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Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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HYDRAULIC CHARACTERISTICS OF AN IMPROVED SYSTEM FOR REAL-TIME DRILLING FLUID DENSITY MEASUREMENT

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Abstract. Relevance. Accurate monitoring of drilling fluid density is crucial for ensuring safety and efficiency in oil and gas well drilling. The use of automated, real-time density measurement systems enhances monitoring responsiveness and enables the timely detection of changes in drilling fluid properties. However, measurement accuracy depends not only on sensor characteristics but also on the acquisition of a representative sample, particularly when dealing with non-Newtonian fluids. **Objective.** To provide a theoretical and numerical assessment of the hydraulic characteristics of an automatic drilling fluid density measurement system to determine rational fluid supply conditions, measuring volume renewal

time, and pressure losses. *Methods.* The governing equations of fluid flow in circular pipes, the Darcy–Weisbach equation, and the Bingham and Herschel–Bulkley models were applied. The effects of flow rate, density, viscosity, and yield stress on the flow parameters within the hydraulic module were investigated numerically. *Results.* An inverse relationship between the measuring chamber filling time and fluid flow rate was established. At flow rates of at least 2 L/s, the chamber volume can be renewed in less than 5 s. The hydraulic losses for the geometry under consideration were found to be negligible. At low flow rates and elevated yield stress, the formation of a central plug was found to increase flow resistance and affect the efficiency of measuring volume renewal. For shear-thinning Herschel–Bulkley fluids, a reduction in the rate of increase in hydraulic losses with increasing flow rate was established. *Conclusions.* The results provide a basis for selecting hydraulic module parameters and operating conditions for cyclic drilling fluid supply. They can be used in the design and adjustment of automated density measurement systems to improve the reliability and timeliness of monitoring under drilling rig conditions.

Keywords: drilling fluid density, drilling fluid, drilling optimization, real-time measurement, hydraulic characteristics

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НАҚТЫ УАҚЫТ РЕЖИМІНДЕ БҰРҒЫЛАУ ЕРІТІНДІСІНІҢ ТЫҒЫЗДЫҒЫН ӨЛШЕУГЕ АРНАЛҒАН ЖЕТІЛДІРІЛГЕН ЖҮЙЕНІҢ ГИДРАВЛИКАЛЫҚ СИПАТТАМАЛАРЫ

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Аннотация. *Өзектілігі.* Бұрғылау ерітіндісінің тығыздығын сенімді бақылау мұнай және газ ұңғымаларын бұрғылаудың қауіпсіздігі мен тиімділігін қамтамасыз етудің маңызды шарты болып табылады. Тығыздықты нақты уақыт режимінде өлшеудің автоматтандырылған жүйелерін қолдану бақылаудың жеделдігін арттыруға және бұрғылау ерітіндісі қасиеттерінің өзгерістерін уақтылы анықтауға мүмкіндік береді. Бұл ретте өлшеу нәтижелерінің сенімділігі датчик сипаттамаларына ғана емес, әсіресе ньютондық емес сұйықтықтармен жұмыс істеген кезде, өлшеу көлемінде репрезентативті сынаманың қалыптасуына да байланысты. *Мақсаты.* Сұйықтықты берудің оңтайлы режимдерін, өлшеу көлемінің жаңару уақытын және қысым шығындарын анықтау үшін бұрғылау ерітіндісінің тығыздығын автоматты өлшеу жүйесінің гидравликалық сипаттамаларын теориялық және сандық тұрғыдан негіздеу. *Әдістері.* Дөңгелек құбырлардағы сұйықтық ағынының гидродинамикалық теңдеулері, Дарси–Вейсбах теңдеуі, сондай-ақ Бингам және Гершель–Балкли модельдері қолданылды. Гидравликалық модульдегі ағыс параметрлеріне көлемдік шығынның, тығыздықтың, тұтқырлықтың және ығысу шегінің әсері сандық түрде зерттелді. *Нәтижелері.* Өлшеу камерасының толу уақыты мен сұйықтық шығыны арасында кері тәуелділік бар екені анықталды. Сұйықтық шығыны кемінде 2 л/с болған кезде камера көлемінің 5 секундтан аз уақытта жаңаруы қамтамасыз етіледі. Қарастырылған геометрия үшін гидравликалық шығындардың шамалы екені көрсетілді. Аз шығын кезінде және ығысу шегі жоғары болғанда орталық пластикалық тығынның қалыптасуы ағыс кедергісін арттырып, өлшенетін көлемнің жаңару тиімділігіне әсер ететіні анықталды. Ығысудан сұйылатын Гершель–Балкли сұйықтықтары үшін шығын артқан сайын гидравликалық шығындардың өсу қарқыны төмендейтіні анықталды. *Қорытындылар.* Алынған нәтижелер гидравликалық модуль параметрлері мен бұрғылау ерітіндісін циклдік беру режимдерін таңдауды негіздейді. Оларды бұрғылау қондырғылары жағдайында бақылаудың сенімділігі мен жеделдігін арттыру мақсатында тығыздықты өлшеудің автоматтандырылған жүйелерін жобалау және баптау кезінде пайдалануға болады.

Түйін сөздер: бұрғылау ерітіндісінің тығыздығы, бұрғылау ерітіндісі,

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ГИДРАВЛИЧЕСКИЕ ХАРАКТЕРИСТИКИ УСОВЕРШЕНСТВОВАННОЙ СИСТЕМЫ АВТОМАТИЗИРОВАННОГО ИЗМЕРЕНИЯ ПЛОТНОСТИ БУРОВОГО РАСТВОРА

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Аннотация. *Актуальность.* Достоверный контроль плотности бурового раствора является одним из важных условий обеспечения безопасности и эффективности бурения нефтяных и газовых скважин. Применение автоматизированных систем измерения плотности в режиме реального времени способствует повышению оперативности контроля и своевременному выявлению изменений свойств бурового раствора. При этом точность и достоверность измерений определяются не только характеристиками измерительных датчиков, но и условиями формирования репрезентативной пробы, особенно при работе с неньютоновскими жидкостями. В связи с этим особую значимость приобретает исследование гидравлических характеристик измерительного модуля и определение рациональных режимов движения бурового раствора. *Цель.* Теоретически и

численно обосновать гидравлические характеристики усовершенствованной системы автоматизированного измерения плотности бурового раствора, определить рациональные режимы подачи жидкости, продолжительность обновления измерительного объема и величину гидравлических потерь. *Методы.* Исследование основано на применении уравнений гидродинамики течения жидкостей в круглых трубопроводах, уравнения Дарси - Вейсбаха, а также реологических моделей Бингама и Гершеля - Балкли. Методами численного анализа исследовано влияние расхода жидкости, ее плотности, вязкости и предельного напряжения сдвига на характеристики течения в гидравлическом модуле автоматизированной измерительной системы. Особое внимание уделено определению времени обновления измерительного объема, оценке потерь давления и анализу влияния реологических свойств бурового раствора на гидравлическое сопротивление. *Результаты.* Установлена обратная зависимость продолжительности заполнения измерительной камеры от объемного расхода бурового раствора. Показано, что при расходе не менее 2 л/с время обновления объема измерительной камеры составляет менее 5 с. Для рассматриваемой геометрии гидравлического модуля расчетные потери давления характеризуются относительно небольшими значениями. Установлено, что при низких расходах жидкости и повышенных значениях предельного напряжения сдвига формирование пластической пробки приводит к увеличению гидравлического сопротивления и снижению эффективности обновления измерительного объема. Для жидкостей, описываемых моделью Гершеля - Балкли и характеризующихся сдвиговым разжижением, выявлено снижение интенсивности увеличения гидравлических потерь по мере роста расхода жидкости. *Выводы.* Полученные результаты позволяют обосновать выбор конструктивных и эксплуатационных параметров гидравлического модуля системы автоматизированного измерения плотности бурового раствора, а также определить рациональные режимы его циклической подачи. Учет расхода жидкости, геометрических характеристик измерительной камеры и реологических свойств бурового раствора способствует совершенствованию процесса формирования репрезентативной пробы. Предложенный подход может использоваться при проектировании и настройке автоматизированных измерительных систем, обеспечивая методическую основу для повышения оперативности и потенциальной достоверности контроля плотности бурового раствора в условиях буровых установок.

Ключевые слова: плотность бурового раствора, автоматизированные измерения, гидравлические характеристики, неньютоновские жидкости, гидравлическое сопротивление, реологические модели, бурение скважин

Introduction. Drilling fluid is one of the key elements of the technological drilling system for oil and gas wells, ensuring the simultaneous fulfillment of several critically important functions: cuttings transport to the surface, cooling

and lubrication of the drilling tool, maintenance of wellbore stability, and regulation of formation pressure through the creation of the required hydrostatic column (Davydenko et al., 2015). Among the numerous parameters of drilling fluid, density holds a special position, as it directly determines the magnitude of hydrostatic pressure in the wellbore and thus has a significant impact on the safety and efficiency of drilling operations (Biletskiy et al, 2022). Deviations in density from design values may lead to both formation fluid influxes and kicks (Bondarenko et al., 2024) and to drilling fluid losses, complications, and accidents, accompanied by significant material and time costs (Biletskyi et al., 2024).

Literary review. Current trends in drilling development are associated with the exploitation of deeper and more geologically and technically complex targets, an increasing share of directional and horizontal wells (Lukin and Kondrat, 2024), as well as the widespread use of drilling fluids with complex compositions and rheologies (Khomenko et al., 2025). Under these conditions, the requirements for operational control of drilling fluid parameters, including density, increase significantly. Traditional density measurement methods based on periodic manual sampling and the use of mechanical instruments, although still widely applied, increasingly fail to meet modern requirements for continuity, accuracy, and reproducibility of measurements (Wu et al., 2016). The discrete nature of such measurements does not allow timely detection of rapid changes in drilling fluid properties, and the results largely depend on personnel qualifications and measurement conditions (Muratova et al., 2025).

In response to these limitations, real-time and semi-automatic drilling fluid density monitoring systems have been actively developed in recent years for direct installation on drilling rigs and operation in a near-real-time mode. Such systems may be based on various physical principles, including the use of radiation characteristics (Khabaz and Yaghobi, 2015), hydrostatic pressure measurements (Ihnatov et al., 2023), acoustic methods (Ofoche and Noynaert, 2020), or analysis of the electromagnetic properties of the medium (Dokhani et al., 2016). Despite the obvious advantages of automation, practical experience with the operation of such devices shows that their metrological performance is largely determined not only by the measurement principle itself, but also by the conditions of hydraulic interaction between the sensing element and the drilling fluid (Ahmadi et al., 2018).

Of particular importance in real-time density measurement systems is the problem of forming a representative drilling fluid sample within the measurement chamber. Unlike laboratory conditions, drilling fluid at the rig is characterized by a variable composition, the presence of a solid phase, gas inclusions, and pronounced non-Newtonian behavior. The supply of drilling fluid to the measurement chamber, its circulation, and subsequent evacuation are carried out through a hydraulic circuit whose parameters significantly affect the fluid renewal rate, velocity, and stress distributions, as well as the stability of the measurement module readings. An insufficient fluid replacement rate or the presence of stagnant

zones may lead to distortion of the measured density and a decrease in data reliability (Shanmugasundar et al., 2024).

The problem that served as the basis for the present study was identified during the development and testing of a real-time drilling fluid density measurement system, which implements an inductive conversion principle and employs a vertically oriented measurement chamber with periodic fluid injection and withdrawal. It was found that, under identical settings of the measurement module, the nature and stability of the readings strongly depend on the flow rate, rheological properties of the drilling fluid, and the geometry of the supply pipelines. In particular, for fluids exhibiting a pronounced yield stress, the formation of a plastic plug was observed, resulting in an increase in the time required for complete fluid replacement in the measurement chamber and potentially compromising the representativeness of the measurement.

Thus, the choice of the topic of the present work is driven by the need for a scientifically substantiated analysis of the hydraulic processes accompanying the operation of a real-time drilling fluid density measurement system, to identify and quantitatively assess the factors that limit its accuracy and reliability. Of particular interest is the consideration of non-Newtonian rheological models widely used to describe drilling fluids, such as the Bingham plastic model and the Herschel–Bulkley model, which allow an adequate representation of yield stress behavior and shear-thinning effects (Radich et al., 2023).

The relevance of the present study is determined by the fact that, in most applied works devoted to real-time drilling fluid density monitoring systems, primary attention is paid to the design of the measuring unit and signal processing algorithms. In contrast, the hydraulic aspects of forming the measured sample are often treated in a simplified manner or remain outside the scope of analysis. Meanwhile, it is precisely the hydraulic module and its operating modes that largely determine the applicability of such systems under real drilling conditions, especially when working with highly viscous and structured drilling fluids.

The aim of the present study is a theoretical and numerical investigation of the hydraulic characteristics of the drilling fluid supply system to the measurement chamber of a real-time density measurement device, focused on evaluating the time required to form a representative sample, flow regimes in the supply pipelines, and the magnitude of pressure losses at various flow rates and rheological parameters of the fluid. Achieving this aim enables the substantiation of requirements for the hydraulic module's parameters, the determination of rational operating modes for the system, and the creation of prerequisites for enhancing the accuracy and reliability of real-time drilling fluid density control under drilling rig operating conditions.

Materials and Methods. The object of the study was a real-time drilling fluid density measurement system intended for operation on drilling rigs. The system includes a vertically oriented cylindrical measurement chamber, a hydraulic module for supplying and discharging drilling fluid equipped with a variable-capacity pump, and an electronic signal registration module.

The research methodology was based on theoretical and numerical analysis of hydraulic processes under steady-state fluid flow in circular pipes. The mean flow velocity was determined from the flow rate and cross-sectional area. At the same time, the time required for complete filling of the measurement chamber was calculated using the continuity equation. The flow regime was assessed using the Reynolds number and then classified as either laminar or turbulent. Pressure losses in the supply pipeline were determined using the Darcy–Weisbach equation, with an analytical expression for the friction factor in the laminar regime and the empirical Swamee–Jain approximation in the turbulent flow region.

To account for the rheological characteristics of drilling fluids, the Newtonian model, the Bingham plastic model, and the Herschel–Bulkley model were employed. In the non-Newtonian models, the flow was considered to consist of a central plastic plug and a shear zone adjacent to the pipe wall. The distribution of shear stresses and the velocity profile were determined based on the corresponding rheological equations, after which the flow rate was calculated by integrating the velocity profile over the cross-section. The inverse problem of determining the pressure drop for a given flow rate was solved numerically using the bisection method.

Calculations were performed for a flow rate range of 0.5–8.0 L/s, drilling fluid densities of 1100–1300 kg/m³, and characteristic values of viscosity and yield stress corresponding to typical drilling fluids. The main calculated parameters analyzed were the mean flow velocity, Reynolds number, pressure losses, and the time required for complete fluid replacement in the measurement chamber. The obtained relationships were used to assess the conditions for forming a representative drilling fluid sample and to substantiate the operating regimes of the hydraulic module of the real-time drilling fluid density measurement system.

Results. The developed real-time drilling fluid density monitoring system is intended for application on drilling rigs in the geological exploration and oil and gas industries. Structurally, the system comprises a measurement chamber, a hydraulic unit, and an electronic module. The measurement chamber is designed as a vertically oriented tubular structure with a cavity filled with drilling fluid, which is cyclically supplied to and removed from the chamber by a variable-capacity pump via the hydraulic module. The electronic module consists of an inductance sensor, a signal conversion unit, and a control panel. In the upper part of the system, an electromagnetic coil and a magnetic core are installed; the core is rigidly connected to a calibration chamber filled with distilled water and air. Instrument adjustment and calibration are performed by changing the water level in this chamber.

A patent application for this technical solution has been filed with the National Institute of Intellectual Property of the Committee for Intellectual Property Rights of the Ministry of Justice of the Republic of Kazakhstan, No. 2024/0926.1, dated November 5, 2024 (Fig. 1).

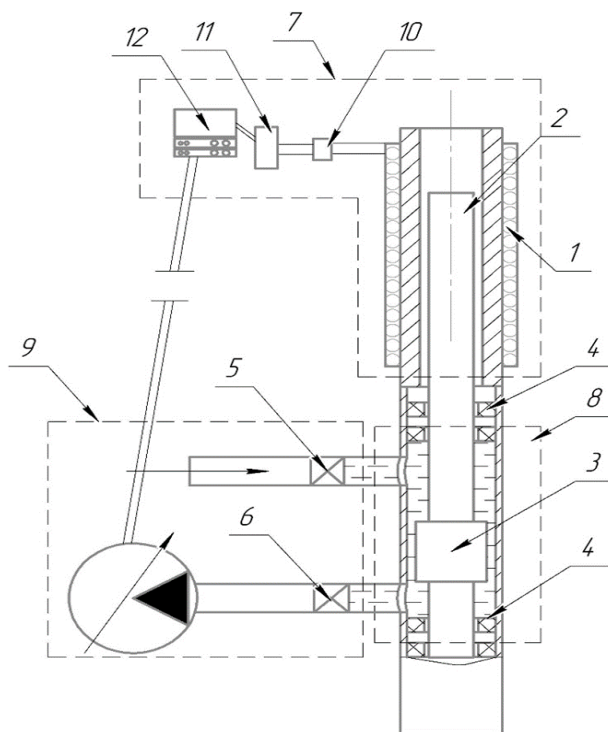


Figure 1. Device for real-time measurement of drilling mud density.

The real-time drilling fluid density measurement system operates as follows. After a specified time interval (set either by the drilling rig operator or by a time relay), the hydraulic module 9 opens valves 5 and 6, allowing the inflow of drilling fluid into the measurement chamber through a variable-capacity pump. After circulation for at least 5 s, the valves are closed, and the measurement is performed. The magnetic core 2, connected to chamber 3 containing distilled water and air (calibration is performed by adjusting the water level in this chamber), begins to move within coil one under the action of Archimedes' principle; guides 4 ensure smooth and accurate movement. This motion changes the inductance of the magnetic field, which is detected by sensor 10 of the electronic module 7. As the density increases, the magnetic core 2 enters the coil 1 (floats upward), thereby increasing the magnetic field inductance; as the density decreases, it exits the coil ("sinks"), reducing the inductance. Prior to installation on the drilling rig, the real-time drilling fluid density measurement system undergoes calibration under laboratory conditions, where the correspondence between inductance values and drilling fluid density is established. During rig operation, the driller, using the electronic module 7 (which includes the inductance sensor 10, converter 11, and control panel 12), observes real-time density readings on the control panel display 12 with an accuracy of $\pm 1.0 \text{ kg/m}^3$.

The study encompasses a theoretical and numerical investigation of the hydraulic characteristics of the drilling fluid supply system to the measurement chamber, to evaluate the time required to form a representative fluid sample, flow regimes in the connecting pipelines, and the expected head losses under typical operating conditions. The main geometric parameters of the measuring section are the internal pipeline diameter D and the length of the measurement chamber L_{chamber} . The chamber volume is defined as $V_{\text{chamber}} = \frac{\pi D^2 L_{\text{chamber}}}{4}$.

For the calculations, values of $D = 0.10$ m and $L_{\text{chamber}} = 1.0$ m were used, which corresponds to a chamber volume of $V_{\text{chamber}} = 7.85 \cdot 10^{-3}$ m³.

The mean flow velocity in the cross-section is defined as

$$v = \frac{Q}{A}, \quad (1)$$

where Q is the volumetric flow rate, m³/s;

$A = \frac{\pi D^2}{4}$ is the cross-sectional area, m².

The ideal time required for complete filling of the chamber at a given flow rate is determined from the continuity equation:

$$t_{\text{fill}} = \frac{V_{\text{chamber}}}{Q}. \quad (2)$$

In the actual measurement chamber, the presence of a movable core, calibration chamber, guides, and valves results in mixing and the formation of stagnant zones. Therefore, the practical sample renewal time is estimated using a non-ideality factor of $k_{\text{mix}} = 2.5\text{--}3.5$:

$$t_{\text{renew}} = k_{\text{mix}} \frac{V_{\text{chamber}}}{Q}. \quad (3)$$

The flow regime is characterized by the Reynolds number Re :

$$Re = \frac{\rho v D}{\mu}, \quad (4)$$

where ρ is the fluid density, kg/m³;

μ is the dynamic viscosity, Pa·s.

Depending on the value of Re , the flow is considered laminar ($Re < 2300$) or turbulent ($Re \geq 2300$) (Umirova et al., 2025). This classification influences the selection of empirical correlations used to calculate the hydraulic friction factor, f .

Pressure losses in the pipeline are determined using the Darcy–Weisbach equation:

$$\Delta p = f \frac{L_{\text{pipe}} \rho v^2}{D} \quad (5)$$

where L_{pipe} is the length of the pipe section through which the fluid is supplied. Standard approximations were used to calculate the friction factor f : for the laminar regime (Ratov et al, 2023)

$$f = \frac{64}{\text{Re}} \quad (6)$$

and for the turbulent regime, the Swamee–Jain formula was applied (Alizadeh et al., 2024):

$$f = \frac{0.25}{\left[\log_{10} \left(\frac{\varepsilon}{3.7D} + \frac{5.74}{\text{Re}^{0.9}} \right) \right]^2} \quad (7)$$

Here ε is the absolute roughness of the pipe wall.

The actual measurement chamber contains a movable core, calibration chamber, guides, and valves. These components introduce local hydraulic resistance, flow turbulence, and stagnant zones. The total minor loss coefficient is assumed to be $\sum \xi \approx 8\text{--}12$, representing typical values for two valves, inlet/outlet sections, and internal components. The total pressure losses are therefore given by:

$$\Delta p_{\text{total}} = \Delta p_{\text{friction}} + \Delta p_{\text{local}} \quad (8)$$

The local hydraulic losses caused by the valves, inlet/outlet sections, and internal chamber components can be determined as follows:

$$\Delta p_{\text{local}} = \sum \xi_i \frac{\rho v^2}{2} \quad (9)$$

The total pressure losses are then given by:

$$\Delta p_{\text{total}} = \Delta p_{\text{friction}} + \sum \xi_i \frac{\rho v^2}{2} \quad (10)$$

The coefficient k_{mix} accounts for the increase in the time required for complete volume replacement relative to ideal plug-flow displacement.

The analysis was performed under steady-state conditions as a baseline estimate. Water hammer was evaluated using the simplified Joukowsky equation, accounting for the valve closure time. The time required for the velocity profile to develop after pump startup for non-Newtonian fluids is estimated as:

$$t_{trans} = \frac{\rho R^2}{\mu_{app}} \cdot$$

(11)

where μ_{app} is the apparent viscosity.

The calculations were performed for flow rates Q ranging from 0.5 to 8.0 L/s, density $\rho = 1100\text{--}1300\text{ kg/m}^3$, dynamic viscosity $\mu = 0,001\text{--}0,05\text{ Pa}\cdot\text{s}$, absolute roughness of the steel pipeline $\varepsilon = 1,5\cdot 10^{-5}\text{ m}$, and supply pipe length $L_{pipe} = 2\text{ m}$.

Based on the above equations, the following characteristics were calculated for each parameter set: mean velocity (v), Reynolds number (Re), friction factor (f), pressure loss (Δp) in the supply pipeline, and chamber filling time t_{fill} .

Results for a Newtonian Fluid (Baseline Estimate). The ideal filling times and practical sample renewal times (for $k_{mix} = 3$) are presented in Table 1 and Fig. 2.

Table 1. Chamber Filling and Sample Renewal Times.

Q, L/s	v, m/s	t_{fill} (ideal), c	t_{renew} ($k_{mix} = 3$), c
0,5	0,064	15,71	47,1
1,0	0,127	7,85	23,6
2,0	0,255	3,93	11,8
3,0	0,382	2,62	7,85
5,0	0,637	1,57	4,71
8,0	1,019	0,98	2,95

Figure 2 shows the dependence of the chamber filling and renewal times on the fluid flow rate. The curves represent ideal plug-flow displacement and the range corresponding to $k_{mix} = 2.5\text{--}3.5$.

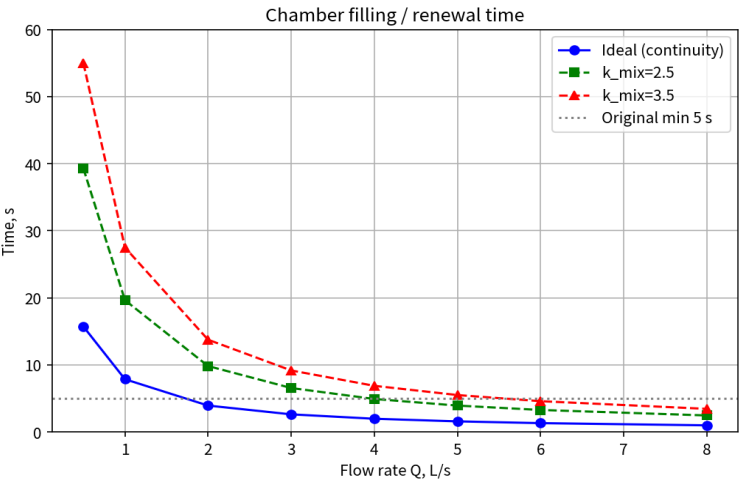


Figure 2. Dependence of chamber filling/refresh time on fluid flow rate.

The relationship presented in Fig. 2 for a fixed chamber volume demonstrates an inverse proportionality $t_{\text{fill}} = \frac{V_{\text{chamber}}}{Q}$. For the considered chamber volume (7.85 L), the filling time at a drilling fluid flow rate of $Q = 2 \text{ L/s}$ is $t_{\text{fill}} = 3.93 \text{ s}$. Taking mixing into account ($k_{\text{mix}} = 2.5\text{--}3.5$), the recommended circulation time before measurement is at least 10–14 s. This requirement has been incorporated into the description of the system operating procedure.

The pressure losses Δp for a Newtonian fluid ($\rho = 1200 \text{ кг/м}^3$, $\mu = 0,01 \text{ Па}\cdot\text{с}$), including frictional and minor losses, are presented in Table 2 and Fig. 3.

Table 2. Pressure Losses (Newtonian Fluid, $\sum \xi = 10$).

$Q, \text{ л/с}$	$\Delta p_{\text{fric}}, \text{ кПа}$	$\Delta p_{\text{local}}, \text{ кПа}$	$\Delta p_{\text{total}}, \text{ кПа}$
0,5	0,004	0,024	0,028
1,0	0,008	0,097	0,105
2,0	0,035	0,389	0,424
3,0	0,068	0,875	0,944
5,0	0,164	2,432	2,596
8,0	0,369	6,225	6,594

Minor losses predominate at higher flow rates; however, their absolute values remain acceptable for the selected pump.

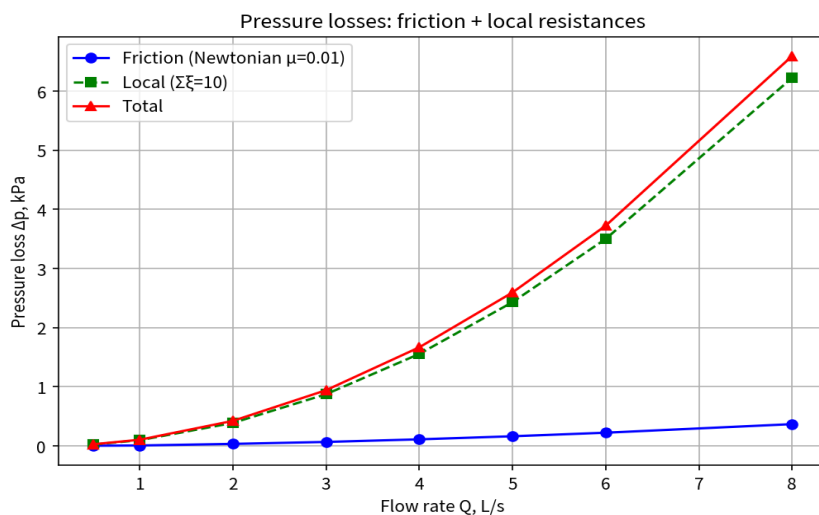


Figure 3. Dependence of pressure losses Δp in the supply pipeline on the fluid flow rate.

The results presented in Fig. 3 show that minor losses predominate; however, their absolute values remain acceptable for the selected pump. These values indicate that the pump head required to ensure cyclic sample delivery along the selected short supply line is relatively low and will not be a limiting factor in

selecting measurement operating conditions. However, the use of narrow channels may substantially increase pressure losses, which should be taken into account when designing the hydraulic module.

The calculations presented in Fig. 3 were performed using a Newtonian approximation (the Darcy–Weisbach equation and the Swamee–Jain correlation) and serve only as a baseline estimate of the order of magnitude, accounting for minor losses. The application of these equations to non-Newtonian drilling fluids is not appropriate.

Let us analyze the hydraulic behavior of the sampling circuit using non-Newtonian rheological models commonly applied to describe drilling fluids, namely the Bingham plastic model and the Herschel–Bulkley model. The considered geometry represents a circular supply pipe with an internal diameter D and a radius $R = D/2$, as well as a measurement chamber of length L_{chamber} . The measurement chamber has an axial length $L_{\text{chamber}} = 1.0$ m and a volume

$$V_{\text{chamber}} = \frac{\pi D^2 L_{\text{chamber}}}{4}.$$

For axisymmetric flow in a circular pipe, the distribution of shear stresses is given by

$$\tau(r) = \tau_w \frac{r}{R}, \quad (12)$$

where τ_w is the wall shear stress.

In turn

$$\tau_w = \frac{R}{2} \frac{dp}{dx}, \quad (13)$$

The pressure gradient dp/dx is related to τ_w by

$$\frac{dp}{dx} = \frac{2\tau_w}{R}. \quad (14)$$

The total pressure drop along a pipe of length L is

$$\Delta p = \frac{2\tau_w L_{\text{pipe}}}{R}. \quad (15)$$

In the Bingham and Herschel–Bulkley models, drilling fluid flow in a circular pipe forms a so-called plastic plug—a central flow region in which the shear stress is below the yield value and the fluid moves as an almost rigid core without internal shear (Rahmati and Tatar, 2019). The relationship between the yield stress and the wall shear stress determines the radius of this zone, r_0 . Accounting

for the parameter r_0 is crucial for the accurate calculation of the velocity profile and hydraulic losses, as the fraction of the unsheared zone directly impacts the required pressure drop and the time required for complete fluid replacement in the measurement chamber.

For the Herschel–Bulkley constitutive law, the local shear rate $\dot{\gamma}(r)$ in the sheared annular region ($r_0 \leq r \leq R$, where r_0 is the plug radius) is given by (Ahmadi, 2016)

$$\dot{\gamma}(r) = \left(\frac{\tau(r) - \tau_0}{K} \right)^{1/n}, \quad (16)$$

where τ_0 is the yield stress, Pa;

K is the consistency index, $\text{Pa} \cdot \text{s}^n$;

n is the flow behavior index.

The plug radius is defined by

$$r_0 = R \frac{\tau_0}{\tau_w}. \quad (17)$$

The volumetric flow rate is determined from the velocity profile as

$$v(r) = \int_r^R \dot{\gamma}(r') dr', \quad (18)$$

and subsequently

$$Q = 2\pi \int_0^R v(r) r dr. \quad (19)$$

The dependence $Q(\tau_w)$ was calculated numerically for given rheological parameters; the inverse problem $\tau_w(Q)$ was solved using the bisection method in order to obtain Δp for a specified flow rate Q .

For the Bingham model ($n = 1$, $K = \mu_p$), the Buckingham–Reiner equation was used:

$$Q = \frac{\pi R^3 \tau_w}{4\mu_p} \left(1 - \frac{4}{3}\phi + \frac{1}{3}\phi^4 \right), \quad \phi = \frac{\tau_0}{\tau_w}. \quad (20)$$

The calculations were performed under the following initial conditions:

$D = 0.10$ m, $L_{\text{pipe}} = 2.0$ m, representative drilling fluid densities (for Reynolds number estimation), and the following sets of rheological parameters.

Newtonian fluid:

$\mu = 0.01$ Pa·s;

Bingham model:

$\tau_0 = 1 \text{ Pa}, \mu_p = 0.01 \text{ Pa}\cdot\text{s};$

$\tau_0 = 5 \text{ Pa}, \mu_p = 0.02 \text{ Pa}\cdot\text{s};$

Herschel–Bulkley model:

$\tau_0 = 2 \text{ Pa}, \quad K = 0.05, \quad n = 0.6;$

$\tau_0 = 5 \text{ Pa}, \quad K = 1, \quad n = 0.6.$

The calculated pressure drops, Δp , as a function of flow rate Q , are presented in Table 3 and Fig. 4.

Table 3. Pressure Losses for Non-Newtonian Fluids (kPa).

Q, L/s	Bingham $\tau_0 = 1$	Bingham $\tau_0 = 5$	HB $\tau_0 = 2$	HB $\tau_0 = 5$
0,5	0,095	0,444	0,188	0,716
1,0	0,102	0,465	0,197	0,843
2,0	0,114	0,496	0,209	1,031
3,0	0,124	0,522	0,219	1,181
5,0	0,143	0,568	0,234	1,429
8,0	0,169	0,630	0,251	1,733

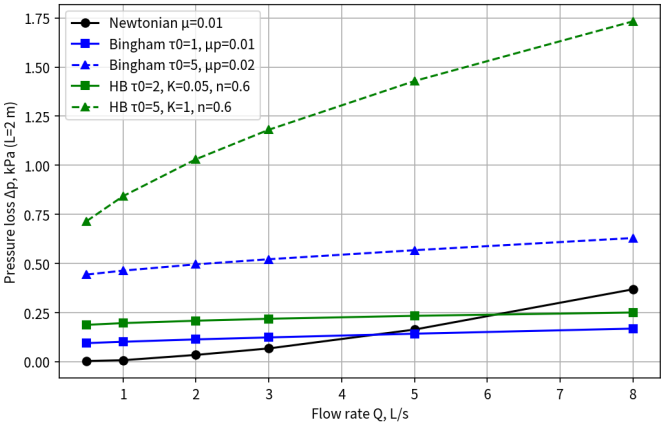


Figure 4. Dependence of pressure losses Δp in the supply pipeline on the fluid flow rate for a Newtonian fluid and for the Bingham and Herschel–Bulkley (HB) models.

For the selected geometry and parameter ranges, the following has been established.

The presence of a yield stress increases the required wall shear stress τ_w and, consequently, the pressure drop Δp at the same drilling fluid flow rate Q . This effect is most pronounced at low flow rates.

At moderate values of τ_0 (several pascals) and typical flow rates $Q \geq 2 \text{ L/s}$, the additional pressure drop remains small (on the order of 10–100 Pa for $L_{\text{pipe}} = 2 \text{ m}$), i.e., within the capabilities of standard pumps.

For shear-thinning Herschel–Bulkley fluids ($n < 1$), lower pressure drops at high flow rates Q are characteristic compared to Bingham fluids with high plastic viscosity, since the apparent viscosity decreases with increasing shear rate.

The analysis confirms that, with sufficient pump capacity and a minimal length of the supply pipeline, the hydraulic module ensures the complete renewal of the chamber volume within a few seconds (see filling times), while maintaining acceptable pressure losses. However, for fluids with high yield stress or in cases of long and/or narrow supply lines, adjusting pump parameters and cycle time intervals is required to ensure representative sampling and prevent flow regimes dominated by plug flow.

Discussion. The results obtained in this study enable a comprehensive assessment of the hydraulic conditions of a real-time drilling fluid density measurement system's operation and clarify the factors that determine the reliability and stability of measurements under real drilling conditions. The performed analysis shows that, for the selected geometric parameters of the measurement chamber and the supply pipeline, the key parameter influencing the formation of a representative sample is the drilling fluid flow rate set by the pump of the hydraulic module.

Calculations of the measurement chamber filling time confirm that at flow rates of about 2 L/s and higher, complete fluid replacement occurs within a few seconds, which corresponds to the practical requirement for a minimum circulation time prior to the start of measurements. This means that, under typical system operating modes, the influence of the residual volume of the previous sample on the measured density is negligible. At lower flow rates, the fluid renewal time increases, and under these conditions, the risk of obtaining averaged or delayed readings grows, especially when drilling fluid properties change rapidly.

The analysis of pressure losses in the supply pipeline shows that, for the considered line length and diameter, hydraulic resistances remain low over the entire investigated range of flow rates and rheological parameters. Even at elevated viscosity and in the presence of a yield stress, the additional pressure drop does not exceed values that could limit pump operation or lead to hydraulic regime instability. This indicates that, for a compact system layout, the energy costs associated with organizing cyclic sample delivery are not a limiting factor.

Accounting for minor hydraulic losses and the k_{mix} coefficient indicates that the actual system requires a longer circulation time than that predicted by the continuity equation alone. This helps prevent averaged or transient readings when working with non-Newtonian fluids that may develop a plug-flow region and stagnant zones. Pressure loss calculations based on rheological models confirm that, for the selected geometry ($D = 0,10$ m and a short supply line), hydraulic resistance is not a limiting factor, even at high yield stress.

At the same time, accounting for the non-Newtonian rheological properties of drilling fluids reveals important flow features that are not captured within the Newtonian approximation. The presence of a yield stress leads to the formation of

a plastic plug in the central part of the flow, which is particularly pronounced at low flow rates. This is accompanied by an increase in the time required for complete fluid replacement in the measurement chamber and may result in the retention of fragments of the previous sample within the chamber volume. For fluids described by the Herschel–Bulkley model, this effect is partially compensated by shear thinning as the flow rate increases; however, at low flow velocities, the influence of the plastic zone remains significant.

The obtained results enable the explanation of the sensitivity of density readings to the operating modes of the hydraulic module observed during the device's development and testing. In particular, instability or inertia of the readings when working with highly structured drilling fluids may be caused not by the features of the measurement principle itself, but by insufficient intensity of fluid renewal in the measurement chamber. This highlights the importance of coordinating the design of the measuring and hydraulic modules in real-time density monitoring systems.

It is worth noting that the present study considered a simplified geometry of the supply pipeline and the measurement chamber, as well as steady-state flow regimes. Under real drilling conditions, the hydraulic scheme may include longer and branched supply lines and may operate in unsteady regimes associated with pump start-up and shutdown, flow rate fluctuations, and changes in drilling fluid properties. Under such conditions, pressure losses and flow behavior may differ significantly from the estimated values, which requires additional analysis at the stage of adapting the system to a specific drilling rig.

Overall, the study's results confirm that, with a rational choice of geometric parameters and drilling fluid supply regimes, a real-time density measurement system is capable of forming a representative sample within a short time, with minimal hydraulic losses. Accounting for the non-Newtonian properties of drilling fluids is a necessary condition for accurately substantiating system operating modes, which enables the improvement of density measurement reliability and accuracy under industrial operating conditions.

Conclusions. The results of the study allow the following conclusions to be drawn:

1. The ideal chamber filling time is inversely proportional to the flow rate. Accounting for mixing ($k_{\text{mix}} = 2,5\text{--}3,5$), the complete sample renewal time at $Q \geq 2$ L/s is 10–14 s, which is adopted as the minimum circulation time.

2. Minor losses caused by valves, the core, and guides predominate over frictional losses along the pipe at $Q \geq 2$ L/s. However, the absolute values of Δp_{total} remain low (< 7 kPa at $Q = 8$ L/s).

3. Pressure loss calculations for the Bingham and Herschel–Bulkley models, based on integration of the velocity profile, indicate a substantial increase in Δp_{at} at low flow rates and high τ_0 . At $Q \geq 2$ L/s, the influence of the plug region becomes acceptable.

4. Transient effects (water hammer and velocity profile development), under smooth valve operation and at the recommended circulation time, do not significantly affect sample representativeness.

5. Appropriate selection of the flow rate ($Q \geq 2$ L/s), minimization of the supply line length, and consideration of minor losses ensure representative sample acquisition and stable system operation under actual drilling site conditions.

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