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Comprehensive assessment of the predictive effectiveness of measures to limit water inflow with a composition based on cross-linked polymer systems

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Комплексная оценка прогнозной эффективности проведения мероприятий по ограничению водопритока составом на основе сшитых полимерных систем

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Keywords:
water cut, water inflow limitation, water-insulating composition based on cross-linked polymer systems, candidate wells, predictive efficiency, hydrodynamic modeling, filtration model, viscosity, concentration, adsorption, permeability, pore volume, statistical model, regression equation, fluid flow rate.

A method for a comprehensive assessment of the predictive effectiveness of carrying out measures to limit water inflow with a water-insulating composition based on cross-linked polymer systems is presented. This method includes the calculation of predictive performance indicators using geological and hydrodynamic modeling with confirmation of the results using statistical models and is shown on the example of the wells of the Vozeyskoye field in the Komi Republic.
To evaluate the predictive efficiency using geological and hydrodynamic modeling, the filtration model of the carboniferous deposit of the Vozeyskoye field, the results of laboratory studies of the rheology of the developed composition based on cross-linked polymer systems, and the technological parameters of candidate wells were used as initial data. For correctly modeling filtration processes that occur during the passage of the water-insulating composition through the pore space, both the change in the solution viscosity, depending on the polymer concentration, and decrease in the rock permeability for water in the presence of the adsorbed polymer were taken into account.
To confirm the results of geological and hydrodynamic modeling with the implementation of the procedure for the sequential inclusion of geological and technological parameters, regression equations were constructed for predicting a decrease in fluid flow rates. The regression equation for the decrease in fluid flow rates made it possible to satisfactorily predict the effectiveness of water shut-off operations using the most informative geological and technological parameters: fluid flow rate before measures to limit water inflow, injection pressure of a water-insulating composition, thickness of the water inflow interval based on the results of geophysical surveys, porosity coefficient, compartmentalization coefficient, formation temperature.
As a result, based on the integration of different methodological approaches, the assessment of the predictive effectiveness of using a composition based on cross-linked polymer systems made it possible to make a decision on the feasibility of conducting pilot work at the selected area of the Vozeyskoye field in the Komi Republic.

Ключевые слова:
обводненность, ограничение водопритока, водоизоляционный состав на основе сшитых полимерных систем, скважины-кандидаты, прогнозная эффективность, гидродинамическое моделирование, фильтрационная модель, вязкость, концентрация, адсорбция, проницаемость, поровый объем, статистическая модель, уравнение регрессии, дебит жидкости.

Представлен метод комплексной оценки прогнозной эффективности проведения мероприятий по ограничению водопритока водоизоляционным составом на основе сшитых полимерных систем. Данный метод включает в себя расчет прогнозных показателей эффективности с использованием геолого-гидродинамического моделирования с подтверждением результатов использованием статистических моделей и показан на примере скважин Возейского месторождения Республики Коми.
Для оценки прогнозной эффективности с помощью геолого-гидродинамического моделирования в качестве исходных данных использованы фильтрационная модель каменноугольной залежи Возейского месторождения, результаты лабораторных исследований реологии разработанного состава на основе сшитых полимерных систем и технологические параметры работы скважин-кандидатов. Для корректного моделирования фильтрационных процессов, протекающих при прохождении водоизоляционного состава через поровое пространство, учтены как изменение вязкости раствора, зависящее от концентрации в нем полимера, так и уменьшение проницаемости породы для воды в присутствии адсорбированного полимера.
Для подтверждения результатов геолого-гидродинамического моделирования с реализацией процедуры последовательного включения геолого-технологических параметров построены регрессионные уравнения прогноза снижения дебитов жидкости. Регрессионное уравнение снижения дебитов жидкости позволяет удовлетворительно прогнозировать эффективность водоизоляционных работ по наиболее информативным геолого-технологическим параметрам: дебит жидкости до мероприятий по ограничению водопритока, давление закачки водоизоляционного состава, мощность интервала водопритока по результатам геофизических исследований, коэффициент пористости, коэффициент расчлененности, пластовая температура.
В итоге проведенная на основе комплексирования разных методических подходов оценка прогнозной эффективности применения состава на основе сшитых полимерных систем позволила принять решение о целесообразности проведения опытно-промышленных работ на выбранном участке Возейского месторождения Республики Коми.

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Introduction

At present, a large number of fields in the Timan-Pechora oil and gas province produce oil with a high percentage of water cut, which reduces the oil recovery factor and leads to an increase in unproductive costs of extraction, treatment and utilisation of associated water.

One of the options for solving the problem of high water cut of well products is to carry out geological and technical measures for water flow limitation (WFL) [1–4]. In this regard, the definition of approaches to planning and implementation of these measures are urgent tasks [5–10].

In 2019 pilot work (PW) was carried out at the Vozeyskoye field in the Komi Republic to test a water-insulating composition based on cross-linked polymer systems developed by PermNIPIneft, a branch of LUKOIL-Engineering LLC [11]. For this purpose, the Branch, together with LLC LUKOIL-Komi, selected a pilot area of the C2+3 formation of the Vozeyskoye field, which is represented by injection well No H-1 and production wells No D-1, D-2, D-3, located in the injection source. The experience of using similar water-insulating compositions is described in a number of research papers [12–32].

In planning PW a method of comprehensive assessment of the predictive effectiveness of WIL measures was implemented by the application of geological and hydrodynamic modeling and statistical models.

Assessment of predictive efficiency by geological and hydrodynamic modeling

At modeling measures on water inflow limitation in hydrodynamic simulators it is necessary to take into account the results of the processes occurring during the interaction of the water-insulating composition with the pore space and the fluids saturating the reservoir [33–35].

Due to the possibility of reproducing polymer filtration in a porous medium, the Tempest MORE 8.1 hydrodynamic simulator was used to simulate the injection of water-insulating compositions. Account of polymers in Tempest MORE adds to the equations of conservation of mass of water, oil, and gas an additional polymer mass conservation equation which is implicitly considered and available for the three-phase three-dimensional model of Black Oil [36–38]:

$$\left[V_p\left(C_{ply}S_w b_w+(1-\varphi)C_{abs}\left(C_{ply},C_{abs}^{\max}\right)\right)\right]^{T+\Delta T}-$$
$$-\left[V_p\left(C_{ply}S_w b_w+(1-\varphi)C_{abs}\left(C_{ply},C_{abs}^{\max}\right)\right)\right]^{T}= \qquad (1)$$
$$=\Delta T\left(F_{ply}+Q_{ply}\right),$$

where V_p – pore reservoir volume, m^3; C_{ply} – concentration of polymer solution, kg/m^3; S_w – water saturation, fractions of units; b_w – water volume factor, fractions of units; φ – reservoir porosity in the cell, fractions of units; C_{abs} – amount of adsorbed p-Polymer for cell, kg/m^3; $C_{abs}{}^{max}$ – maximum value of the amount of adsorbed polymer for the cell for the entire period from the beginning of the calculation to the current date, kg/m^3; F_{ply} – polymer flow between cells; Q_{ply} – polymer inflow to and from wells; T – moment of time; ΔT – time step.

Equation (1) shows that the important parameters affecting the water inflow limitation measures are the concentration of polymer composition C_{rly} and the amount of adsorbed polymer C_{abs}.

In the course of hydrodynamic modeling of the processes occurring during WIL measures at the Voseyskoye PW site, the viscosity multiplier in the model C_{mult} and the concentration of the water-insulating composition C_{plu}, are related by the dependence $C_{mult} = C_{mult}(C_{plu})$, which was obtained during laboratory studies of the rheology of the composition for its different concentrations (Table 1).

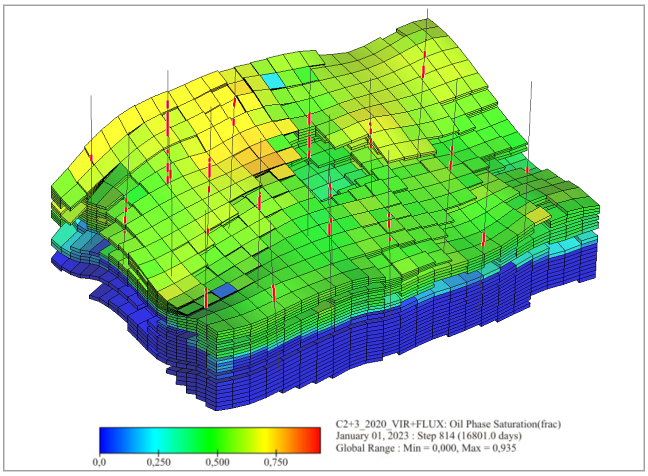

Fig. 1. Sectoral model of the pilot site of the Voseyskoye field by the example of oil saturation distribution cube

Table 1

Dependence of viscosity of water-insulating composition on concentration at shear rate 5,11 c^{-1}

C_{ply}, %	C_{mult}
0	1.0
4	256
9	1861

The presence of the polymer affects the flow in the formation in two ways: as a change in the viscosity of the solution, which depends on the concentration of the polymer in it and as a reducing permeability of the rock for water in the presence of adsorbed polymer [39–41]. In a simple reversible model the amount of adsorbed polymer is a function of its concentration $C_{abs} = C_{abs}(C_{rly})$, but in the case of injection of water-insulating compositions based on cross-linked polymer systems, the adsorption process is irreversible, i.e.

$$C_{abs} = \max\,[C_{abs}(C_{ply}),\ C_{abs}{}^{\max}]. \qquad (2)$$

The model of polymer adsorption and associated permeability reduction was developed by G.J. Hirasaki and G.A. Pope [40]. Hirasaki and G.A. Pope [40]. According to this model, the mass of polymer adsorbed by the rock is determined by the formula:

$$m_p^A = V_p\left(1-\varphi\right)C_A\frac{\alpha}{\eta}\left[M_p\eta\right]^{1/3}\left(\varphi/k\right)^{1/2}, \qquad (3)$$

where C_A – a constant whose value depends on the system of measurement units; φ – reservoir porosity in the cell, fractions of units; k – permeability, μm^2; M_p – molar mass of polymer, Dalton; $\eta=\dfrac{\mu_p-\mu_w}{C_{ply}\mu_w}$ – function depending on polymer properties; μ_p, μ_w – viscosity of polymer solution and mixing water respectively, mPa ·c.

In order to assess the predictive efficiency of water inflow limitation measures, a three-dimensional filtration model of the C_{2+3} site of the Voseyskoye field was created by geological and hydrodynamic modelling in Tempest MORE 8.1 simulator.

In order to optimise and reduce the time of calculations, a separate sector was allocated along the boundaries of the pilot site, including the area of 18 wells,

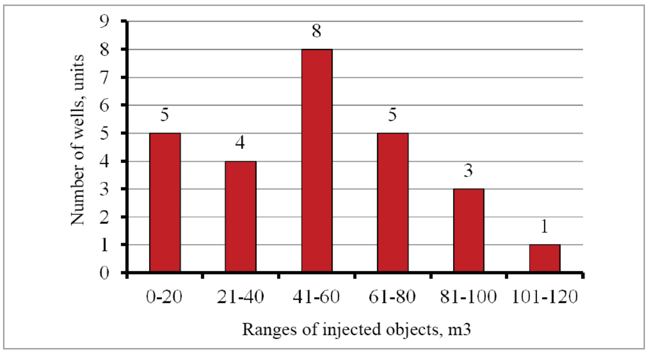

Fig. 2. Distribution of values of injected into wells volumes of water-insulating compositions based on cross-linked polymer systems

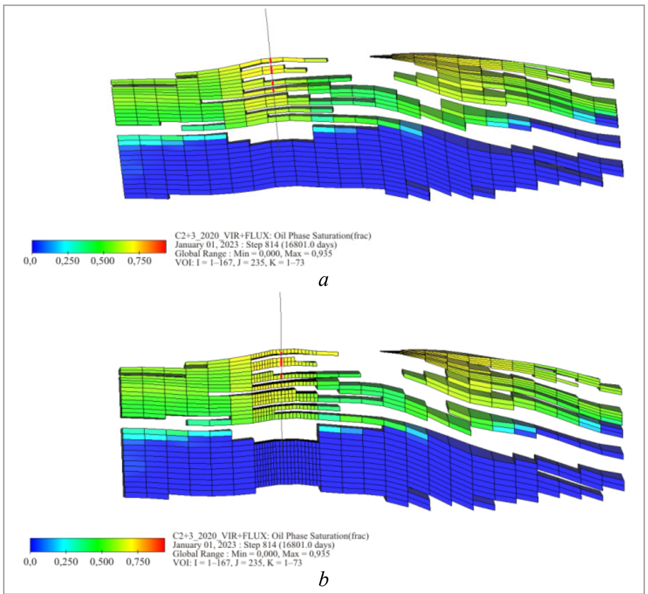

Fig. 3. Section of well No. D-1 by the example of the current oil saturation cube: *a* – without cell refinement; *b* – with cell refinement

Table 2

Pore cell volumes, penetrated by candidate wells

Well number	Minimum pore volume of cells, m^3	Minimum pore volume of cells, m^3	Average pore volume of cells m^3
Д-1	97.05	2035.24	773.71
Д-2	36.48	1821.49	628.31
Д-3	77.54	1927.49	777.25

Table 3

Pore cell volumes penetrated by candidate wells after refinement

Well number	Minimum pore volume of cells, m^3	Minimum pore volume of cells, m^3	Average pore volume of cells m^3
Д-1	2.55	58.07	17.58
Д-2	0.87	49.95	14.37
Д-3	1.55	79.63	18.65

three of which are candidate wells for testing the developed water- insulating composition based on cross-linked polymer systems (Fig. 1).

For correct modelling of filtration processes occurring during water-insulating operations at the Voseyskoye field, it is necessary to compare the volumes of the composition planned for injection and the pore cell volume of three selected candidate wells.

Fig. 2 shows the distribution of values of the volumes of water-insulating compositions based on cross-linked polymer systems injected into the wells, constructed for all water inflow limitation measures carried out in the fields of the Komi Republic during the period preceding the pilot works on testing the composition developed by the Branch.

Table 2 shows the average, minimum and maximum pore volumes of the geological and hydrodynamic model cells, which were penetrated by the candidate wells selected for pilot works.

As a result of water inflow limitation measures at the wells of the Komi Republic fields, the actual volume of the injected composition varies from 10 to 120 m3 (Fig. 2). The average pore volume of the model cells opened by the candidate wells (see Table 2) significantly exceeds the actual volume of the injected composition. Thus, it can be concluded that the entire volume of injected agent remains within a single column of cells along the candidate wellbores.

To solve the problem of modelling of water inflow limitation measures on three-dimensional hydrodynamic models it was decided to change the scale of meshes in the area of candidate wells by means of local mesh refinement. Thus, the meshes in the area of the wells were desintegrated 300 times: 10 times in the X and Y directions, 3 times in the Z direction (Fig. 3).

Table 3 shows the average, minimum and maximum pore volumes of the cells opened by the candidate wells after the refinement procedure. The data in the table show that the pore volume of the cells became comparable to the injection volume.

To assess the predictive operation modes of candidate wells No. D-1, D-2, D-3 of the Voseyskoye field after water inflow limitation measures, the following forecast variants were calculated on the geological and hydrodynamic model:

1. Base variant without WIL measures.
2. The variant with carrying out the WIL measures with the composition on the base of cross-linked polymer systems on three candidate wells.

Forecast period is three years with a calculation step of one month. The start of the forecast is 01.01.2020.

The results of calculation of forecast production indicators for candidate wells of the Voseyskoye field are presented in Fig. 4. According to Fig. 4 it has been revealed that the predictive efficiency of water inflow limitation with cross-linked polymer systems is established in all candidate wells.

Estimation of predictive efficiency by building predictive statistical models

To create statistical models of the predictive efficiency of water inflow limitation measures the results of measures taken earlier at the fields of the Komi Republic with water-insulating compositions based on cross-linked polymer systems have been analyzed.

The main indicator of the effectiveness of measures to limit water inflows - reduction of liquid flow rates – was chosen as the dependent variable. Multiple regression models were used to predict the values of dependent variables based on a set of a number of independent variables: liquid flow rate, water-oil factor, thickness of water inflow interval based on geophysical survey results, effective oil saturated thickness, porosity, permeability, partitioning, sandiness coefficients, reservoir pressure, reservoir temperature, pressure of water-insulating composition injection, volume of injected water-insulating composition, distance from the bottom perforation hole to the oil water contact (OWC) and the density of produced water.

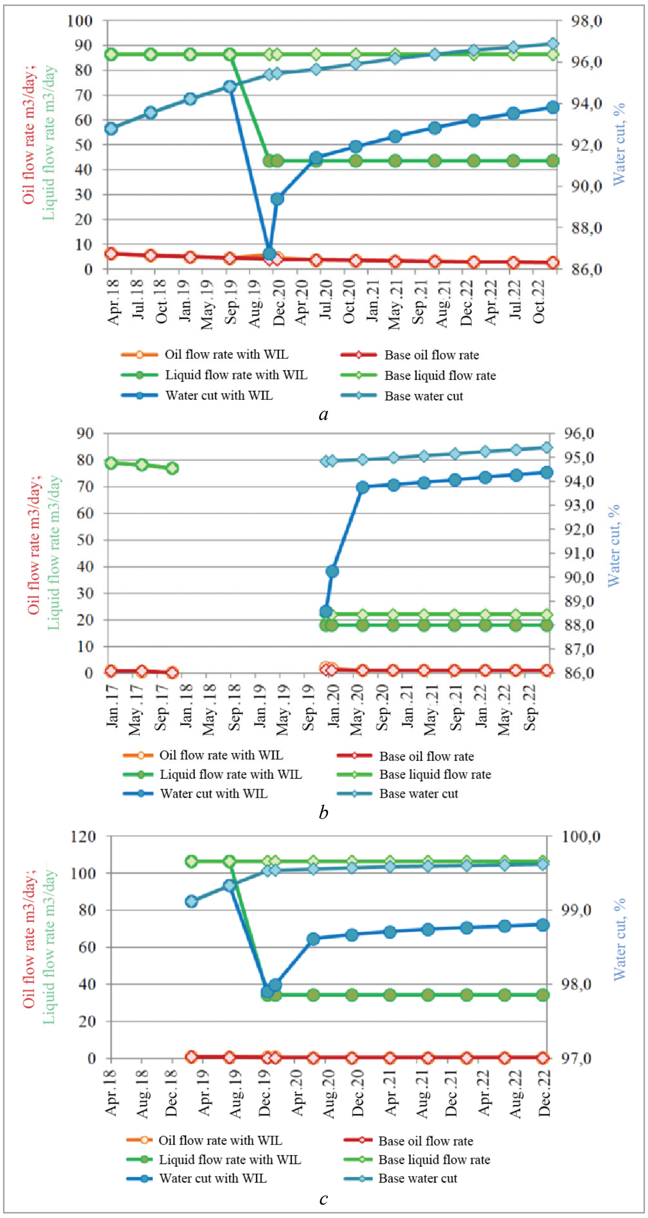

Fig. 4. Results of calculation of forecast production indicators by wells: *a* – No. D-1 of the Voseyskoye field for two variants (with WIL measure and base); *b* – No. D-2b – No. D-2 of the Voseyskoye field for two variants (with WIL measure and base); *c* – No. D-3 of the Voseyskoye field for two variants (with WIL measure and base)

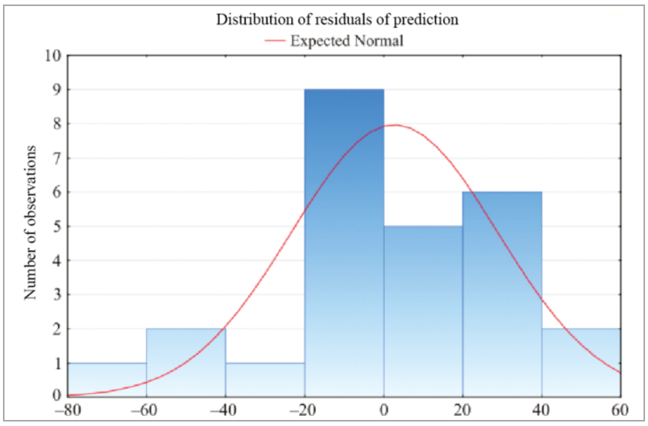

Fig. 5. Histogram of distribution of residuals of prediction of liquid flow rate reduction after WIL measures for fields of the Komi Republic

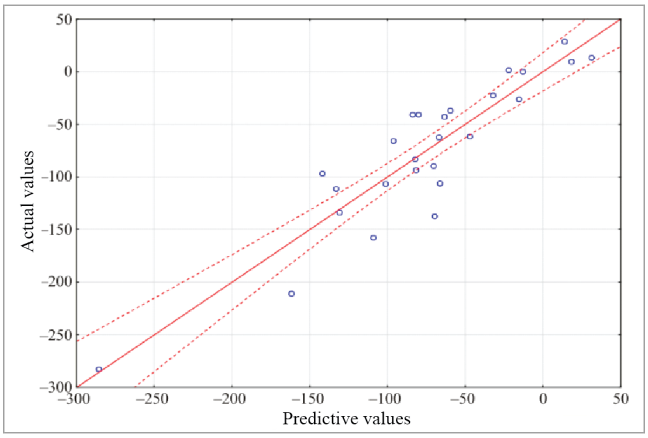

Fig. 6. Comparison of predicted and actual values of liquid flow rate reduction after WIL measures for the fields of the Komi Republic

In accordance with the technique of constructing multivariate regression equations, the statistical model was built by the method of stepwise regression with the implementation of the procedure of sequential inclusion of geological and technical parameters [42, 43]. Initially, the regression equation of technological efficiency from the most informative parameter has been considered. Then this equation includes the parameter, which together with the previously selected one has the greatest informativeness (Table 4).

The data in Table 4 show that the final regression equation of liquid flow rate reduction has a sufficiently high quality of prediction: the coefficient of determination R^2 is 0.84 [44, 45].

To check the quality of the regression equation we analysed the residuals (Fig. 5) and compared the predicted and actual values of liquid flow rate reduction (Fig. 6).

In Fig. 5 there is a satisfactory agreement of the histogram of residuals with the normal distribution.

The obtained regression equation (see Fig. 6) gives high quality prediction of liquid flow rate reduction after water limitation measures. Thus, this statistical model can be used to assess the predictive efficiency.

Comparison of the Results of Predictive Efficiency Assessment

Table 5 presents a comparison of the results of assessing the predictive efficiency by geological and hydrodynamic modeling, the construction of predictive statistical models and the actual results obtained at candidate wells after testing the developed water-insulating composition based on cross-linked polymer systems.

Based on the data given in Table. 5, there is a fairly high coincidence of the results obtained for wells No D-2 and D-3. The discrepancy in the results for well No D-1 is explained by the deviation of the actual work from the planned one: the actual interval of injection of the composition was increased due to the lack of work on filling the lower part of the perforation interval.

In general, the predictive efficiency of measures to limit water inflow has been establishedat candidate wells No D-1, D-2, D-3 of the Vozeyskoye field with a composition based on cross-linked polymer systems.

The assessment of the predictive efficiency of the proposed technology, carried out on the basis of the integration of various methodological approaches, made it possible to make a decision on the expediency of carrying out pilot work at the selected site.

Table 4

Multivariate Regression Equations for Predicting Fluid Flow Rate Reduction for wells with completed WIL measures in the Komi Republic

Variant of calculation	R^2	p-value	F- criterion	Regression Equation
1	0.48511	0.00008	22.612	$\Delta Q_f = 44.05 - 0.77 \cdot Q_f$
2	0.55709	0.00009	14.464	$\Delta Q_f = 34.541 - 0.623 \cdot Q_f - 0.894 \cdot P_{inj}$
3	0.59126	0.00016	10.608	$\Delta Q_f = 11.985 - 0.675 \cdot Q_f - 0.839 \cdot P_{inj} + 2.342 \cdot H_{wif}$
4	0.63875	0.00018	9.283	$\Delta Q_f = 11.408 - 0.612 \cdot Q_f - 0.668 \cdot P_{inj} + 3.578 \cdot H_{wif} - 2.044 \cdot K_{dism}$
5	0.72982	0.00004	10.805	$\Delta Q_f = -33.794 - 0.565 \cdot Q_f - 0.852 \cdot P_{inj} + 3.708 \cdot v - 3.738 \cdot K_{dism} + 1.139 \cdot T_{res}$
6	0.83539	0.00000	16.070	$\Delta Q_f = -324.064 - 0.602 \cdot Q_f - 0.627 \cdot P_{inj} + 3.111 \cdot H_{wif} - 2.652 \cdot K_{dism} + 2.443 \cdot T_{res} + 1178.257 \cdot K_p$

Note: ΔQ_f – Reduction of fluid flow rates, m^3/day; Qf – fluid flow rate before WIL measures, m^3/day; P_{inj} – pressure of the water-insulating composition injection, MPa; H_{wif} – capacity of the water inflow interval; K_{dism} – dismemberment coefficient, units.; T_{res}– reservoir temperature; K_p – Porosity coefficient, fractions of units.

Table 5

Comparison of actual results and results of the assessment of predictive efficiency

Well	Fluid flow rate Rrduction, m^3/day		
	Calculation on a Geological and Hydrodynamic Model	Calculation on a Statistical Model	Actual Value
№ D-1	–42.8	–84.9	–89.2
№ D-2	–59.1	–60.4	–49.2
№ D-3	–72.1	–85.0	–92.9

Conclusion

On the example of planning measures for water inflow limitation by a composition based on cross-linked polymer systems the use of a comprehensive assessment of predictive efficiency which includes the main and control methods has been shown. The main method is the calculation of predictive indicators of oil production and fluids on a geological and hydrodynamic model. But since in the hydrodynamic modeling there is a probability of a discrepancy between the predictive and the actual results due to the complexity of the geological structure of the objects of the Komi Republic an additional method for assessing the predictive efficiency by statistical models is used. The construction of multivariate regression equations takes into account the accumulated experience in the application of water inflow limitation technologies in the fields of the Komi Republic and, accordingly, has a high quality of prognosis which allows us to consider this method as a control one.

In case of significant discrepancy between the results obtained during the comprehensive assessment it is recommended to conduct an additional analysis of the study of the object under consideration, identify uncertainties, develop a program to manage possible risks and, if possible, update the current filtration model.

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