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Optimization of drilling fluid formulations

Optymalizacja receptur płynów wiertniczych

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ABSTRACT: The article presents a decomposition of the problem of selecting formulations for drilling fluids, which includes the formalization of requirements for their composition and properties, the construction of a set of acceptable formulations and the justification of a subset of equivalent formulations by component composition, selection of the optimal component composition and content of chemical reagents, as well as the composition and concentration of surfactants. The model was built using expert procedures and the results of multifactorial experimental studies on the effect of chemical reagents on the properties of drilling fluids. The formalization of the content of the formulation components was performed based on a decision-making model with a flexible selection of the optimality criterion from several classes, which reflects the functional features of the use of technological fluids in the relevant mining and geological conditions. Fragments of the model for selecting the formulation of the Biocar-TF drilling mud for drilling within the interval of 5752–6572 m of well 43 Semyrenky at temperatures up to 160°C are described. To ensure high initial quality of the opening to productive horizons and prevent possible complications, an additive criterion based on HTHP filtration loss and mud cake permeability was used. Fragments of the results of the selection of killing fluid formulations for well 526 of the Bugrivativske oil field are presented according to the criteria of the cost per unit volume, surface tension at the interface between the killing fluid filtrate and oil, and the cutting carrying index. The feasibility of using technological fluid formulations of according to various optimality criteria is illustrated.

Keywords: biopolymer drilling mud, formulation selection model, optimality criteria, surfactant, technological properties.

STRESZCZENIE: W artykule przedstawiono analizę problemu doboru receptur płuczek wiertniczych, obejmującą sformalizowanie wymagań dotyczących ich składu i właściwości, stworzenie zbioru dopuszczalnych receptur oraz uzasadnienie podzbioru receptur równoważnych pod względem składu, wybór optymalnego składu i zawartości odczynników chemicznych, a także składu i stężenia środków powierzchniowo czynnych. Model opracowano z wykorzystaniem procedur eksperckich oraz wyników wieloczynnikowych badań eksperymentalnych dotyczących wpływu odczynników chemicznych na właściwości płuczek wiertniczych. Formalizację zawartości składników receptury przeprowadzono w oparciu o model decyzyjny z elastycznym wyborem kryterium optymalności spośród kilku klas, co odzwierciedla cechy funkcjonalne zastosowania cieczy technologicznych w określonych warunkach górniczo-geologicznych. Opisano fragmenty modelu doboru receptury płuczki wiertniczej Biocar-TF do wiercenia w przedziale od 5752 do 6572 m odwiertu 43 Semyrenky w temperaturach do 160°C. W celu zapewnienia wysokiej początkowej jakości udostępnienia horyzontów produktywnych oraz zapobieżenia możliwym komplikacjom zastosowano kryterium dodatkowe oparte na stratach filtracyjnych w warunkach HTHP oraz przepuszczalności osadu filtracyjnego. Przedstawiono fragmenty wyników doboru receptury cieczy do zatłaczania dla odwiertu 526 złoża naftowego Bugrivativske, z uwzględnieniem takich kryteriów, jak koszt na jednostkę objętości, napięcie powierzchniowe na granicy faz między filtratem cieczy do zatłaczania a ropą oraz wskaźnik wynoszenia zwiercin. Przedstawiono również zasadność stosowania receptur płynów technologicznych zgodnie z różnymi kryteriami optymalności.

Słowa kluczowe: biopolimerowa płuczka wiertnicza, model doboru receptury, kryteria optymalności, surfaktant, właściwości technologiczne.

Introduction

In modern oil and gas well construction technologies, drilling fluid systems are widely used in drilling, well development, stimulation, and workover operations (Mitchell and Lake, 2007; Caenn et al., 2017). These systems are in contact with the rock throughout the entire duration of operations. Therefore, the efficiency of drilling and completion of wells is determined by the compatibility of fluid composition and properties with geological and drilling conditions, as well as with the system of technological and environmental restrictions.

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A variety of drilling conditions impose specific multifunctional requirements on drilling fluids, and a wide range of materials and chemical reagents enables numerous formulations. In this context, the drilling fluid formulations must meet certain additional conditions, which are usually expressed in the form of optimality criteria and a system of constraints.

A considerable number of studies (Caenn et al., 2017; Mohamed et al., 2021; Skoff et al., 2023) have been devoted to the selection of the component composition and properties of drilling fluids for specific drilling conditions, and appropriate methodologies and software have been developed based on these studies. Below is a brief and far from complete review of articles (Healy et al., 2015; Kesserwan et al., 2018; Houston et al., 2022; Skoff et al., 2023) on the selection of drilling fluid formulations.

Drilling fluids should, first of all, meet the most important functional requirements (Mitchell and Lake, 2007; Caenn et al., 2017), such as effective wellbore cleaning, prevention of complications and minimization of the risk of well control incidents, stabilization of well walls, prevention of formation damage, and increased drilling performance. The intended use of drilling fluids (well drilling, initial opening of productive horizons, well development, and workover) (Healy et al., 2015; Aftab et al., 2020; Espinoza, 2020; Mohamed et al., 2021), geological and drilling conditions (Witthayapanyanon et al., 2014; Razak and Devadass, 2020), well trajectory (Hussein et al., 2013; Szczygieł, 2019; Zhang and Edwards, 2022), mechanisms of physical and chemical effects on rock stability (Eme et al., 2015; Pino et al., 2018; Espinoza, 2020), causes of permeability damage in productive horizons (Hussein et al., 2013; Myslyuk et al., 2014; Szczygieł, 2019), and other factors determine the functional characteristics of the formulation selection.

For drilling wells in difficult conditions (HPHT, risks of wellbore instability, loss of circulation, etc.), significant attention is devoted to the development of drilling fluid formulations incorporating nanomaterials and nanocomposites (Gokapai et al., 2024; Oseh et al., 2024). Acting as multifunctional additives, nanomaterials enhance wellbore sealing and stability (Taghdimi et al., 2023; Anioke et al., 2025), stabilize rheological and filtration properties under high-temperature conditions (Gokapai et al., 2024; Oseh et al., 2024), reduce the surface tension at the drilling mud filtrate-oil interface (Taghdimi et al., 2023) and improve frictional performance (Anioke et al., 2025), etc.

Formulations of drilling fluids are substantiated using various approaches that take into account the results of industrial data analysis (Healy et al., 2015; Razak and Ong, 2020; Raptanov et al., 2021; Houston et al., 2022), laboratory and bench studies (Ferras et al., 2017; Mohamed et al., 2021; Orun et al., 2023), and modeling of drilling or well completion under difficult conditions (Pino et al., 2018; Aftab et al., 2020; Raptanov et al., 2021). Optimal formulations of drilling fluids are selected based on criteria such as minimizing the risk of complications (Subbiah et al., 2018; Konate et al., 2020; Raptanov et al., 2021; Zhang and Edwards, 2022), bottomhole pressure (Hussein et al., 2013; Witthayapanyanon et al., 2014), formulation cost (Cobianco et al., 2003; Razak and Devadass, 2020) and permeability damage (Myslyuk et al., 2014; Yonebayashi et al., 2017; Houston et al., 2022).

Expert systems (Al-Yami et al., 2016; Okoro et al., 2019; Al-Yam et al., 2020; Skoff et al., 2023) play an important role in making design or management decisions regarding the selection of effective drilling fluids, accumulating information on best practices for the use of drilling fluids under various drilling or completion conditions. Expert systems can be used as a training tool for young engineers and an interactive consultation system for various engineering aspects of drilling and completion (Al-Yami et al., 2016).

Monitoring and controlling the technological properties of drilling fluids play an extremely important role in the successful drilling of wells. In this regard, the application of automated monitoring and control systems for drilling fluids is promising (Abdul Razak et al., 2024), including those based on fuzzy logic. Such systems accumulate the experience and knowledge of drilling fluids specialists and ensure their transfer to a digital process control system.

A model for optimal formulation selection

The review of papers (Godwin et al., 2011; Hussein et al., 2013; Eme et al., 2015; Skoff et al., 2023) demonstrates the complexity of the problem of selecting the optimal formulation of drilling fluids. This is due to various factors, namely the peculiarities of formalizing the requirements for the optimal formulation, the type of mathematical models, their information support, dimensionality, etc. In this regard, we consider a model for selecting optimal formulations of drilling fluids, which is a development and generalization of the ideas presented by Mysliuk and Salyzhyn (2007), Myslyuk et al. (2012), Myslyuk and Voloshin (2021), Myslyuk and Zholob (2021).

In general, the decomposition of the model for optimal formulation selection can be formalized in the following sequence.

1. Formalization of requirements for the selection of composition and properties of process fluids, namely systems of constraints on component composition C_f and criteria G_f for their selection.
2. Construction of a set of acceptable formulations $A = \{a_1, a_2, \ldots, a_n\}$ for process fluids by component composition.

3. Substantiation, using expert procedures, of a subset of equivalent formulations $A_e = \{a_k, a_l, \ldots, a_m\}$ of process fluids by component composition, which can be distinguished from the set A using the Bellman – Zadeh model (Bellman and Zadeh, 1970) or fuzzy relations R of non-strict preference (Orlovsky, 1977).

According to the Bellman–Zadeh model (Bellman and Zadeh, 1970), expert procedures are used to build fuzzy constraints $C_f(a_i, \mu_C(a_i))$ and criteria $G_f(a_i, \mu_G(a_i))$, namely membership function $\mu_C(a_i)$ and $\mu_G(a_i)$ of the relevant constraints and criteria defined in the segment [0,1], which characterize their degree of fulfilment for the alternative a_i, $i = \overline{1,n}$.

The fuzzy solution to the problem of selecting the component composition of the process fluid is given by (Bellman and Zadeh, 1970):

$$\begin{cases} D\left(a_i, \mu_D(a_i)\right) = C_f\left(a_i, \mu_C(a_i)\right) \cap G_f\left(a_i, \mu_G(a_i)\right),\ i = \overline{1,n}; \\ \mu_D(a_i) = \mu_C(a_i) \wedge \mu_G(a_i),\ i = \overline{1,n} \end{cases} \tag{1}$$

Then, a subset of equivalent formulations of process fluids is determined from the condition:

$$A_e = \sup \mu_D(a_i),\ i = \overline{1,n} \tag{2}$$

The use of fuzzy relations R of non-strict preference with a membership function $\mu_R(a_i, a_j)$, $i, j = \overline{1,n}$ is appropriate in the case of comparative evaluations of alternative formulations, i.e., by a single criterion. In such a situation, membership functions $\mu_R(a_i, a_j)$, $i, j = \overline{1,n}$ are estimated using expert procedures.

Selection of non-dominated alternatives on a set A with a membership function (Orlovsky, 1977):

$$\mu_R^*(a_i) = 1 - \sup_{a_j \in A}\left\{\mu_R(a_j, a_i) - \mu_R(a_i, a_j)\right\},\ a_i \in A \tag{3}$$

generally allows the construction of a subset of equivalent alternatives:

$$\sup \mu_D(a_i) \Rightarrow A_e,\ a_i \in A \tag{4}$$

Note that solutions (2) and (4) can be represented by one or more alternatives.

4. Selection of component concentrations for equivalent drilling fluid formulations using decision-making models with a flexible choice of the optimality criterion from some of their classes K (Mysliuk and Salyzhyn, 2007; Myslyuk et al., 2012)

$$\begin{cases} k(x^v) \to \min,\ k \in K,\ v \in A_e,\ x^v \in D^v; \\ \varphi(x^v) \le 0 \end{cases} \tag{5}$$

where: $x^v = (x_1^v, x_2^v, \ldots, x_m^v)^T$ is a vector of chemical reagents concentrations of a v-component composition;
$\varphi(x^v)$ is a system of constraints on chemical reagents concentrations.

Formalization of problem (5) requires justification of the optimality criterion $k(x^v)$, a system of constraints $\varphi(x_v)$ based on the concentration of chemical reagents x^v, as well as the domain D^v of their determination.

Class K can be represented by the following optimality criteria (Mysliuk and Salyzhyn, 2007; Myslyuk et al., 2012):

- cost per unit volume of the process fluid formulation

$$k(x^v) = c_0^v + c^v x^{vT} \tag{6}$$

- compliance of m indicators of $g_j(x^v)$ properties with the set $\hat{g}_j(x^v)$ values

$$k(x^v) = \sum_{j=1}^{m} \alpha_j \left(g_j(x^v) - \hat{g}_j(x^v)\right)^2 \tag{7}$$

- $k_p(x^v)$ permeability damage index of a core sample

$$k(x^v) = 1 - (k_p(x^v)) / (k_{p0}(x^v)) \tag{8}$$

- cutting carrying index (Myslyuk, 2023), in accordance with the optimality principle in (5)

$$k(x^v) = 1 - (v_a(x^v)) / (v_{\max}(x^v)) \tag{9}$$

where: c_0^v are chemical reagent concentration-independent costs per unit volume of the killing fluid;
c^v is a vector of costs per unit concentration of chemical reagents;
α_j is a weighting factor for the j-indicator of properties;
$k_{p0}(x^v)$ is the initial permeability of core sample;
$v_a(x^v)$ is the average flow rate;
$v_{\max}(x^v)$ is the maximum flow rate.

In terms of information, model (5), considering (6)–(9), is implemented using methods of design of experiments, on the basis of which regression relationships $g_j(x^v)$ of property indicators and the system of constraints $\varphi(x^v)$ are constructed. The choice of the optimal basic formulation of the process fluid is carried out according to the algorithm

$$\min\left\{k(x^v)\right\} \Rightarrow (x_*^v, v_*),\ v \in A_e \tag{10}$$

First, for each v the concentrations x_*^v are determined, and then the optimal v_* set of chemical reagents is determined. The selection of the optimal formulation in accordance with procedures (10) should be confirmed by a control experiment.

5. Selection of the composition and content of surfactants used to control the surface tension at the drilling mud filtrate-oil (condensate) interface is carried out for the process fluid formulation selected in according to the change in style step 4 using model (5). In this case, the optimality criterion may reflect the surface tension or the cost of the surfactant composition, provided that the system of constraints $\varphi(x^v)$ is satisfied.

It should be noted that the above model 1–5 for selecting optimal formulations of drilling fluids helps to reduce the volume of laboratory tests required for their information support.

Selection of biopolymer drilling mud formulation for high-temperature conditions

Using the example of exploration well 43 Semyrenky, we consider the selection of drilling mud formulation that should meet the requirements for high-quality exposure of productive horizons and ensure the stability of borehole walls. The practical experience of Geosynthesis Engineering company in drilling fluids service and a set of conducted studies indicate the high efficiency of the Biocar-TF drilling mud in such conditions (Myslyuk and Zholob, 2021).

Biocar-TF is an environmentally friendly biopolymer drilling mud with thermal stability up to 170°C, weighted exclusively with water-soluble salts and calcium carbonate, exhibiting high inhibitory properties and ensuring wellbore stability and permeability recovery coefficient ranging from 0.95 to 0.98. The system of restrictions for the design well was formulated to preserve the natural state of the productive horizons by reducing the penetration of drilling mud components into the pore space. Table 1 shows the initial data for selecting the optimal drilling mud formulation.

Table 1. Initial data for selecting the formulation of the Biocar-TF drilling mud

Parameter	Value
Well depth [m]	6572
Project productive horizons	B-19–B-24
Bottomhole temperature [°C]	141–155
Pressure gradient [MPa/m]	0.0118–0.0151
Drilling mud density ρ [kg/m^3]	1600
Gel strength after 10 sec θ_{10s} [Pa]	2.4–5.7
Gel strength after 10 min θ_{10} [Pa]	5.3–17.7
pH index	10.2–10.9
Filtration loss *API* [cm^3/30 min]	0.2–1.2
Filtration loss *HTHP* [cm^3/30 min]	11–13.5
Yield stress τ_0 [Pa]	0.68–2.02
Consistency index k [Pa·s^n]	0.46–1.15
Flow index n	0.68–0.74
Thermal stability [°C]	160
Permeability recovery coefficient	≥ 0.96

To ensure the required density, the Biocar-TF drilling mud contains a mixture of sodium formate (50% *wt./vol.*) and potassium formate (230% *wt./vol.*), as well as calcium carbonate (15% *wt./vol.*) to form a filtration cake. The technological properties of the drilling mud were studied at different concentrations (% *wt./vol.*) of xanthan gum c_{XG}, starch c_s, and Alevron reagent (a mixture of finely dispersed plant- and animal-derived protein substances, TU U 20.1-34962841-009:2014) c_a according to the design of experiments (Table 2) (Myslyuk and Zholob, 2021).

Myslyuk and Zholob (2021) measured the technological properties in accordance with the requirements of API (API 13B-1). The HTHP filtration loss was determined using standard OFITE ceramic filters modeling rock, with a diameter of 63.5 mm and a height of 6.4 mm with the lowest permeability of 0.95 D. The permeability of the mud cake p_{mc} was determined according to the method given by Jaffal et al. (2017). The rheological properties were determined using an HPHT rotational viscometer OFITE 1100 at temperatures of 25–170°C. The viscometry data were processed within the design of experiments framework in the class of rheologically stationary models according to the methods given by Myslyuk (1988, 2019) and Myslyuk and Salyzhyn (2012).

The condition for effective initial exposure of productive horizons and ensuring wellbore stability is achieved through appropriate selection of drilling mud properties and technological operation parameters. In such situations, the biopolymer drilling mud formulation should be selected using a multicriteria optimization model.

Given that the information support for the model for selecting a drilling fluid formulation (5) was obtained from the results of relevant experimental studies carried out by Mysliuk and Salyzhyn (2007) and Myslyuk et al. (2012), it is advisable to justify the formulation considering several optimality criteria through a convolution of criteria. This allows model (5) to be used to select the optimal drilling fluid formulation (Mysliuk and Salyzhyn, 2007).

Important indicators of technological properties that have a direct impact on the quality of initial exposure of productive horizons include *HTHP* filtration loss and permeability p_{mc} of the mud cake. Table 2 shows the results of *HTHP* and p_{mc} indicators of the Biocar-TF drilling mud simulated using regression models (Myslyuk and Zholob, 2021) for the bottomhole conditions of well 43 Semyrenky (temperature 160°C and pressure drop 3.5 MPa). It should be noted that in the experimental studies of *HTHP* and p_{mc} parameters (Myslyuk and Zholob, 2021), temperature and pressure differential were varied across five levels, namely: 130, 140, 150, 160, and 170°C, and 1, 2, 3, 4, and 5 MPa, respectively.

To select the formulation of the biopolymer drilling mud in accordance with model (5), the additive k_a and multiplicative k_m criteria were used, which take into account the influence of HTHP filtration loss and permeability p_{mc} of the mud cake for reservoir conditions:

$$k_a = \alpha_1 \frac{HTHP}{HTHP^{\max}} + \alpha_2 \frac{p_{mc}}{p_{mc}^{\max}} \tag{11}$$

$$k_m = \left(\frac{HTHP}{HTHP^{\max}}\right)^{\alpha_1} \left(\frac{p_{mc}}{p_{mc}^{\max}}\right)^{\alpha_2} \tag{12}$$

where:

α_1, α_2 – weighting coefficients established by experts in accordance with the drilling conditions of the project well, subject to the requirement $\alpha_1 + \alpha_2 = 1$;

$HTHP$ – experimental value of HTHP fluid loss [cm^3/30 min];

$HTHP^{\max}$ – maximum permissible value of HTHP fluid loss [25 cm^3/30 min];

p_{mc} – experimental value of mud cake permeability [D];

$p_{mc}^{\max}$ – maximum permissible value of mud cake permeability [D].

The non-dimensional form of recording criteria (11) and (12) makes it possible to combine relative indicators or criteria of different physical nature in the multicriteria evaluation of a formulation. In this case, the weighting coefficients are $\alpha_1 = 0.8$ and $\alpha_2 = 0.2$.

Table 3 shows the results of modeling Biocar-TF formulations using the MudExpert system (Mysliuk and Salyzhyn, 2007) for different combinations of the weighting coefficients of criteria (11) and (12) (the numerator contains information for k_a, and the denominator for k_m). Figure 1 shows the pattern of the distribution of constant levels $k_a(c_a, c_s) = idem$ and $k_m(c_a, c_s) = idem$, along with their corresponding values, in the coordinates $c_a - c_s$ at $c_{XG} = 0.268\%$ (Fig. 1a) and $c_{XG} = 0.400\%$ (Fig. 1b). Based on the solution of problem (5), the permissible concentration ranges and optimal formulations for the additive (see Fig. 1a) and multiplicative (see Fig. 1b) criteria under the given conditions were identified.

It can be concluded that, for specific geological and drilling conditions, the use of complex optimality criteria allows the choice of a formulation taking into account the trade-offs between the criteria. The information uncertainty of expert estimates for weighting coefficients does not have a significant impact on the selection of chemical reagent concentrations.

During the drilling of well 43 Semyrenky, the technological properties of the Biocar-TF biopolymer drilling mud remained stable and did not require any additional treatments. The chosen formulation based on the additive criterion (11) ensured

Table 2. Design of experiment and results of the tests for selecting the formulation of Biocar-TF

Test	Factors [% (*wt./vol.*)]			Test results			
	c_{XG}	c_s	c_a	HTHP [cm^3/30 min]	p_{mc} [D]	k_a	k_m
1	0.40	2.5	0.50	18.3	0.0767	0.6400	0.6005
2	0.20	2.0	1.00	16.4	0.0392	0.5526	0.4809
3	0.35	2.0	0.75	17.2	0.0854	0.6109	0.5838
4	0.40	3.5	1.00	16.3	0.0124	0.5304	0.3802
5	0.20	3.5	0.50	19.4	0.0434	0.6516	0.5614
6	0.40	1.5	1.25	12.9	0.0165	0.4245	0.3338
7	0.20	2.5	1.25	13.1	0.0218	0.4347	0.3573
8	0.25	3.0	1.00	14.5	0.0301	0.4853	0.4134
9	0.30	2.0	1.25	13.3	0.0249	0.4433	0.3714
10	0.40	2.0	0.25	23.0	0.2199	0.8919	0.8900
11	0.20	3.0	0.25	22.0	0.0631	0.7487	0.6691
12	0.25	2.5	0.75	17.5	0.0577	0.6009	0.5473
13	0.30	2.5	0.25	23.6	0.1145	0.8364	0.7974
14	0.35	3.0	1.25	14.5	0.0157	0.4751	0.3629
15	0.25	1.5	0.25	29.3	0.2821	1.1376	1.1354
16	0.20	1.5	0.75	21.4	0.0774	0.7397	0.6818
17	0.30	3.0	0.50	18.8	0.0509	0.6377	0.5652
18	0.30	3.5	0.75	16.0	0.0249	0.5297	0.4306
19	0.25	3.5	1.25	13.4	0.0173	0.4411	0.3474
20	0.35	2.5	1.00	14.8	0.0350	0.4984	0.4331
21	0.35	1.5	0.50	21.9	0.2295	0.8635	0.8631
22	0.40	3.0	0.75	16.1	0.0294	0.5360	0.4474
23	0.30	1.5	1.00	16.0	0.0570	0.5524	0.5082
24	0.25	2.0	0.50	22.5	0.1217	0.8063	0.7769
25	0.35	3.5	0.25	19.6	0.0269	0.6463	0.5144

stability and low *HTHP* filtration loss values, which enabled a high-quality initial exposure of productive horizons to be achieved. The borehole remained stable, and reaming was associated exclusively with a change in the bottomhole assembly or was of a preventive nature. Based on the well development results, the expected commercial flow rate was obtained.

This example illustrates the possibility of substantiating and selecting the optimal formulation of a biopolymer drilling mud, taking into account complex criteria for the relevant geological and drilling conditions of well drilling.

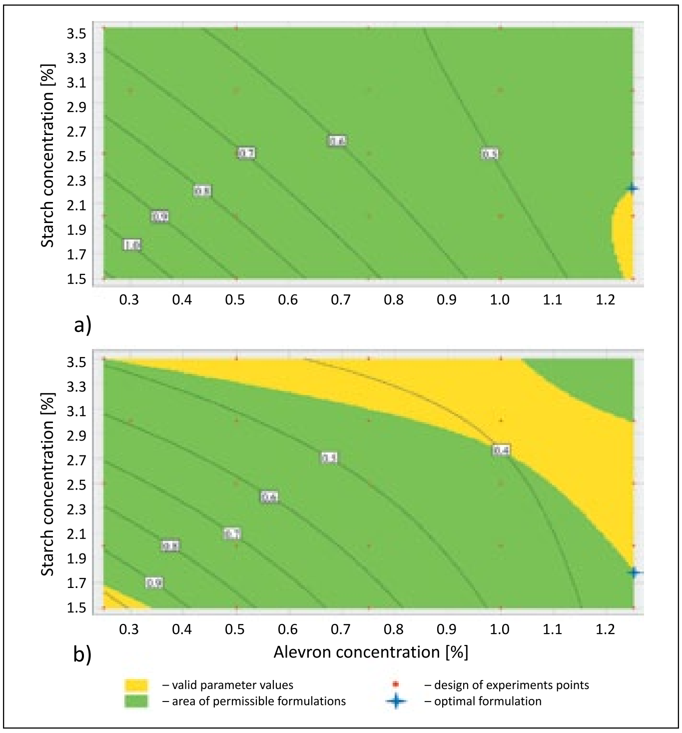

Figure 1. Visualization of the optimal formulation selection of Biocar-TF drilling mud at $\alpha_1 = 0.8$ and $\alpha_2 = 0.2$ for additive (*a*) and multiplicative (*b*) criteria

Selection of well killing fluids

Using well 526 of the Bugrivativske oil field as a case study, we consider the selection of a killing fluid formulation that must meet the requirements of the operation and the optimality criterion. Table 4 shows some initial data for selecting a killing fluid formulation.

Based on the experience of killing wells under similar geological and technical conditions, a formulation based on a biopolymer (Duovis xanthan gum) and PAC-R agent (a high-quality modification of polyanionic cellulose) was substantiated using procedures (3) and (4) (Myslyuk and Voloshin, 2021). The combined use of these chemicals is effective in regulating rheological and filtration properties over a wide range of changes in mineralization and pH of the medium. Sodium chloride (DSTU 4246:2003) was used to regulate the density, and compatible nonionic surfactants,

Table 3. Modeling results for optimal formulations of Biocar-TF drilling mud

Test		Optimal chemical reagents concentrations [% (*wt./vol.*)]			Technological properties								Comprehensive optimization criteria
α_1	α_2	c_{XG}	c_s	c_a	ρ [kg/m^3]	*HTHP* [cm^3/30 min]	p_{mc} [D]	pH	$\theta_{10s/10}$ [Pa]	τ_0 [Pa]	k [Pa·s^n]	n	k_a / k_m
0	1.0	$\frac{0.348}{0.348}$	$\frac{1.98}{1.98}$	$\frac{1.23}{1.23}$	1600	$\frac{13.45}{13.45}$	$\frac{0.012}{0.012}$	10.21	$\frac{4.27/9.66}{4.27/9.66}$	$\frac{1.303}{1.303}$	$\frac{0.756}{0.756}$	$\frac{0.720}{0.720}$	$\frac{0.044}{0.044}$
0.1	0.9	$\frac{0.368}{0.384}$	$\frac{2.18}{1.82}$	$\frac{1.17}{1.25}$	1600	$\frac{13.90}{13.35}$	$\frac{0.015}{0.012}$	10.23	$\frac{4.31/10.17}{4.47/10.02}$	$\frac{1.318}{1.620}$	$\frac{0.780}{0.823}$	$\frac{0.731}{0.709}$	$\frac{0.104}{0.059}$
0.2	0.8	$\frac{0.352}{0.396}$	$\frac{1.98}{3.46}$	$\frac{1.21}{1.03}$	1600	$\frac{13.56}{15.87}$	$\frac{0.014}{0.012}$	10.20	$\frac{4.49/9.73}{3.88/11.77}$	$\frac{1.323}{2.118}$	$\frac{0.763}{0.765}$	$\frac{0.720}{0.816}$	$\frac{0.150}{0.075}$
0.3	0.7	$\frac{0.324}{0.396}$	$\frac{1.62}{3.50}$	$\frac{1.25}{1.03}$	1600	$\frac{13.30}{15.92}$	$\frac{0.014}{0.013}$	10.31	$\frac{4.14/8.87}{3.86/11.81}$	$\frac{1.376}{2.182}$	$\frac{0.733}{0.764}$	$\frac{0.703}{0.819}$	$\frac{0.195}{0.099}$
0.4	0.6	$\frac{0.340}{0.392}$	$\frac{1.98}{3.46}$	$\frac{1.23}{1.01}$	1600	$\frac{13.44}{15.79}$	$\frac{0.012}{0.012}$	10.28	$\frac{4.22/9.53}{3.90/11.73}$	$\frac{1.264}{2.143}$	$\frac{0.743}{0.759}$	$\frac{0.721}{0.816}$	$\frac{0.241}{0.129}$
0.5	0.5	$\frac{0.332}{0.396}$	$\frac{1.78}{3.46}$	$\frac{1.25}{1.05}$	1600	$\frac{13.28}{15.87}$	$\frac{0.012}{0.014}$	10.23	$\frac{4.19/9.19}{3.88/11.77}$	$\frac{1.317}{2.118}$	$\frac{0.739}{0.765}$	$\frac{0.711}{0.816}$	$\frac{0.287}{0.169}$
0.6	0.4	$\frac{0.268}{0.400}$	$\frac{2.22}{3.46}$	$\frac{1.25}{1.05}$	1600	$\frac{13.27}{16.00}$	$\frac{0.012}{0.013}$	10.20	$\frac{3.72/8.39}{3.85/11.85}$	$\frac{1.038}{2.155}$	$\frac{0.616}{0.770}$	$\frac{0.740}{0.819}$	$\frac{0.335}{0.216}$

cont. Table 3

Test		Optimal chemical reagents concentrations [% (*wt./vol.*)]			Technological properties									Comprehensive optimization criteria
α_1	α_2	c_{XG}	c_s	c_a	ρ [kg/m^3]	*HTHP* [cm^3/30 min]	p_{mc} [D]	pH	$\theta_{10s/10}$ [Pa]	τ_0 [Pa]	k [Pa·s^n]	n	k_a/k_m
0.7	0.3	$\frac{0.268}{0.400}$	$\frac{2.22}{1.78}$	$\frac{1.25}{1.25}$	1600	$\frac{13.27}{13.37}$	$\frac{0.012}{0.013}$	10.22	$\frac{3.72/8.39}{4.53/10.18}$	$\frac{1.038}{1.771}$	$\frac{0.616}{0.852}$	$\frac{0.740}{0.705}$	$\frac{0.384}{0.280}$
0.8	0.2	$\frac{0.268}{0.400}$	$\frac{2.22}{1.78}$	$\frac{1.25}{1.25}$	1600	$\frac{13.27}{13.37}$	$\frac{0.012}{0.013}$	10.24	$\frac{3.72/8.39}{4.53/10.18}$	$\frac{1.038}{1.771}$	$\frac{0.616}{0.852}$	$\frac{0.740}{0.705}$	$\frac{0.433}{0.438}$
0.9	0.1	$\frac{0.200}{0.400}$	$\frac{2.74}{1.50}$	$\frac{1.25}{1.25}$	1600	$\frac{12.91}{13.11}$	$\frac{0.035}{0.023}$	10.28	$\frac{3.25/7.30}{4.64/9.91}$	$\frac{1.716}{2.158}$	$\frac{0.491}{0.866}$	$\frac{0.776}{0.690}$	$\frac{0.477}{0.427}$
1.0	0	$\frac{0.228}{0.228}$	$\frac{3.38}{3.38}$	$\frac{1.25}{1.25}$	1600	$\frac{12.90}{12.90}$	$\frac{0.080}{0.080}$	10.26	$\frac{3.77/8.80}{3.77/8.80}$	$\frac{3.098}{3.098}$	$\frac{0.516}{0.516}$	$\frac{0.817}{0.817}$	$\frac{0.516}{0.516}$

solpen-10t (an aqueous mixture of surfactants and auxiliary agents, TU U 24.6-23913269-001:2001) and neonol (oxyethylated monoalkylphenol based on propylene trimers, TU 2483-077-05766801-98), were used to control the surface tension at the filtrate–oil interface of the Bugrivativske field. The killing fluid formulation was justified based on the criterion of cost per unit volume of the formulation (6) C_{fc}, the interfacial tension coefficient σ at the filtrate-oil interface (a special case of criterion (7)), and the cuttings carrying index (9) k_{CCI}. The first case, considering the restrictions on the value of the coefficient σ, is relevant for killing technologies involving complete replacement of the wellbore fluid. The second case can be considered in relation to well-killing technologies with blocking pills. The third case is most relevant when performing workover or maintenance operations for which well killing is necessary.

Table 4. Initial data for selecting the formulation of the killing fluid

Parameter	Value
Well depth [m]	3590
Project productive horizon	C1v2
Bottomhole temperature [°C]	70
Pressure gradient [MPa/m]	0.0107
Fracturing pressure gradient [MPa/m]	0.0181
Perforation interval [m]	3560–3570
Density of killing fluid ρ [kg/m^3]	1050–1160
Gel strength after 1 min θ_1 [Pa]	4–10
Gel strength after 10 min θ_{10} [Pa]	4–12
Yield stress τ_0 [Pa]	up to 3.5
Consistency index k [Pa·s^n]	up to 2.5
Flow index n	up to 0.6
Surface tension index σ [mN/m]	up to 8
Compatibility with drilling mud and rock	compatible
Thermal stability [°C]	100
Permeability recovery coefficient	≥ 0.94

The investigation of killing fluid formulations was carried out according to the design of experiments for variable factor concentrations at 5 levels: sodium chloride c_c = (10, 15, 20, 25, 30)% wt.; solpen-10t c_s = (0, 0.10, 0.25, 0.50, 1.00)% vol.; neonol c_n = (0,0.05,0.10,0.25, 0.50)% vol. at temperatures of 20/70°C (Table 5). Table 6 shows the design and results of the experiments at temperatures of 20°C (numerator) and 70°C (denominator). The most appropriate rheological model for design of experiments (see Table 5), in accordance with the methodology given by Myslyuk (1988, 2019) and Myslyuk and Salyzhyn (2012), is also the Herschel–Bulkley model.

The solution to problem (5), taking into account the accepted criteria and constraints, was obtained using the MudExpert system (Mysliuk and Salyzhyn, 2007). Figure 2 shows, in the $c_s - c_n$ coordinates, the distribution of constant-level lines of the killing fluid formulation selection criteria $c_{uv}(c_s, c_n) = idem$, $\sigma(c_s, c_n) = idem$ and $k_{CCI}\,(c_s, c_n) = idem$, with their corresponding values, highlighting the permissible regions of surfactant concentrations and their optimal levels.

Table 6 shows the composition and technological properties of the killing fluids according to the adopted optimality criteria. The cost per unit volume of killing fluid formulations for criterion C_{fc} is 164 \$/m^3, for criterion σ – 183 \$/m^3, and for criterion k_{CCI} – 175 \$/m^3. The above example illustrates the functional and economic capabilities of well-killing technologies using competitive formulations of process fluids. Obviously, under

Table 5. Design of experiments and tests results for selecting the killing fluid formulation

Test	Factors [%]			Test results					Optimality criteria		
	c_c (*wt.*)	c_s (*vol.*)	c_n (*vol.*)	ρ [kg/m^3]	$\theta_{1/10}$ [Pa]	τ_0 [Pa]	k [Pa·s^n]	n	C_{fc} [\$/m^3]	σ [mN/m]	k_{CCI}
1	25	0	0	1140	7.2/8.6 4.8/4.8	2.415 1.782	1.825 1.083	0.400 0.433	159.5	11.59	0.2043
2	15	0.25	0.05	1070	7.2/8.6 4.3/4.8	2.559 0.895	1.493 1.521	0.412 0.373	149.2	6.69	0.2023
3	10	0	0.50	1040	8.6/9.6 4.8/5.3	2.870 1.469	2.151 1.484	0.365 0.369	146.9	2.66	0.1917
4	30	0.10	0.25	1170	6.7/8.6 5.7/8.1	1.667 2.170	2.066 1.218	0.385 0.447	168.4	6.36	0.2072
5	20	0.50	0.50	1100	6.7/9.1 4.3/4.3	2.237 3.231	1.540 0.578	0.410 0.505	160.7	2.24	0.1892
6	25	1.00	0.50	1130	6.2/7.7 4.8/4.8	3.696 2.332	1.223 0.774	0.451 0.475	168.5	4.50	0.2018
7	25	0.10	0.05	1140	6.2/7.2 4.8/4.8	2.266 1.658	1.705 1.150	0.414 0.425	160.4	8.56	0.2048
8	30	0.50	0.05	1160	7.2/8.1 5.7/7.2	3.285 2.377	1.322 0.974	0.442 0.479	167.9	8.18	0.2101
9	30	0	0.10	1180	8.1/9.1 4.8/5.3	2.694 1.389	1.485 1.375	0.434 0.384	166.5	7.96	0.1973
10	10	0.25	0	1050	8.1/8.6 4.8/5.3	4.127 2.197	1.172 1.095	0.448 0.413	142.7	7.63	0.1911
11	20	0.25	0.10	1110	6.7/7.7 4.3/4.8	2.606 0.985	1.310 1.139	0.429 0.409	155.6	5.47	0.2093
12	20	0	0.05	1120	7.2/8.1 4.3/4.3	1.899 1.402	1.483 1.079	0.419 0.417	154.1	9.04	0.2042
13	20	1.00	0.25	1110	7.2/7.7 4.3/4.3	2.451 0.958	1.516 1.369	0.422 0.388	160.0	2.94	0.2052
14	30	0.25	0.50	1170	6.2/8.1 6.2/7.7	2.859 2.017	1.412 1.379	0.438 0.427	171.5	4.13	0.2051
15	10	1.00	0.05	1030	6.7/8.6 6.2/8.1	2.692 0.425	1.280 1.281	0.430 0.438	146.2	3.73	0.2023
16	25	0.5	0.10	1140	6.7/8.1 4.3/4.8	0.845 1.747	2.566 0.968	0.356 0.443	162.5	6.16	0.2056
17	15	0.5	0	1080	5.7/6.2 4.3/4.8	2.492 1.362	1.430 1.512	0.408 0.374	149.6	5.18	0.1955
18	20	0.10	0	1120	7.2/8.1 4.3/4.8	2.237 1.466	1.540 1.108	0.410 0.400	154.0	9.02	0.1974
19	25	0.25	0.25	1140	5.7/7.2 4.8/4.8	1.001 1.782	2.424 1.083	0.366 0.433	163.1	6.85	0.2043
20	15	1.00	0.10	1070	5.7/6.2 4.3/4.8	2.009 1.245	1.500 1.371	0.417 0.384	152.6	3.95	0.1994
21	10	0.10	0.10	1050	6.7/8.1 4.3/4.8	3.083 0.215	1.255 2.013	0.444 0.335	143.2	8.87	0.2010
22	15	0.10	0.50	1090	5.7/6.7 4.3/4.8	1.422 1.879	1.962 0.959	0.368 0.435	153.2	1.80	0.2005
23	10	0.50	0.25	1040	8.1/8.6 4.3/4.8	0.314 1.257	3.098 1.316	0.320 0.388	146.3	1.24	0.1999
24	30	1.00	0	1170	7.7/9.1 5.7/7.7	0.748 2.351	2.126 1.050	0.388 0.462	169.3	9.14	0.2066
25	15	0	0.25	1080	7.2/8.6 4.3/4.8	1.962 1.923	1.873 1.351	0.375 0.390	150.3	3.33	0.1917

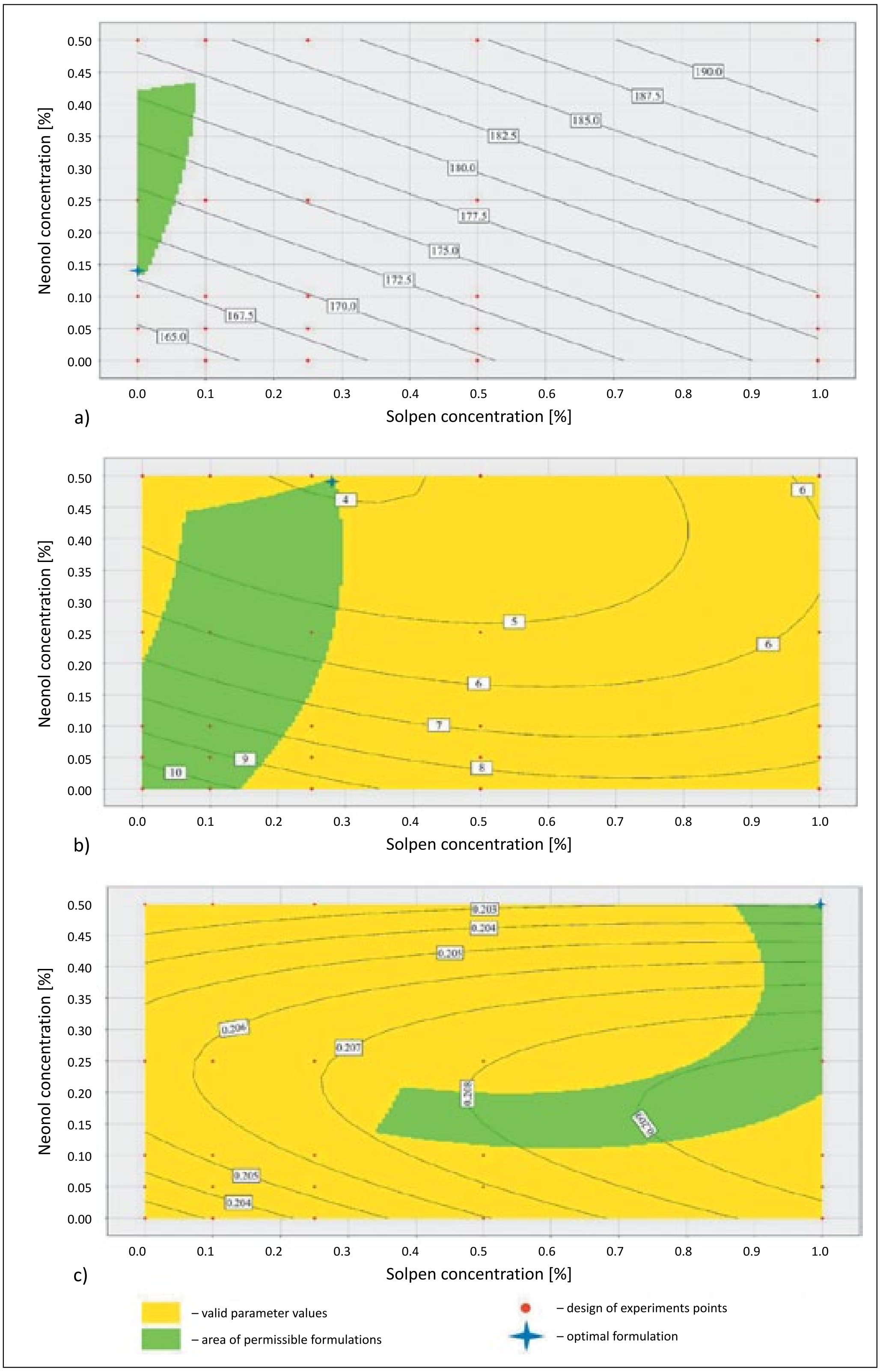

Figure 2. Influence of solpen and neonol concentrations on the choice of the killing fluid optimal formulation: a) according to criterion C_{fc}; b) according to criterion σ; c) according to criterion k_{CCI}

such conditions, it is effective to apply decision-making models in combination with a set of studies of the technological and surface tension properties of killing fluids, as well as their impact on filtration processes in the productive horizon and wellbore cleaning.

Conclusions

Modern trends in the construction of technologically complex wells under complicated geological and drilling conditions require careful selection of effective technological fluid

Table 6. Results of selecting the killing fluid optimal formulation

Components and properties of the killing fluid	Optimality criterion		
	C_{fc}	σ	k_{CCI}
Fluid composition			
Duovis [% (*wt.*)]	0.3	0.3	0.3
PAC-R [% (*wt.*)]	0.5	0.5	0.5
Sodium chloride [% (*wt.*)]	27.6	28.4	28.8
Solpen-10t [% (*vol.*)]	0.00	0.28	0.96
Neonol [% (*wt.*)]	0.14	0.49	0.179
Fluid properties at 20/70°C			
Density ρ [kg/m^3]	1161/–	1160/–	1160/–
Interfacial tension σ [mN/m]	7.95/–	3.95/–	6.64/–
Gel strength after 1 min θ_1 [Pa]	7.1/6.8	6.2/5.7	6.7/6.1
Gel strength after 10 min θ_{10} [Pa]	8.4/8.1	8.2/7.8	8.2/5.3
Yield stress τ_0 [Pa]	2.022/1.461	2.656/2.441	1.799/1.874
Consistency index k [Pa·s^n]	1.803/1.285	1.435/1.099	1.842/1.274
Flow index n	0.405/0.409	0.427/0.458	0.400/0.430

formulations from among competing alternatives. This requires the use of approaches based on the analysis of industrial information, laboratory and bench studies, and modeling of well construction processes based on local criteria for the optimality of process fluid formulations.

A hierarchical model for selecting the optimal formulation of process fluids was proposed. It includes the substantiation of a subset of equivalent formulations, selection of a base formulation and its component composition, and selection of a surfactant composition to ensure the required interfacial properties. The model was developed based on expert procedures and fuzzy logic, the results of multifactorial studies of the influence of chemical reagents and well conditions on the properties of process fluids, as well as regression analysis methods.

Using the additive criterion of the *HTHP* filtration loss and the permeability of the mud cake p_{mc}, the optimal formulation of the Biocar-TF drilling mud aimed at maximum preservation of the reservoir properties of productive horizons was selected, and it was adopted as the base for drilling within the interval 5752–6572 m of well 43 Semyrenky. The use of the Biocar-TF drilling mud formulation confirmed the high stability of its technological properties, its inhibitory effect on the thickness of unstable rocks, and the high quality of initial exposure of productive horizons.

Using the example of well 526 of the Bugrivativske field, the feasibility of modeling killing fluid formulations based on various optimality criteria was demonstrated, namely cost per unit volume, surface tension at the interface between the killing fluid filtrate and oil, and cuttings carrying index.

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