OIL AND GAS PRODUCTION

Concerning the use of statistical estimates of productive bed parameters using pressure recovery curves

MYSLIUK M.A.,

Doctor of technical Science IFNTUOG

PETRUNIAK V.Ya.

JV "Poltava Oil and Gas Company"

Nowadays hydrodynamic monitoring of productive beds is mostly conducted with the help of pressure recovery curves (PRC). Common methods of interpretation of hydrodynamic research on the PRC [1-6] are based on deterministic productive bed evaluation that does not correspond to information provision and limits their practical use.

Some authors [7, 8] proposed a method of processing of data of productive bed PRC hydrodynamic monitoring, which lays in selection of the most adequate model of a class of possible hydrodynamic modeling of the reservoir. Model and parameters of a productive bed are estimated with the use of maximum likelihood function. Note that in this case the evaluation of bed parameters satisfies the condition of effectiveness.

In the applied aspect of data interpretation of hydrodynamic data for productive bed lays in building statistical estimates of the bed parameters, formulation and verification of relevant statistical hypotheses, simulation of hydrodynamic processes which take place during implementation of active impact on the productive bed. The aforementioned elements of application of statistical information are considered below:

Data processing $(\{\bar{p}_{c_i}\}, \{t_i\}, i = \overline{1, n})$ of PRC hydrodynamic study lays in estimation of a_0 and a_1 parameters of the following linear model

$$\varphi = a_n + a_1 \psi(t), \qquad (1)$$

where p_{c_i}, t_i – results of time and pressure measurement; φ, $\psi(t)$ – approximating functions that depend on interpretation method and fluid type (oil, gas).

For example, for D.K. Horner method and oil reservoir [2–4]

$$\varphi = p_c, \ \psi(t) = \ln\frac{t}{T+t}, \ a_0 = p_П, \ a_1 = \frac{\eta Q_c}{4\pi kh}; \qquad (2)$$

for the modified D.K. Horner method and oil reservoir [2–4]
for a fiery seam at $T < 20 t_{вт}$ [1]

$$\varphi = p_c - p_c(T), \ \psi(t) = \ln\frac{t}{T+t}, \ a_0 = \frac{\eta Q_c}{4\pi kh}\ln\frac{2{,}25\kappa T}{R_{СП}^2}, \ a_1 = \frac{\eta Q_c}{4\pi kh}; \qquad (3)$$

for a fiery seam at $T > 20 t_{вт}$ [1]

$$\varphi = p_c^2, \ \psi(t) = \ln t, \ a_0 = (p_c(0))^2 + \frac{a_1 \ln(2{,}25\kappa^2)}{R_{СП}^2} + bQ_{c_0}^2,$$

$$a_1 = \frac{\eta Q_{c_0} p_0 \bar{z}_П T_П}{2\pi kh T_0}; \qquad (5)$$

etc. Where: T, $t_{вт}$ – duration of well operation with the flow rate Q_c or Q_{c_0}, till its stop and pressure recovery; $p_п$, $T_п$ – reservoir pressure and temperature; k, κ – permeability and piezoconductivity of the bed; η – fluid viscosity; h – bed thickness; $R_{сп}$ – equivalent well radius; Q_{c_0} – gas flow rate in normal conditions (p_0 = 0,1013 МПа, T_0 = 293 K); $\bar{z}_п$ –

gas-compressibility factor in bed conditions.

Note, that there is a statistical dependence between the evaluation of the parameters of the model (1) according to the results of the PRC measuring and covariance matrix [7, 8]

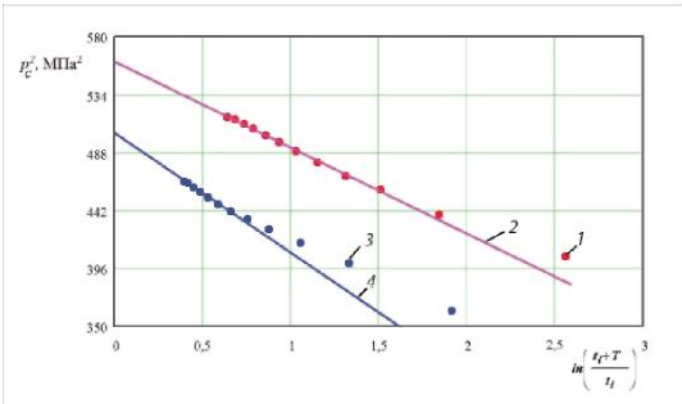

Fig. 1. PRC of well No. 206 of Movchanivsky oil-gas condensate field before (study date 27.03.2009) and after (1-5.04.2009) intensification: *1, 3* – measurement data; *2, 4* – results of processing acc. to D.K. Horner method

$$O \equiv \begin{vmatrix} \sigma_0^2 & r_{01}\sigma_0\sigma_1 \\ r_{01}\sigma_0\sigma_1 & \sigma_1^2 \end{vmatrix} = (\varphi'(t)C^{-1}\varphi'^{T}(t))^{-1}, \qquad (6)$$

where σ_0^2, σ_1^2 - dispersion evaluation of a_0 and a_1, respectively;

r_{01} – correlation coefficient evaluation between these parameters; $\varphi'(t)$, $\varphi'^{T}(t)$ – derivative matrix according to estimated bed parameters and its transposed matrix; *C* – covariance matrix for a random component in the task of processing of hydrodynamic research data [7, 8].

With the confidence probability α, ellipsoid of estimated model parameters (1) is defined by an inequality [9]

$$(a - \hat{a})^{T} O^{-1} (a - \hat{a}) < F_{\alpha;q;n-q}, \qquad (7)$$

where – quantile of *F*-distribution of with degrees of freedom *q*

and $F_{\alpha;q;n-q}$ *n-q*; *q* – vector length for model parameters (1).

Statistical evaluation of a_0 and a_1 composite bed parameters (water permeability $G = kh/\eta$,permeability *k* etc.) is made with the use of such dependencies as (2)–(5) and others with regard to information on laws and parameters of distribution of input values.

In general, for different laws of distribution of known values methods of statistical modeling or Monte Carlo simulation [10] are used for statistical evaluation of composite parameters β . Let the vector of composite of the parameters of the reservoir be given with (2) - (5), etc. as

$$\beta = \beta(\lambda, \zeta, \xi), \qquad (8)$$

where λ [9]– exactly known values; ζ – inaccurately known statistically independent values, ξ – inaccurately known statistically dependent variables. In this case, the algorithm for constructing of statistical estimates of β is reduced to simulation of random variables ζ та ξ, forming the sample of layer component parameters and for their statistical evaluation.

In terms of applied sciences, the availability of statistical information requires the formulation and testing of statistical hypotheses, and in some cases - building of statistical models of decision making [7, 9, 11, 12]. Of the highest priority are statistical hypotheses on vector estimated parameters like H_0: $a = a_*$ and H_0: $a = b$, де a, $\hat{b}$ –, where a and b are vectors of bed parameters, a_* - a fixed vector of bed parameters. The first of these hypotheses is tested using statistics [9]

$$K = (\hat{a} - a_*)^T Q^{-1} (\hat{a} - a_*) < F_{\alpha, \ldots} \qquad (9)$$

which corresponds to F-distribution. To check the H_0: $a = b$ hypothesis we can use a correlation criteria of the likelihood function [11]

$$K = \frac{L(a)}{L(b)} < c, \qquad (10)$$

where $L(a), L(b)$ – are likelihood functions $(L(a) \geq L(b))$.

This parameter is assumed according to confidence probability α of the criterion of verifiability of the hypothesis [11]:

General data on studied objects

Well	Horizon index	Perforation interval (top/bottom) ,m	Effective thickness, m	Study date	Bed temperature, °C		Gas properties			Well operation time before stop	Study duration, h
							$\bar{\rho}_r/\sigma_\rho$,	η/σ_η, мПа·с			
206	T-1-2-3	2439 2478	48.9	27.03.09	85	1,3727 0,0206	0,637 0,025	0,011 0,0008	0,858 0,043	47	97
206	T-1-2-3	2439 2478	48.9	01–05.04.09	84	2,9502 0,0443	0,637 0,025	0,011 0,0008	0,858 0,043	9	10
167	T-1-2	2577 2998	46.2	20–25.02.10	89	0,0463 0,0007	0,626 0,025	0,011 0,0008	0,874 0,044	48	114
167	T-1-2	2577 2998	46.2	05–08.03.10	89	1, 3704 0,0206	0,626 0,025	0,011 0,0008	0,874 0,044	20	63
p_r – relative gas density by air, standard deviation											

Table 1

Table 2

Results of PRC interpretations for Movchanivsky oil-gas condensate field before and after intensification works

Well	Before intensification				After intensification			
	a_0/σ_0, МПа²/МПа²	a_1/σ_1, МПа²/МПа²	r_{01}	L, МПа⁻⁴	a_0/σ_0, МПа²/МПа²	a_1/σ_1, МПа²/МПа²	r_{01}	L, МПа⁻⁴
206	562,628 0,7956	-70,915 0,8574	-0,973	2,540	504,779 1, 3756	-99,167 3,0088	-0,994	0,882
167	356,811 0,5870	-66,333 1,6170	- 0,9 99	13,613	333,647 0,0554	-278,4 41 0,1947	-0,999	591,928

$$c = \frac{\alpha}{1-\alpha}, \qquad (11)$$

$$\sup P_0(K > c) = \alpha, \qquad (12)$$

where P_0 - distribution of sample (10) for b. parameter.

Testing of statistical hypotheses (9) and (10) with a given confidence probability α provides justification for judgments about effective influence of various methods of action on the bottomhole formation zone. More important is the use of statistical information in decision-making, which generalizes the estimation of parameters and their ranges of reliability, formulation and testing of statistical hypotheses, and so on.

In problems of decision making in an explicit form (monetary or conditional) a numerical function (loss function) is introduced, that represents effects resulting from each step in the given conditions [12]. Availability of information on statistical estimated parameters allows for the construction of probability space for possible states of bed properties, which provides reliability of modeling of hydrodynamic processes and building of loss function during implementation of the technology at bottomhole formation zone. The loss function reflects a situation that goes beyond estimation and testing of a hypothesis.

Let us consider statistical evaluation of productive bed parameters using data obtained as the result of hydrodynamic studies of some wells of Movchanivsky oil-gas condensate field (GOCF) before and after their treatment with hydrochloric acid.

Gas flow rate of the well No. 206 amounted to 254.88 thousand m^3 gas a day and 79.5 tonnes condensate a day. After formation treatment (35 m^3 of 15% hydrochloric acid solution) the gas flow rate reached 91.05 thousand m^3 gas a day and 8 tonnes condensate a day

The well No. 167 was put into operation with the gas flow rate of 4 thousand m^3 a day. After formation treatment (200 m^3 of 15% hydrochloric acid solution) the gas flow rate reached 118.37 thousand m^3 gas a day and 1 tonne condensate a day.

General information about the objects of study is given in Table. 1. Taking into consideration the recommendations [1], the PRC processing for wells was performed by (1) and (4) according to the method [7, 8]. Class ϑ of possible hydrodynamic models of productive bed (2) was generated parametrically depending on the number of points of the linear plot of the diagnostic chart. The most appropriate hydrodynamic model of the reservoir was selected with the use of the minimum variance adequacy criterion. The main results of PRC interpretation before and after intensification are given in Table. 2.

Table 3 Results of productive bed parameters estimation at the wells of Movchanivsky GOCF

Statistical estimate of the bed parameters	Well No. 206		Well No. 167	
	BEFORE intensification	After intensification	BEFORE intensification	After intensification
$p_п$, МПа	23.718 23.720	22.469 22.467	18.890 18.889	18.266 18.266
$G = (kh/\eta)10^{12}$, м³/Па·с	328.7 327.2	502.9 501.4	12.15 12.15	85.88 85.68
$k \cdot 10^{15}$, м²	0.0742 0.0736	0.1136 0.1128	0.0029 0.0029	0.021 0.020
σ_p, МПа	0.016	0.029	0.015	0.001
$\sigma_G \cdot 10^{12}$, м³/Па·с	17.99	29.48	0.693	4.39
$\sigma_k \cdot 10^{15}$, м²	0.0069	0.0108	0.00028	0.0019
r_{pG}	-0.210	-0.466	-0.412	-0.007
r_{pk}	-0.127	-0.290	-0.246	-0.007
Гск	0.556	0.581	0.597	0.546

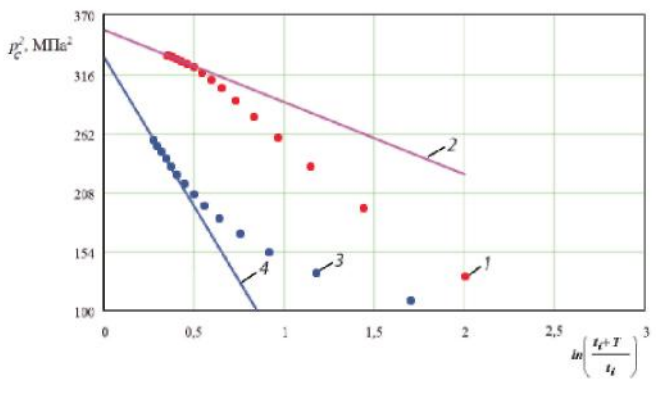

Fig. 2. PRC of well No. 167 of Movchanivsky oil-gas condensate field before (study dare 20 - 25.02.2010) and after (5 - 8.03.2010) intensification: 1, 3 – measurement data; 2, 4 – results of processing acc. to D.K. Horner method

Fig. 1 and 2 show the productive bed PRC measurements before and after the intensification at the well No. 206 and 167 at Movchanivsky GOCF and the results of their treatment. The analysis shows compliance with the terms diagnostic measurement data (1) with due consideration of (4). Fig. 3 demonstrates ellipsoids of parameter estimates of the model (1) [confidence probability $\alpha = 0.05$] for the PRC of the well No. 167. Table. 2 shows the evaluation of the maximum likelihood function values for the parameters of the bed according to the results of PRC processing, the conditions (10) of testing of the statistical hypotheses H_0: $a = b$ with confidence probability α = 0,05 are not fulfilled for the wells in question. This indicates a statistically significant difference of estimates of the model parameters of the bed (1) before and after intensification, which is also clearly illustrated in Fig. 1-3.

Table 3 shows the results of the PRC estimation of productive bed parameters before and after hydrochloric acid treatment at the wells 206 and 167 of Movchanivsky GOCF. Statistical estimation of the bed parameters was prepared for models (1) and (4) and (8) with the help of Monte-Carlo simulation. Simulation of a_0 and a_x parameters was performed for a normal two-dimensional distribution with the covariance matrix (6), in case of η, Q_{c_0} і $\bar{z}$ – for normal case of probability distribution. Initial data for η, Q_{c_0} і $\bar{z}$ is given in Table 1. The sample volume for statistical modelling amounts to 400.

Bed parameters estimates (see Table 3) which include data on mathematical expectation of bed pressure $p_п$, water conductivity G, permeability coefficient *к,* their standard deviations (σ_p, σ_G, σ_k) and correlation coefficients r_{pG} r_{pG}(між $p_п$ і G), r_{pk} (між $p_п$ і k), r_{Gk} (між G і k), r_{pk} are complete according to D. Horner method for a fiery seam. With the purpose of comparison the denominator (see Table 3) shows estimates of the mean value of bed parameters excluding information on data accuracy. Analysis of these data indicates that they differ slightly. In some cases (for different distribution laws of probability with greater volatility of output values, etc.) the differences between the estimated parameters of the bed may be more significant.

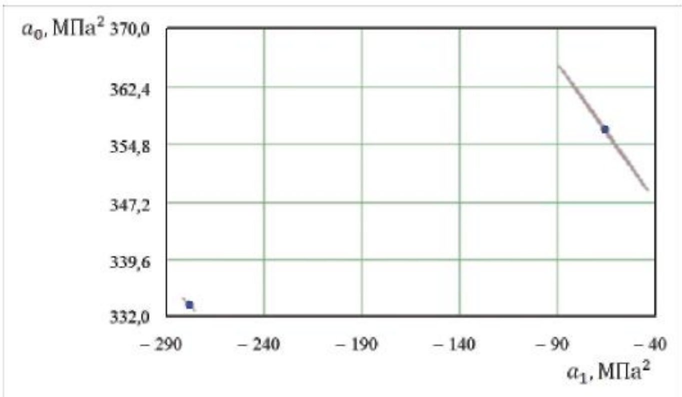

Fig. 3. Ellipsoids of PRC estimation of model parameters (*1*) of for the well No. 167 before and after the intensification

Table 4 Estimated parameters for the productive bed of well No. 167 at Movchanivsky GOCF

Statistical evaluation of bed parameters	Number *n* of statistical experiments					
	50	100	200	300	500	1000
$p_п$, МПа	18,26	18,266	18,266	18,266	18,266	18,266
$G = (kh/\eta)10^{12}$, м³/Па·с	85,09	86,54	85,64	85,86	85,65	85,57
$k \cdot 10^{15}$, м²	0,020	0,021	0,020	0,021	0,020	0,020
σ_p, МПа	0,001	0,0015	0,0013	0,0016	0,0014	0,0015
$\sigma_G \cdot 10^{12}$, м³/Па·с	5,431	4,496	4,173	4,303	4,415	4,519
$\sigma_k \cdot 10^{15}$, м²	0,001	0,0021	0,0017	0,0018	0,0018	0,0019
r_{pG}	-0,068	-0,136	-0,038	-0,090	-0,031	-0,024
r_{pk}	-0,028	0,012	-0,070	-0,083	0,024	-0,022
r_{Gk}	0,650	0,658	0,581	0,573	0,621	0,566

Table. 4 shows the results of the estimation of the reservoir parameters (mathematical expectation and matrix covariance elements) of the well No. 167 (study date 05 - 08.03.2010) depending on the number of statistical experiments, analysis of which indicates the stability of the statistical estimates of the bed parameters at n> 200.

Data given in the Table 3 indicate, in particular, the impact of hydrochloric acid treatment on the productive bed properties. The results of hydrodynamic studies of the well No. 206 show a 1.5 times increase of water conductivity that occurred during processing of the T-1-2-3 horizon, but its gas flow rate decreased. The probable reason for the latter is mudding with terrigenous acid sediments of productive horizon, where the main gas and condensate extraction was made before intensification. Increasing in water conductivity of the T-1-2-3 horizon is associated with its carbonate sediments. Hydrodynamic studies of the well No. 167 indicate significant increase in water conductivity (7.1 times) and gas flow rate (29.6 times) and improvement of work progress.

Thus, the use of information on the accuracy of estimation of the productive bed parameters is an important generalization of the PRC processing method. This allows considering the statistical estimates of the productive bed parameters during modeling of tasks of oil and gas fields development, in condition of information uncertainty it permits the use of statistical models for decision making for the purpose of selection of sound projects.

References

1. **Гриценко А.И.** Руководство по исследованию скважин / А.И. Гриценко, З.С. Алиев, О.М. Ермилов, В.В. Ремизов, Г.А. Зотов. – М.: Наука, 1995. – 523 с.

2. **Шагиев Р.Г.** Исследование скважин по КВД / Р.Г. Шагиев. – М.: Наука, 1998. – 304 с.

3. **Хисамов Р.С.** Гидродинамические исследования скважин и методы обработки результатов измерений / Р.С. Хисамов, Э.И. Сулейманов, Р.Г. Фархуллин, О.А. Никашев, А.А. Губайдуллин, Р.К. Ишкаев, В.М. Хусаинов. – М.: ОАО «ВНИИОЭНГ», 2000. – 228 с.

4. **Иктисанов В.А.** Определение фильтрационных параметров пластов и реологических свойств дисперсных систем при разработке нефтяных месторождений / В.А. Иктисанов. – М.: ОАО «ВНИИОЭНГ», 2001. – 212 с.

5. **Bourdet D.** Use of Pressure Derivative in Well-Test Interpretation / D. Bourdet, J.A. Ayoub, Y.M. Pirard // SPE Formation Evaluation. – 1989. – June. – Pp. 293–302.

6. **Чодри А.** Гидродинамические исследования нефтяных скважин / А. Чодри. – М.: ООО «Премиум Инжиниринг», 2011. – 687 с.

7. **Мыслюк М.А.** Методика обработки кривых восстановления давления / М.А. Мыслюк // НТВ «Каротажник». – 2009. – Вып. 7. – С. 112–120.

8. **Мислюк М.А.** До оцінки параметрів продуктивних газових пластів за кривими відновлювання тиску / М.А. Мислюк, В.Я. Петруняк // Нафт. і газова пром-сть. – 2012. – № 2. – С. 38–40.

9. **Ермаков С.М.** Математическая теория планирования эксперимента / С.М. Ермаков, В.З. Бродский, А.А. Жиглявский [и др.]. – М.: Наука, 1983. – 392 с.

10. **Ермаков С.М.** Статистическое моделирование / С.М. Ермаков, Г.А. Михайлов. – М.: Наука, 1982. – 296 с.

11. **Боровиков А.А.** Математическая статистика. – М.: Наука, 1984. – 472 с.

12. **Мислюк М.А.** Моделювання явищ і процесів у нафтогазопромисловій справі / М.А. Мислюк, Ю.О. Зарубін. – Івано-Франківськь: Екор, 1999. – 426 с.

The authors of this article

Mysliuk Mikhailo Andriyovich

Dr. of technical sciences, professor of the Faculty of Drilling of Oil and Gas Wells at Ivano-Frankivsk National Technical University of Oil and Gas. Research fields - the choice and decision-making during process of drilling and drilling process simulation.

Petruniak Volodymir Yaroslavovich

Oil and gas engineer at "Poltava Petroleum Company", research student at of the Faculty of Drilling of Oil and Gas Wells at Ivano-Frankivsk National Technical University of Oil and Gas. Graduated from the Yu.Kondratyuk Poltava National Technical University, specialty: “Oil and gas”. Research fields - Hydrodynamic study of productive beds.