Adaptive identification and interpretation of pressure transient tests of horizontal wells: challenges and perspectives

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Abstract. The paper deals with a topical issue of defining oil reservoir properties during transient tests of horizontal wells equipped with information-measuring systems and reducing well downtime. The aim is to consider challenges and perspectives of developing models and algorithms for adaptive identification and interpretation of transient tests in horizontal wells with pressure buildup curve analysis. The models and algorithms should allow analyzing flow behavior, defining oil reservoir properties and determining well test completion time, as well as reducing well downtime. The present paper is based on the previous theoretical and practical findings in the spheres of transient well testing, systems analysis, system identification, function optimization and linear algebra. Field data and results of transient well tests with pressure buildup curve analysis have also been considered. The suggested models and algorithms for adaptive interpretation of transient tests conducted in horizontal wells with resulting pressure buildup curve make it possible to analyze flow behavior, as well as define the reservoir properties and determine well test completion time. The algorithms for adaptive interpretation are based on the integrated system of radial flow PBC models with time-dependent variables, account of additional a priori information and estimates of radial flow permeability. Optimization problems are solved with the case study of PBC interpretation for five horizontal wells of the Verkhnechonsk field.

1. Introduction

Today, oil and gas companies intensively drill and exploit horizontal wells, which is attributed to implementation of resource efficient technologies. These wells are equipped with information-measuring systems to conduct transient well tests. Since petroleum reservoirs are structurally complex and the monitoring technologies of field exploration and development need to be improved, transient testing enhancement is a critical issue, which implies development of methods and algorithms to process research data and reduce well downtime.

It is noteworthy that the main source of information on the reservoir properties is transient well testing based on pressure buildup curve (PBC). The obtained data are necessary to manage oil recovery, work out field exploration and development projects, develop geological and technical models of petroleum recovery processes.

Currently, there are three basic approaches to develop methods and algorithms for adaptive identification and interpretation of PBC data:

1. Conventional approach to transient test data interpretation based on PBC analytical models [1-3].

2. Interpretation of transient test data based on hydrodynamic simulation of the reservoir using differential equations containing partial derivatives [4-5].
3. Adaptive identification and interpretation of transient tests in wells equipped with information-measuring systems [6,7].

Conventional approach to transient test data interpretation using PBC analytical models implies flow behavior analysis and solving an inverse problem of identifying filtration properties essential for the reservoir and well using a reservoir simulator corresponding to the definite flow.

One of the methods widely applied in transient test interpretation by both Russian and foreign specialists is the analysis of bottom hole pressure derivative (grapho-analytical method). For example, for the radial flow the slope of the tangent line to the bottomhole pressure derivative $\Delta p_r^{'} = \mathrm{d}p_r / \mathrm{d}\lg(t)$ within the coordinates $\lg(\Delta p_r^{'}) - \lg(t)$ is equal to zero, while for the linear flow it is 0.5 [1–3].

However, with intensive implementation of telemetric systems, which allows monitoring hydrodynamic properties and real-time well operations, the application of conventional methods becomes challengeable.

This makes adaptive identification of transient tests in horizontal wells a promising method of real-time flow behavior analysis [6,7].

The challenge of transient test data interpretation based on hydrodynamic simulation of the reservoir using equations for flow filtration and their finite difference analogues is solving an inverse problem of identification during well test time. Currently, solving problems of real-time identification is a critical issue, since this is one of the limitations for hydrodynamic simulation to be applied in в real-time processing of data obtained via transient tests conducted in horizontal wells [8].

Another limitation essential for conventional methods of transient test data identification and interpretation based on PBC analytical models is their being quite expensive. This is due to the fact that the data are interpreted after well test completion, which results in well downtime and decrease in the amount of hydrocarbon recovery.

Today, obtaining real-time data necessitates implementation of new technologies, which ensure identifying filtration properties and to classify the reserves during well test time, without setting a time limit for test completion in advance. This approach was suggested and is currently developed by the Department of Geology and Oil Field Development, Tomsk Polytechnic University. It based on adaptive identification and interpretation of transient test conducted in the wells equipped with information-measuring systems [6,7,9,10].

The present paper continues the research on adaptive identification and interpretation of transient tests conducted in horizontal wells. It describes new data obtained in the course of the research on real-time flow behavior analysis and identification of reservoir properties during transient well test based on PBC models with time-varying parameters and additional a priori obtained data on the radial flow permeability of the reservoir.

2. Models and Algorithms of Real-Time Flow Behavior Analysis and PBC Interpretation

The method of flow behavior analysis during transient tests in horizontal wells is based on the estimate of radial flow permeability $k_{r,t}^{*}$, obtained at the current moment t:

$$k_{r,t}^{*} = \frac{c_s q \mu B}{L \cdot \alpha_{2,t}^{*}} \tag{1}$$

where $\alpha_{2,t}^{*}$ is the estimate of the system of integrated PBC models for the radial flow with time-dependent parameters $\alpha_{1,t}, \alpha_{2,t}$ and account of a priori data [7,10]:

$$\begin{cases} P_з^*(t) = P_з^*(t_0) + \dfrac{c_s q \mu B}{k_{r,t} L} \ln\left(\dfrac{2,25 k_{xy}\, t}{m\, \mu\, r_{\text{пр}}^2}\right) + \xi_t = \alpha_{1,t} + \alpha_{2,t} \ln(t) + \xi_t, \\ \overline{\boldsymbol{\alpha}}_t = \boldsymbol{\alpha}_t + \boldsymbol{\eta}_t, t \in [t_0, t_{nk}], \end{cases} \tag{2}$$

(1) and (2) contain notations as follows: $P_{з,t}^*, P_з^*(t_0)$ – values of bottomhole pressure at time t and t_0, respectively; $k_{r,t} = \sqrt{k_{z,t} k_{y,t}}$ – radial flow permeability; $k_{z,t}, k_{y.t}$ – vertical and horizontal permeabilities ; q_0 – flow rate at the moment of shut-in t_0, μ, B – oil viscosity and formation volume factor, respectively; $r_{\text{пр}}^2$ – modified well radius; L – effective wellbore length; c_s – constant dependent on the system of units; $\overline{\boldsymbol{\alpha}}_t$ – vector of additional a priori data and parameters estimates; $\boldsymbol{\alpha}_t = (\alpha_{1,t} = f_1(t), \alpha_{2,t} = f_2(t))$ – estimated parameters given as unknown single-valued functions of time $f_1(t), f_2(t)$; t_{nk} – time of transient test completion; $\xi_t, \boldsymbol{\eta}_t$ – random variables, i.e. error in the bottomhole pressure measurement and estimates, PBC model inaccuracy, etc.

Using adaptive identification, the optimal estimates of the parameters $\alpha_{1,t}, \alpha_{2,t}$ (2) with bottomhole pressure $P_з^*(t_n)$ at discrete instants of time $t_n, n = \overline{1, nk}$ with uncertain random variables $\xi_t, \boldsymbol{\eta}_t$ and functions $f_1(t), f_2(t)$ are calculated by solving optimization problems [9,10]:

$$\boldsymbol{\alpha}_n^*(\boldsymbol{\beta}_n, h_n) = \arg\min_{\boldsymbol{\alpha}_n} (J_0(\boldsymbol{\alpha}_n, h_n) + J_a(\boldsymbol{\alpha}_n, \boldsymbol{\beta}_n)), \tag{3}$$

$$\boldsymbol{\beta}_n^*, h_n^* = \arg\min_{\boldsymbol{\beta}_n, h_n} J_0(\boldsymbol{\alpha}_n^*(\boldsymbol{\beta}_n, h_n)) \tag{4}$$

where $\arg\min_x f(x)$ is the minimum point x^* of the function $f(x)$ ($f(x^*) = \min_x f(x)$);
$J_0(\boldsymbol{\alpha}_n) = \sum_{i=1}^{n} \omega(h_n) \cdot \psi_0(\Delta P_з^*(t_i) - \alpha_{1,n} - \alpha_{2,n} \ln(t_i)))$, $J_a(\boldsymbol{\alpha}_n^*, \boldsymbol{\beta}_n) = \sum_{j=1}^{2} \beta_{j,n} \psi_{a,j}(\overline{\alpha}_{j,n} - a_{j,n})$ – empirical measures of PBC model quality; $\boldsymbol{\beta}_n = (\beta_{j,n}, j = \overline{1,3})$ – vector of control parameters defining the importance (weight) of additional a priori data $\overline{\alpha}_{j,n}$; $\psi_0, \psi_{a,j}$ – known loss functions; $w((t_n - t_i)/h_n)$ – weighting functions with decay parameter h_n for adaptive identification and interpretation ($w(x_1) < w(x_2), x_1 < x_2$); $\Delta P_з^*(t_i) = P_з^*(t_i) - P_з^*(t_0)$.

The criterion to define the start of the radial flow regime is such a value of $t_{r,n}^* \in t_r + \tau$, that

$$\left| k_{r,n+\tau}^* - k_{r,n}^*) \right| \le \varepsilon, \tau > 0 \tag{5}$$

is a valid inequality, where $t + \tau$ – time interval, within which the estimates of radial flow permeability are stabilized $k_{r,n}^* = c_s q \mu B / L \cdot \alpha_{2,n}^*(\boldsymbol{\beta}_n^*, h_n^*)$ (1) with account of (3),(4). Stabilization of radial flow permeability estimates (1) means that its derivative is equal to nil:

$$\left| \frac{\partial}{\partial t} k_{r,t}^* \right| \approx 0 \tag{6}$$

Therefore, formula (6), as well as (5), can be used to define time instants of the radial flow.

The solution on the time of test completion t_{nk} can be taken via visual analysis of the dependency graph (3) or using the criterion for estimates stabilization (5).

The algorithm given below represents the method of adaptive interpretation of PBC during transient tests conducted in horizontal wells with flow behavior analysis:

1. Collecting initial data on the bottomhole pressure with the specified volume $n=n_0$, additional a priori data and evaluation of reservoir properties (for example, see figure 1 and table 1).
2. Solving identification problems:

2.1. Calculating quality measures $J_0(\boldsymbol{\alpha}_k, h_k), J_a(\boldsymbol{\alpha}_k, \boldsymbol{\beta}_k)$ in (3),(4).

2.2. Solving problems (3), (4) using the method of function optimization.

3. Checking condition (5), defining the start of radial flow regime, and estimating radial flow permeability.
4. Research completion if the estimates of radial flow permeability and PBC model parameters are stabilized; otherwise, collecting initial data on the bottomhole pressure with volume $\Delta n \geq 1(n = n_0 + \Delta n)$ and starting new research with stage 2.

3. Results of PBC interpretation with flow behavior analysis

The results of a case study of PBC interpretation with flow behavior analysis for five horizontal wells of the Verkhnechonsk field are given in figures 1–4 and tables 1, 2. For example, figure 1 shows the data on bottomhole pressure in wells 1 and 2. Figures 2–4 shows estimates of radial flow permeability (1), (3), estimates of radial flow permeability derivative (6) and PBC derivative

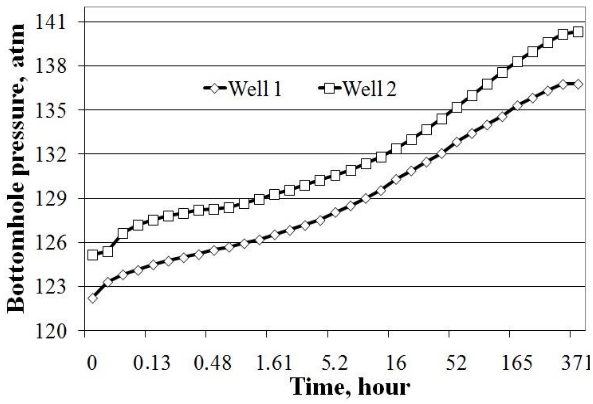

Figure 1. Pressure buildup curves

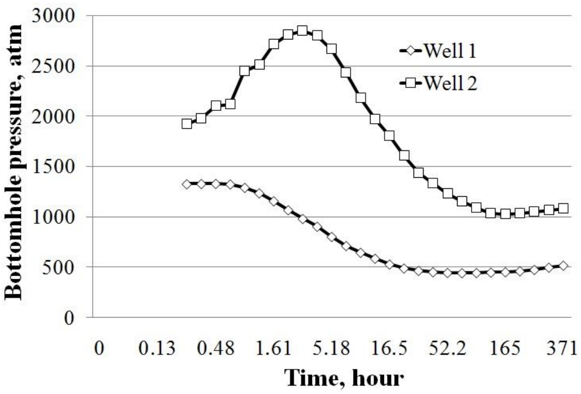

Figure 2. Estimates of radial flow permeability

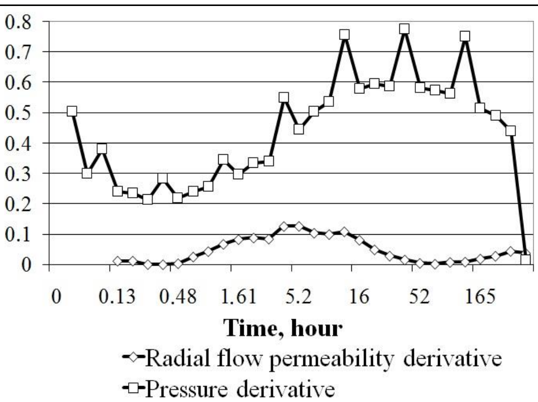

Figure 3. Diagnostic plot identifying flow regime in well 1

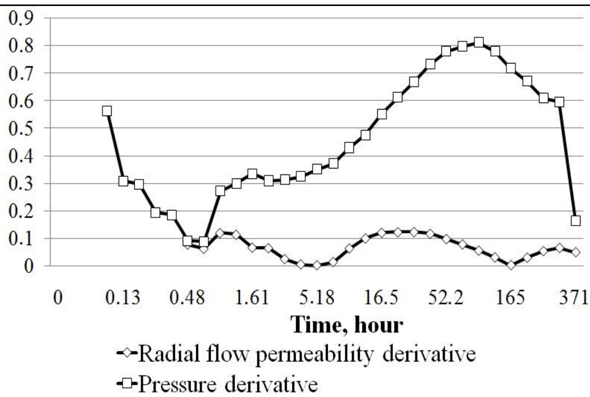

Figure 4. Diagnostic plot identifying flow regime in well 2

The estimates of radial flow permeability obtained using the method of adaptive interpretation (MAI) and quadratic performance indices $\psi_0(x) = \psi_a(x) = x^2$, additional a priori data on the radial flow permeability $\bar{k}_{r,n}$ given in table 1 and by solving the system of linear equations with $\beta_{1,n} = \beta_{2,n} = \beta_n$:

$$(F_n^T W(h_n^*) F_n + \beta_n \mathbf{I})\, \boldsymbol{\alpha}_n^*(\beta_n^*, h_n^*) = (F_n^T W\,(h_n^*) \Delta P_з^* + \bar{\boldsymbol{\alpha}}_t),$$

where $F_0 = (1, \Delta P_з^*(t_i), i = \overline{1, n})$ is $2 \times n$ matrix; $\mathbf{I}$ – 2×2 diagonal matrix; $W(h_n) = \mathrm{diag}(w(h_n) = \exp((n-i)/h_n^*), i = \overline{1, n-1})$ – diagonal matrix of weighting functions with decay parameter h_n^*; $\bar{\boldsymbol{\alpha}}_t = (0, \bar{\alpha}_{2,t} = c_s q \mu B / L\bar{k}_{r,n})$. The estimates of the control parameter β_n^* и decay parameter h_n^* were defined by solving problem (4) using the downhill simplex method [11].

Figures 2–4 indicate that the criteria (5), (6) allow identifying early-time and late-time radial flow regimes and recommending the time of test completion. For example, late-time radial flow regime will be established in well 1 after about 50 hours, which indicates the appropriate time of transient test completion.

Table 1. Initial and additional a priori data on wells 1 and 2

Initial data and estimates of reservoir and well properties (International System of Units (SI))	Well	
	1	2
1. Dynamic viscosity of oil, cP	3.92	3.92
2. Oil compressibility factor, atm^{-1}	1.78×10^{-4}	4.27×10^{-5}
3. Well radius, m	0.108	0.108
4. Atmospheric pressure, atm	1.033	1.033
5. Temperature, standard conditions (+20^0 C) ^{0}K	293	293
6. System compressibility factor, atm^{-1}	4.32×10^{-4}	4.32×10^{-4}
7. Porosity	0.13	0.13
8. Effective wellbore length , m	4.78	7.2
9. Well yield before shut-in, m^3/day	176	163.2
10. Estimate of radial flow permeability	-	-

Table 2. PBC interpretation results for five wells

Well	Interpretation method	Defined parameters		
		Test time, hour	Radial flow permeability, mD	Reservoir pressure, atm
1	Saphir	371.37	418	138.5
	MAI	52.2	444	137.5
2	Saphir	144.27	3760	141.8
	MAI	40.86	3760	144.5
3	Saphir	179.14	1010	135.1
	MAI	34.39	1089	135.2
4	Saphir	190.97	597	142.2
	MAI	52.83	607	143

5	Saphir	167.8	253	150.2
	MAI	32.75	226	149.4

It is worth noting that the horizontal flow observed between radial flows can be easily identified by the maximum point of the estimate derivative for the radial flow permeability (4), which is proved by the results of data interpretation for other horizontal wells (see table 2).

Table 2 shows that the method of adaptive interpretation with radial flow behavior analysis allows reducing well downtime compared to that caused by the planned tests via Saphir software. For the five wells presented in table 2 there is a fivefold reduction in the test time, from 1053.55 to 213.03 hours. The cost of five wells downtime is \$ 1 500 000 if the price is \$ 50 per barrel.

4. Conclusion

The present research has described the challenges concerning identification and interpretation of transient tests conducted in horizontal wells equipped with information-measuring systems by analyzing PBC. The perspectives of adaptive identification and interpretation have been explored.

The algorithms have been developed to carry out adaptive identification and interpretation of the data on flow behavior analysis during the time of transient well test with resulting PBC, as well as to define the reservoir properties and determine well test completion time.

The case study of PBC interpretation with flow behavior analysis for five horizontal wells of the Verkhnechonsk field has indicated that the suggested models and optimal algorithms of adaptive identification and interpretation make it possible to significantly reduce well downtime, which results in cost advantage.

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