w – inner diameter of drilling rods, [m];
F – area of drilled ground or rock, [m^2]. For the pilot borehole: $F = \frac{\pi}{4} \cdot D_0^2$, for specific stages of reaming:

$$F = \frac{\pi}{4} \cdot \left(D_i^2 - D_{i-1}^2\right)$$

η – plastic viscosity, [Pas];
h_n – height of overburden, [m];
h – depth of trajectory of borehole axis measured in respect to the starting point, [m];
He – Hedstrom number, [-];
k – coefficient of the drilling mud consistency described by the Ostwald de Waele model, [Pas^n];
L – length of a section of the borehole axis, [m];
n – exponent in the Ostwald de Waele model, [-];
m – number of bit or reamer nozzles, [-]
p_h – increase of the drilling mud pressure related with the necessity to overcome the resistance of flow, [Pa];
p_h – hydrostatic pressure of the column of drilling mud, [Pa];
p_r – resistance of the drilling mud flow, [Pa];
r – radius of flow cross-section, [m];
Re_{kr} – Reynolds critical number, [-];
$\overline{Re}_{kr}$ – generalized Reynolds critical number, [-];
ρ – density of the drilling mud, [kg/m^3];
ρ_n – density of the overburden ground and rocks, [kg/m^3];
τ – static stress, [Pa];
τ_0 – yield point, [Pa].
v_T – flow rate of the drilling mud in the analyzed section of the annular space [m/s].
v_{rmax} – maximal rate of the movement of the string, depending on the HDD technical parameters [m/s].
v_w – drilling rate, [m/s]

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