Coupling well hydrodynamic tests data with results of digital simulation for better identification of reservoir properties

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Abstract. In the study the existing approaches for stabilization time estimation are given and compared with the results of hydrodynamic simulation. A deviation from an assumed ellipsoid shape of drainage area has been observed for a horizontal well based on the simulation results. Then this geometrical definite form was taken into account in the gas influx equation. On its basis the time period of pseudo-steady state was estimated. As a result, stabilized horizontal gas well tests are considered to be not effective as the time period is too long when pseudo-steady state is reached and it’s impossible to carry out the test in reality. However, it is suggested to continue a well test for a reduced period by adapting well tests on the model and matching simulation output with gauge measurements.

1. Introduction
A goal of the study is to develop an approach for gas well tests interpretation using geologic-hydrodynamic simulation of field development. In this work stabilized well tests of horizontal gas wells are observed. Multipoint well tests are for stabilized ones. These gas wells tests are conducted in order to find recovery rates’ dependence of pressure empirically to find coefficients for flow equation which allow estimating flow properties of the reservoir. A condition to conduct practical measurements is the achievement of steady-state pressure distribution in a reservoir from a well to an external boundary where constant pressure is maintained. As for well tests interpretation a reservoir is assumed to be homogeneous, a steady state implies that pressure at each point is constant [1]. As there is no maintenance of reservoir pressure, during gas production reservoir pressure decreases, therefore a concept of pseudo-steady state is used [2]. In a homogeneous reservoir during pseudo-steady state any change of pressure at each point depends on time linearly [1]. It is difficult to achieve such measurement conduction conditions for a horizontal well: in low permeable reservoirs the period to reach stabilization state can take much more time than is considerable for well testing, when a well test goes on at the rate being not equal to a usual operational one for this well. As the result for well test interpretation it is necessary to identify the time period to reach pseudo-steady state to compare it with one spent on real well tests carried out on a field. There are several methods to estimate stabilization time. Authors of the study [3] suggest to calculate it using the following equation:

$$t_s = \frac{1200 \cdot \phi \cdot S_g \cdot \mu_g \cdot r_e^2}{k \cdot p_r},$$  

(1)
where \( t_s \) – time period to reach stabilization, hours; \( \phi \) – porosity; \( \mu_g \) – gas viscosity, cP; \( S_g \) – gas saturation; \( k \) – effective permeability for gas, mD; \( \bar{p}_{r}\) – average reservoir pressure, pounds per square inch; \( r_e \) - distance to an external boundary of a reservoir, ft. This time means the moment when pressure disturbance has reached boundaries of a reservoir or boundaries of zones of drainage created by surrounding wells.

In the publications of Russian scientists [4, 5] it is assumed that a state can be considered as stabilized one when pressure disturbance has reached one half of a distance between the well and an external boundary of the reservoir. In this case an analytical approach for stabilization time is:

\[
\frac{t_{st}}{s} = C \cdot \frac{R_k^2 \cdot \phi \cdot \mu}{k \cdot P_{res}},
\]

where \( C \) – a coefficient varying in a range of 0,122-0,35; \( R_k \) – a radius of a reservoir, m; \( t_{st} \) – time required for pressure stabilization, seconds; \( \phi \) – porosity; \( \mu \) – viscosity, mPa·s; \( k \) – permeability, m²; \( P_{res} \) – reservoir pressure, Pa.

A problem of an analytical estimation of stabilization time is that values of permeability and a distance from constant pressure boundary are unknown. In reality pressure gauge readings are usually taken when the change of registered parameters becomes minimal, when a change of pressure is less than a measurement error.

2. The 3D hydrodynamic simulation to identify the conditions of pseudo-steady state

It was decided to use hydrodynamic simulator Eclipse 100 (Schlumberger) to identify a moment of achievement of pseudo-steady state according to the results of the numerical experiment. A thin (relative to a reservoir extension), homogeneous, isotopic reservoir with impermeable top and bottom and an edge aquifer was simulated. A reservoir is penetrated by a horizontal well with a downward well full formation exposing. Relation of a gross pay to length of a simulated fragment equals to 0,027. A well path is shown in Figure 1. Table 1 and Table 2 demonstrate the parameters of the simulated reservoir, parameters of the aquifer, respectively.

Work of the horizontal well with a constant rates at 500 thousand cubic meters per day and at 1 million cubic meters per day was initiated on the model; three variants of the simulated fragment have been observed: variant 1 – with permeability of 1 mD, variant 2 – with 5 mD, variant 3 – with 10 mD.

![Figure 1. Well path of the tested well.](image-url)
Table 1. Parameters of the simulated reservoir.

| Parameter                          | Value         |
|-----------------------------------|---------------|
| Number of cells                   | 135x135x6     |
| Size of cells, m                  | 10x10x6       |
| Net pay, m                        | 29.2          |
| Length of a horizontal part of the well, m | 311           |
| Depth of entrance of the well into reservoir, m | 3287.4      |

Table 2. Parameters of aquifer.

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Porosity, $\phi$           | 0.125                                      |
| Permeability, l/Pa          | 14.504                                     |
| External radius, m          | 152.4                                      |
| Thickness, m                | 500                                        |
| Angle of influence, degrees | 360                                        |
| Permeability, mD            | equal to permeability of the fragment in every case |

3. Analysis of simulation results

According to the simulation results it was identified that since the moment of well operation initiation a shape of drainage area was constantly changing. Its distinctive geometry samples are shown in Figure 2. Firstly, the boundary created inclined elliptical cylinder shape. Then it became straight elliptical cylinder. Truncated elliptical cone resulted the simulation output. These changes are logical and just prove the effect of mutual work of different physical forces. It means we can use the created shape sizes for special purposes. As well this data was used for well tests results interpretation.

It is worth mentioning that depending on reservoir properties of the simulated fragment a period when a drainage area is of a certain shape differs. For example, for 1 mD there was no transition of external drainage area boundary into a shape of a truncated cone. Different shapes of drainage areas correspond flow regimes towards a horizontal well after it started production (Figure 3) [6].

The first regime of flow towards a horizontal well is a pseudoradial flow in a vertical plane (Figure 3a). Pseudoradial flow has its name because of anisotropy: flow in a vertical direction moves slower than in a lateral one, therefore a shape of a perfect circle is absent.

Figure 2. Shapes of drainage area during simulation
As a boundary of a drainage area has reached top and bottom of a reservoir, flow becomes linear (Figure 3b), but it cannot stay linear forever because of a finite length of the horizontal part of the well [7]. When a shape of drainage area stops repeating the geometry of the well path, flow regime changes to radial one (Figure 3c). When boundaries of a reservoir start influencing gas flow, pseudo-steady state is supposed to be achieved.

In Figure 4 movement of drainage zone is shown. Colors characterize pressure distribution. According to the approach described in the study [6], pseudo-steady state is achieved when a drainage area reaches reservoir boundaries. Visualization of an external drainage area boundary movement via 3D hydrodynamic software post processing allows to see this moment realized though the time period is too long for real tests. After it meets the model boundaries, according to the approach from the work [6] pseudo-steady state is supposed to be reached.

**Figure 4.** Evolution of shape geometry for a disturbance zone in a reservoir as time passes

4. **The use of simulation results to estimate reservoir properties**

To estimate a reservoir properties it is necessary to describe analytically a shape of drainage area formed in a pseudo-steady state regime and use it in a flow equation for gas flowing to a horizontal well which assumes action of a binomial flow law in the totally drained area, homogeneity and isotropism of rock porous media.
Mass flow rate [8]:

\[ \rho \omega = \frac{Q \phi}{F}, \]

where \( Q \phi \) – mass flow rate of gas, kg/s, \( F \) – area of a cross section of a reservoir orthogonal to gas flow, m². \( F \) is a side surface of a straight elliptic cylinder or a truncated overturned elliptic cone (Figures 5 and 6). In the case of a cone, area of a side surface can be calculated using an equation for a cylinder, lengths of semi axes are equal to lengths of semi axes of a medium plane of a cone (Figure 6):

\[ F = P \cdot h, \]

where \( h \) – reservoir thickness, m; \( P \) – perimeter of an ellipse in a cylinder base, m.

A perimeter of an ellipse can be found using one of approximation formulas:

\[ P \approx 4 \cdot \frac{\pi \cdot a \cdot b + (a - b)^2}{a + b}, \quad (3) \]

where \( a \) and \( b \) – lengths of a big and a small semi axes of an ellipse in a base of cylinder, m.

After a mass flow rate is put into Forchheimer Law, we get the following flow equation for gas flowling towards a horizontal well:

\[ P_k^2 - P_c^2 = \frac{\mu \cdot z \cdot P_0 \cdot T_{res}}{2 \cdot k \cdot h \cdot T_0} \cdot Q_0 \cdot \int_{a_c}^{a_k} \frac{a + b(a)}{\pi a b(a) + (a - b(a))^2} da + \]

\[ + \frac{\rho_0 \cdot z \cdot P_0 \cdot T_{res}}{B \cdot \varepsilon \cdot h^2 \cdot T_0} \cdot Q_0 \cdot \int_{a_c}^{a_k} \frac{a + b(a)}{\pi a b(a) + (a - b(a))^2} \cdot \frac{1}{(a + b(a))^2} da, \quad (4) \]

where \( P_k \) and \( P_c \) – weight-averaged reservoir and bottom hole pressures, Pa; \( \mu \) – gas viscosity, Pa·s; \( z \) – gas deviation factor; \( k \) – permeability, m²; \( h \) – net pay, m; \( Q_0 \) – gas flow rate at standard conditions \( (P_0 = 0,1 \text{ MPa}, T_0 = 293 \text{ K}) \), m³/s; \( a \) and \( b \) – major and minor semi axes of constant pressure surfaces (Figures 5,6), m. To estimate the length of a minor semi axis \( b \) is represented in dependence on \( a \) – the length of a major semi axis \( a \) has been concluded, therefore, \( b = f(a) \). Index \( k \) corresponds a surface of equal pressure of weight-average reservoir pressure, index \( c \) – of a surface of bottom hole pressure.

Integration of the equation is carried out by numerical methods. Distinctive sizes of isobaric surfaces of bottom hole and weight-average reservoir pressures can be identified using pressure maps from simulation via Petrel software (Figure 7).

Following numerical experiment was conducted for two permeability values of the simulated fragment, 1.33 mD and 6.91 mD. The horizontal well production rate was laid down at 350000 m³/days for both variants of permeability. Further, according to the equation (6) such value of a major semi axis \( a_k \) were estimated for different dates, so that permeability of a reservoir every time was equal to the prescribed one (1.33 mD or 6.91 mD depending on the variant). The experiment was carried out to identify pseudo-steady state of the system. The results of the numerical experiment are shown in Figures 8 and 9.
Figure 7. Map pressure from geologic-hydrodynamic simulation

Time of stabilization can be taken equal to the moment after which the length of a major semi axis $a_k$ doesn’t change practically. So, for 1.33 mD variant stabilization begins approximately after 119 days of operation, for 6.91 mD – in 58 days. Length of a major semi axis $a_k$ relating to permeability of 1.33 mD in each case is less than a half of the length of the fragment, 675 m, which means that there is an effective drainage area existing.

Consequently, it was identified that a criteria for offence of pseudo-steady state of a gas-porous medium system was the formation of effective reduced pressure area, where gas comes from. It implies that after reaching this state a pattern of pressure distribution in a reservoir and a shape of drainage area do not change. In the Figure 10 shapes of drainage areas for variants with permeability of 1 mD and 7 mD at recovery rate of 500 thousand cubic meters per day are shown. In this picture a color scale is adjusted, maximum and minimum values of pressure at each date were changed so that a shape of drainage area could be identified visually.

Figure 8. Change of major semi axis $a_k$ length in time for 1.33 mD variant

Figure 9. Change of major semi axis $a_k$ length in time for 6.91 mD variant
Comparison of stabilization time values calculated via formulas (1), (2) and the one from simulation has been made. The results are shown in the Table 3.

| Permeability, mD | Stabilization time (1), days | Minimal stabilization time (C=0.122), equation (2), days | Maximum stabilization time (C=0.35), equation (2), days | Stabilization time from modeling, days |
|------------------|-------------------------------|--------------------------------------------------------|--------------------------------------------------------|---------------------------------------|
| 1.33             | 108                           | 57                                                     | 164                                                    | 119                                   |
| 6.91             | 21                            | 11                                                     | 32                                                     | 58                                    |

As a result, for the variant with the smaller permeability, 1.33 mD, values of stabilization time according to equation (1) and from modeling, differ by 10.2%. As for the variant with permeability 6.91 mD, the difference of stabilization time estimated from simulation and from equation (1) differ dramatically, in 2.76 times.

Usage of expression (2) becomes complicated because of the coefficient C which varies from 0.122 till 0.35. It gives variance of start time for pseudo-steady state. It is worth mentioning that in any case duration of well tests becomes equal to stabilization time from the Table 3 what is impossible in reality. There is possibility of well tests results adaptation using a hydrodynamic simulator, making a forecast of these results change as time passes, that allows to reduce duration of real well tests.

For this goal it is suggested to simulate a procedure of well tests on an actual model of reservoir, therefore, initially the well is operated at the same rate as during the real tests. Bottom hole pressure is adapted on the model to the value measured by a manometer during well tests.

While simulating time can align with real duration of a well test or be longer in case when achievement of stabilization requires it. Later stabilization time is estimated as a moment when bottom hole pressure starts to depend on time linearly. Also a change of the shape of drainage area should be mentioned. A generalized view of a plot is demonstrated in Figure 11, where values of bottomhole pressures measured during well tests on the field are shown as a solid line, and a dashed line shows continuation of a case in simulation, which allows to actualize the well test with a numerical experiment and to find stabilization time.
5. Conclusions

Existing methods of stabilization time estimation have been observed after initiation of a well operation. The study showed that it’s possible to use hydrodynamic modeling for estimation of time to reach pseudo-steady state. The flow equation for well tests of a horizontal well fully penetrating a reservoir has been modified taking into account a shape of drainage area defined via simulation. It can be calculated. The form of the area is defined as an elliptic cylinder in the model. Also it is assumed that a binomial law acts in all the volume.

It was observed during a numerical experiment that weighted-average reservoir pressure was corresponded to the length of a major semi axis which is less than a half of length of the simulated field fragment. It proves existence of an effective drainage area, sizes of which should be taken into account in gas flow equations.

References

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*Figure 11.* Chart of adaptation of a test on the model