Testing of a Stand for Analysis of Drilling Mud Friction Factor

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Testovanie stendu pre analýzu koeficientu odporu výplachu

A concept and realization of a universal laboratory stand for analyzing hydromechanical effects accompanying the drilling mud flow are presented in the paper. Requirements for basic technical subassemblies of the stand are defined. The principles of a flow meter, pressure converters and digital data readers are presented. Then a scheme of a laboratory stand, its principle and procedure are discussed. The process of stand testing through an empirical determination of the Faning friction factor for Newtonian fluids is presented and compared with literature data.

***Key words:** drilling fluids, friction factor*

Introduction

Various technological fluids are used in the drilling technology, e.g. a drilling mud, sealing slurries, fluids for fracturing and supporting fractures, acid muds, overpacker muds, etc.

One of the most important engineering tasks is establishing hydraulic dependences during re-pumping of technological fluids. This is determined by, among others, a dynamically changing approach to the description of rheological properties of fluids. New drilling fluids additives, frequently based on polymers, cause that classic rheological models frequently give an incomplete description of these fluids. It follows from the analysis of dependences between the measurements of tangent stresses and the settling rate of the presently applied drilling mud that linear models of plastic-viscous fluids (Newtonian, Bingham's) fail to precisely describe the behaviour of actual fluids. Among the better known complex models are nonlinear rheological models, e.g. exponential Herschel-Bulkley model, with which the relation between the tangent stresses and the setting rate in the drilling mud can be described more accurately. However, the dependence of the flow rate of the pumped fluid and the resulting resistance of flow has not been established so far. Therefore, a concept of a laboratory stand for deriving necessary relations on the basis of results of numerous measurements was created [1, 2, 3].

For doing it, boundary conditions of a technological process were determined, necessary calculations were made and a suitable research equipment was purchased. The basic device was a flow meter, consisting of an electromagnetic sensor and a signal converter. This choice of the device was dictated by the fact that the analyzed fluids are good conductors of electric energy (basic for this type of flow meters) and the price to measurement accuracy ratio is very attractive as compared to other such devices [6]. The pressure gradients were measured with digital pressure converters. Data were stored by digital data readers based on the flash memory.

Characteristic of measurement equipment

For minimizing the uncertainty of measurement, the newest available design solutions for measuring the flow rate, pressure and the data reading were applied.

Flow meter

An electromagnetic flow meter was applied for the laboratory stand. Owing to the relatively high accuracy and no additional resistances produced, this type of flow meters is frequently used in various branches of industry.

A relation between the vector of electromagnetic field and the flow rate of the conductor fluid in this field and in the induced one is used in the electromagnetic flow meter. This clearly shows that the electromagnetic flow meter can be used in practice only for measuring flows of conductor fluids.

The idea of measurement operations is presented in Fig. 1.

Electromagnets generating the magnetic field, the stream of which penetrates the medium flowing in the pipe, are disposed in a vertical direction, perpendicular to the pipe's axis. Electrodes are disposed perpendicular to the pipe's axis and the magnetic stream. The voltage value is proportional to the product

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of magnetic induction, active length of the conductor (pipe diameter) and the rate of the conduction (fluid). Knowing the value of measured voltage, magnetic induction and the active length of conductor, it is possible to determine the volumetric flow rate. The pipeline section, making up the flow meter, is cased with an insulation. The pipe is made of nonmagnetic metal. The most frequently used insulation materials are neoprene, polyurethane, teflon, linatex and ceramics, whereas the electrodes are made of nonmagnetic stainless steel, tantalum or platinum and iridium alloys.

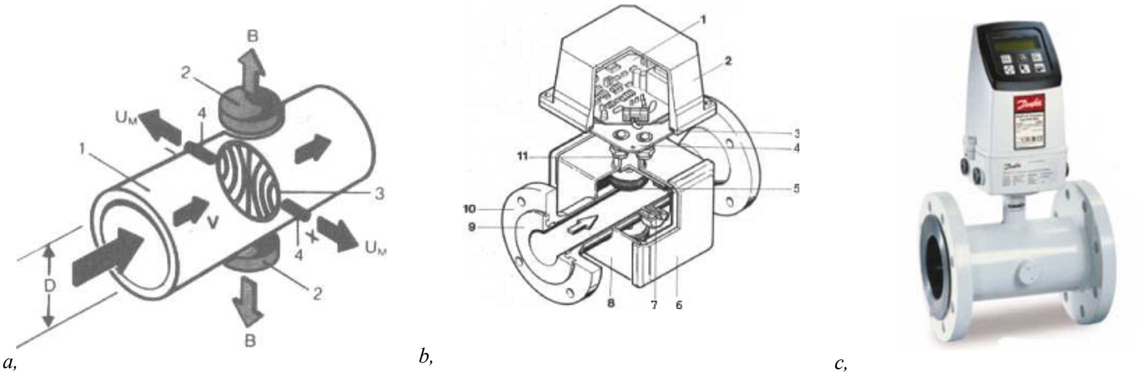

Fig. 1. The idea of measurement operations:a) principle: 1-measurement pipe, 2-magnet coil, 3-selected flow cross-section, 4-measurement electrode, B-magnetic induction, UM-voltage in electrode, v-flow rate; b) design: 1-converting module, 2-casing of converter, 3-sealing, 4-inter-module, 5-magnet coil, 6-cover of meter casing, 7-measurement electrode, 8-casing of meter, 9-measurement section, 10-collars, 11-cable outlets with throttles; c) flow meter.

The laboratory stand made at the Faculty of Drilling, Oil, and Gas is equipped with a flow meter MAGFLO by Siemens (Danfoss). The geometrical parameters of the flow meter were designed and the device was ordered in Siemens.

Pressure converters

From pressure converters available on the market, a VEGA product was selected (rys. 2).

Converters VEGABAR 14 enable a constant pressure measurement. The gas or hydrostatic pressure of fluid acts on a ceramic membrane of the converter, changing the volume of the ceramic measurement cell. The electronics converts the changes of cell's capacity into an electrical signal (the current stays in the range 4 to.20 mA) proportionate to the pressure. Owing to the ceramic-capacity measurement cell CERTEC, the high long-term stability of the converter and the resistance to overloads were obtained [7].

Fig. 2. Pressure converter Vegabar 14 by Vega.

Digital data readers

Digital data readers were used at the laboratory stand. They belong to a new generation of readers, the technological solution of which is far from traditional paper band readers. These are totally electronics-based reader devices, small in size and lightweight. They do not have any mechanical elements and possess their own source of supply. They store data in their inner semiconductor memory. They are programmed and data-read by programs installed on PCs. These programs provide a configuration of readers in the sampling time intervals, delay of reading start-up, saving in the memory, setting alarm thresholds and possibly a modem communication.

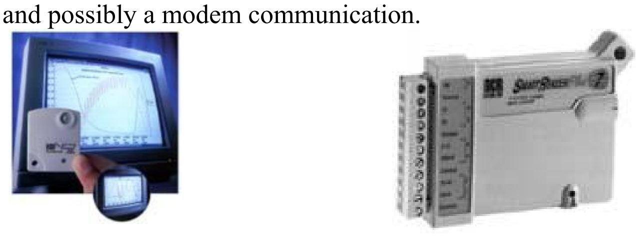

Fig. 3. Readers by ACR Systems – OWL 500 and Smartreader Plus.

The changes of saved data can be observed real-time with the use of a program RealTime. Data can be read with the use of a program, the plots can be processed by introducing appropriate denotations and descriptions. The zoom function enables reading data at a great detail. The format of files with stored data is read by calculation programs, e.g. MS Excel. The computer is connected by a serial port (RS 232C).Electric and non-electric data were gathered by readers by the ACR Systems Inc. (Fig. 3.). The data are stored digitally in the semiconductor memory. The configuration and reading of reader's memory is performed by a serial port of an IBM PC. The readers SMARTREADER enable storing 32768 results of measurements at the 8 bit resolution (1/256). The SMARTREADER plus enables storing 21500 results at the 12 bit resolution (1/4096). Ther data can be stored in two modes: a continuous (after filling up the memory, the newest data are stored in place of oldest ones – „first-in, first-out") or till the memory is full („fill-then-stop"). These devices are equipped with an inner clock controlling the frequency of sampling the measurement signal. The measurement cycle is programmed during a configuration of the reader with the use of a computer and is from 8 sec to 5 days long for SmartReader or from 25/sec to 8 hrs. for SmartReader plus. These devices have their own supply system (cell 3.6V, 1Ah), enabling ca. 10 years of recorder's operation without the cell replaced. All models (except for SR9 plus) have an inbuilt thermistor sensor of temperature, facilitating storing ambient temperature data for each measurement. The readers can operate at a temperature from -45 to 70°C. The software TrendReader for Windows, RealTime Monitor, TalkBack is used for the data transmission from the recorder to the computer, the configuration of the recorder, the analysis and presentation of the data measurement results, the alarm settings, etc. [4, 5].

A concept of universal laboratory stand for indoor and field measurements

The laboratory stand designed and constructed at the Department of Drilling and Geoengineering, Faculty of Drilling, Oil and Gas, AGH-UST consisted of the following elements:

- electromagnetic flow-meter MAGFLO by Siemens (Danfoss) equipped with an electromagnetic sensor of flow Danfoss MAG 3100 (accuracy W=0.25) and signal converter Danfoss MAG 5000;
- 4 pressure converters VEGABAR 14 (maximal pressure: 0.25 bar – 2 items, 1 bar, 2.5 bar. All with the accuracy W=0.25, the input signal from 4 to 20 mA) by VEGA;
- flow rate rectifier of pumped fluid, made at AGH-UST;
- Smartreader Plus by ACR Systems;
- rotary pump (power: 2.2 kW);
- sensor of temperature;
- unique, set of heads, fastening elements and connections by Serwnaft (Kraków);
- software Trendreader by ACR Systems;
- software RheoSolution, worked out at the Faculty of Drilling, Oil and Gas, aiding the optimal selection process of rheological model and rheological parameters of a given fluid [8]
- PC;

The whole system is supplemented with a 12-degree rotary viscosity meter FANN, thanks to which dependences between the setting rate of a fluid and the tangent stresses can be determined. The density measurements made at a later stage, are made with the Baroid scales. An idea scheme of the stand is presented in Fig. 4.

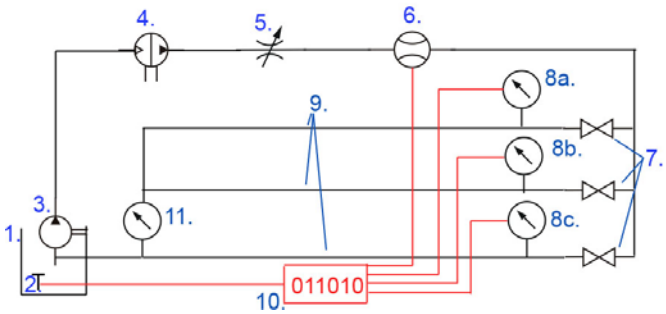

Fig. 4. Scheme of a laboratory stand; 1.- fluid container; 2.- temperature sensor; 3.- rotary pump; 4.- flow rate rectifier; 5.- adjustable throttle; 6. – flow meter; 7.- cuf-off valves; 8a, 8b, 8c – pressure converters at the beginning of the measuring section; 9.- measurement section; 10.- digital data reader Smartreader plus; 11.- pressure converter at the end of the measurement section.

The principle of a laboratory stand is as follows:

A pump pumps the fluid from a container equipped with an inner sensor of temperature. The fluid flows through a device stabilizing the stream of the fluid, i.e. the flow rate rectifier. Then the fluid gets to the flow meter with the use of an elastic, reinforced pipe. After passing through the flow meter, the fluid gets to a set of the pressure converters (separate for each pipe). The flow meter, sensor of temperature and pressure converters cooperate with a digital data reader Smartreader-plus by the Canadian ACR Systems (enables servicing 8 devices concurrently). A measurement section made of 3 replaceable pipes of various diameters, each 3 meters long, are disposed after the pressure converters. The pipes are ended with a manifold and pressure converter, connected to the digital reader Smartreader-plus. The manifold is supposed to eliminate the influence of pressure in pipes, which are not used for the specific measurement. The selection of a pipe through which the fluid flows, is made by a special head, made specifically for the stand. The head is made of interconnected ball valves, thanks to which a selected flow section can be easily changed. The length of a measurement section may be also changed. Two measurement lengths are available: 2 m and 2.5 m. Changes are made with the use of another manifold connected to the pressure converter. After passing through the measurement section, the fluid is directed to a container with a rubber hose and in this way the circulation gets closed. The whole is supplemented by a fluid cooler made of a spiral copper pipe with cool water running inside. The spiral surrounds the rotary pump, which is the source of heat inside the containers, and could increase the temperature of the tested fluid in an uncontrollable way.

The measurement of technological parameters lies in an simultaneous identification of four measured values during the fluid's flow: the momentary flow rate, the flow pressure at the beginning of pipes, the flow pressure at the end of pipes and the temperature of the flowing fluid. The measurement of technological parameters lies in an concurrent identification of four parameters during the fluid's flow: the momentary flow rate, the flow pressure at the beginning of pipes, the pressure flow at the end of pipes and the temperature of the flowing fluid. A digital data reader is used. It enables archivization of data with the assumed step of time. A flash-type inner memory is used. After the measurement, it is read by a TrendReader program for PC. The maximal number of measurements is a resultant of time of sampling of specific elements connected to the reader and the time of sampling of the reader itself. In the case of the analyzed laboratory stand this is 10 records per sec. The read data can be processed with other popular computer programs, e.g. Excel, Statistica.

Testing laboratory stand

The laboratory stand is used for calculating flow resistances of non-Newtonian fluids. This leads to the calculation of the Faning friction factor for the fluid described with any rheological model.

Using the Faning equation, the coefficient of friction-based losses can be determined from the formula

$$f = \frac{\pi^2 \cdot p \cdot D^5 \cdot}{32 \cdot L \cdot \rho \cdot Q^2} \quad , \tag{1}$$

Making necessary measurements at the laboratory stand, the value of the coefficient of friction-based losses f can be determined empirically.

For Newtonian fluids, the Faning friction factor in turbulent flow conditions is determined with the formulae known from the literature: Blasius, Mises, Nikuradse and other formulae [1], [3].

For coarse pipes, the coefficient of friction-based losses should be determined from the Colenbrook equation [1]:

$$\frac{1}{\sqrt{f}} = -4\log(0.269 \cdot \frac{\varepsilon}{D} + \frac{1.255}{Re \cdot \sqrt{f}}) \quad , \tag{2}$$

It can be proved that at ε=0, equation (2) is transformed to the Cullender and Smith dependence for smooth pipes [1]:

$$\frac{1}{\sqrt{f}} = 4\log(Re \cdot \sqrt{f}) - 0.395 \quad , \tag{3}$$

Equation (3) can be solved numerically. The Blasius equation in the following form, is an approximation of equation (3) for $Re<10^5$ [1]:

$$f = \frac{0.0791}{Re^{0.25}} \quad , \tag{4}$$

The laboratory stand was tested be performing a cycle of measurements of resistances of Newtonian fluid's flow through smooth pipes of various inner diameter for various flow rates. Rolled pipes (standard PN-84/H-74220), of inner diameters D_1=0.016 m, D_2=0.0215 m, D_3=0.0272 m were used. Tap water at temperature $t=20^0$C, density $\rho=1000$ kg/m^3 and dynamic viscosity $\eta=0.001004$ Pas was pumped. The scope of changes of flow rate was assumed for $Q\in[0.00050$ m^3/s; 0.0020 m^3/s]. 4000 measurements were made.

The obtained results were used for determining Faning friction factor from equation (1). The uncertainty of evaluation of coefficient f for each measurement was determined on the basis of stumble propagation law.

$$df = \frac{\partial f}{\partial p}dp + \frac{\partial f}{\partial D}dD + \frac{\partial f}{\partial L}dL + \frac{\partial f}{\partial \rho}d\rho + \frac{\partial f}{\partial Q}dQ \tag{5}$$

By calculating the respective partial derivatives and accounting for the dependence (1), we get:

$$df = \left(\frac{dp}{p} + 5\frac{dD}{D} - \frac{dL}{L} - \frac{d\rho}{\rho} - 2\frac{dQ}{Q}\right) \cdot f \tag{6}$$

The uncertainty of evaluating specific measurement values depend on the accuracy of the used apparatuses or the measurement paradigm and are: dp=24.4 Pa, dD=0.001 m, dL=0.001 m, dρ=10 kg/m^3, dQ= 0.00000049 m^3/s

The calculated empirical values of the Faning friction factor were compared with theoretical values established on the basis of the Blasius equation. The results of the comparison are presented in Fig. 5. For readibility's sake, only 60 experimental results were listed in the plot.

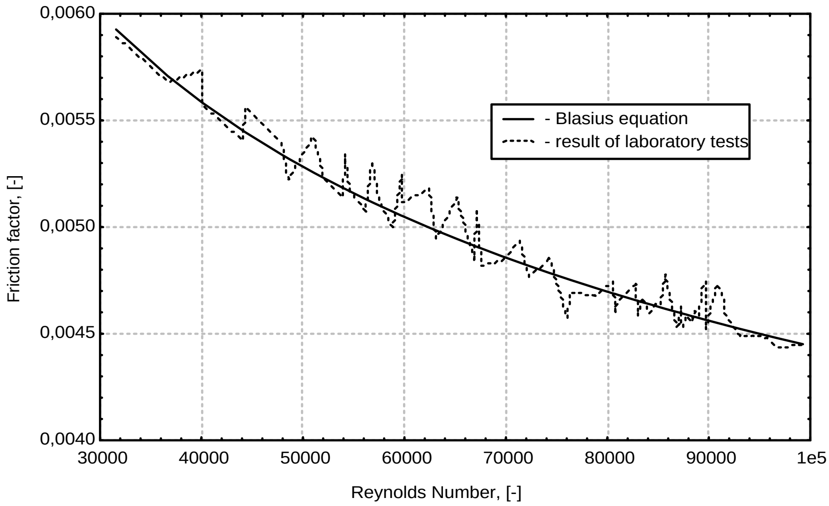

Fig. 5. Theoretical vs. experimental value of friction factor for Newtonian fluid.

It follows from the performed measurements and calculations that the results of experiments made on a Newtonian fluid (tap water) at the laboratory stand coincide with the theoretical values. The maximal discrepancy between the obtained data is 4 %. This prompts a conclusion that the laboratory stand designed and construed at the Department of Drilling and Geoengineering AGH-UST can be successfully used for measuring hydromechanical effects accompanying the flow of drilling fluids.

Summing up

New recipes of drilling muds necessitate a modification of existing muds and a creation of new rheological models of fluids. Qualitative and quantitative relations between properties of pumped fluids and hydrodynamic parameters of flow also should be determined.

For establishing relations for construing, a special laboratory post should be made. Such a stand was created at the Faculty of Drilling, Oil and Gas, thanks to which scientific researches can be carried out on the technology of drilling fluid flow.

The usability of the stand was tested with tap water. The results of 4000 measurements did not show any discrepancy between experimental and theoretical results.

Denotations

D – inner diameter of pipe, [m];
ε – coarseness of surface, [m];
η – dynamic viscosity of Newtonian fluid, [Pa•s];
f – Faning friction factor, [-];
L – length of the measurement section, [m];
p – pressure gradient in the measurement section, [Pa];
Q – flow rate, [m^3/s];
ρ – density of the drilling mud, [kg/m^3];
Re – Reynolds number, [-];

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