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Estimating reservoir heterogeneities from pulse testing

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ABSTRACT

Analytical interpretation approaches of interference tests do not yield reliable results about the characterization of reservoirs and determination of flow pattern in fields with a significant degree of heterogeneity. In the present study we report on numerical modeling of pulse testing in the frequency domain. We built a numerical simulator in the Fourier domain for the interpretation of harmonic well tests in strongly heterogeneous reservoirs. The model was used for analyzing the pressure signal at the pulser well and at the observer well and its applicability to determine reservoir heterogeneities was demonstrated. Applications to synthetic and field data are discussed. One synthetic case was a channeled reservoir in which the channel bends and the effective flow path between the two wells in the system were unknown. Another synthetic case concerned a homogeneous reservoir containing a flow barrier. In both cases we successfully quantified the amount of heterogeneity, provided that a basic knowledge about the reservoir characteristics was available. We also applied our technique to a real case, a gas storage field. Here, we were able to exclude the existence of a flow barrier and to quantify the variation in the permeability-thickness *kh* between the region around the pulser well and that surrounding the observer.

1. Introduction

Well testing is a valuable source of information for reservoir properties. Test data is interpreted on the basis of the pressure transient theory, which has been developed for various physical reservoir concepts and flow conditions (Lee, 1982; Gringarten, 2008).

It is well recognized that all the hydrocarbon reservoirs are heterogeneous to a certain degree. The heterogeneity manifests itself in terms of variable rock and/or fluid properties and may be observed both in the lateral and vertical directions. The characterization of subsurface heterogeneity has been addressed in field experiments, theoretical analyses, and numerical approaches. Neuman et al. (2004) suggested characterizing subsurface heterogeneity in greater detail by conducting multiple cross-hole interference tests. Exact analytical solutions exist for a restricted class of problems that involve some simple geometry: layered reservoirs, single linear discontinuities, radial composite systems, etc. Rosa and Horne (1993) computed the exact solution in the case of an infinite homogeneous reservoir containing a single circular permeability discontinuity. Most of these analytical solutions are written in the Laplace domain. Numerical methods can treat much more general situations. In numerical modeling approaches, statistical variations can be introduced in the hydraulic properties of the subsurface in which the pumping test is conducted (e.g., Copty and Findikakis, 2004; Ye et al., 2004).

Pulse testing, which is the subject of the present paper, was first proposed in 1966 by Johnson et al. Later, other authors have elaborated on the idea (Kuo, 1972; Rosa and Horne, 1997; Hollaender et al., 2002; Renner and Messar, 2006; Rochon et al., 2008; Ahn and Horne, 2010; Fokker and Verga, 2011). Harmonic pulse testing is a form of interference testing in which the signal is generated by producing from, or injecting into, a well (called active well or pulser well). Two different rate values, q_1 of duration T1 and q_2 of duration T2, where T1 and T2 are not necessarily the same, are produced in a sequence. The total test duration can take up weeks or even months because of the time lag existing between the time when a rate change is made at the active well and the time when the pressure transient is detected in the observation well. The amplitudes of the pressure response measured at the observation well (also called responder) for each flow period are small, frequently less than 1 bar and sometimes less than 0.1 bar, because the signal progressively attenuates while travelling through the reservoir. Highly sensitive pressure gauges are thus recommended to detect these small disturbances because pressure variations over the sampling time (1 millibar in the considered real case) have to be larger than the resolution of the pressure gauge (Startzman, 1971). As an example, conventional strain gauges have a resolution of 0.2 psi while standard quartz gauges have a resolution about 0.001 psi (Vella et al., 1992).

Using pulse tests one can quantify directional reservoir properties, such as permeability. Because pulse tests do not require the

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Nomenclature

t	Time
T	Cycle time
τ_c	Characteristic time
ω	Angular frequency
Q_ω	Rate Fourier coefficient
P_ω	Pressure Fourier coefficient
A_ω	Amplitude ratio
φ_ω	Phase shift
P	Pulser well
O	Observer well
J_{fo}	Objective function
L	Path length
A	Channel oscillation amplitude
n_w	Channel wave number
d	Channel or barrier width
ℓ	Barrier length
PO	Geometrical distance between the pulser well (P) and the observer well (O)

observation wells to be shut-in and a pulsing pressure of few bars is sufficient to detect and interpret the signal generated at the active well by modulating the rate, significant modifications to the production strategy are not needed. The duration of the pulse and the flow rate are estimated *a priori* on the basis of a given set of reservoir parameters to ensure that a pressure variation can be clearly detected at the responder. Furthermore, the oscillating response due to repeating pulses is easier to identify in a noisy reservoir environment than a single pulse interference signal, and it is less affected by a possible drift of the pressure gauge.

A harmonic approach to pulse test interpretation was proposed earlier in the literature (Renner and Messar, 2006; Ahn and Horne, 2010; Fokker and Verga, 2011). This approach does not relate to the pressure derivative analysis as in conventional well testing, but it is based on Fourier transformation, which unravels the signal by picking out the imposed frequencies and the corresponding response function. As the energy density of the signal is concentrated in a limited number of narrow frequency bandwidths, it is easy to isolate the response components and to evaluate the corresponding amplitude and phase. Together they provide information about the reservoir properties in the volume of investigation. The phase shift represents the relative delay of the pressure cycle with respect to the imposed flow cycle.

Analysis of pulse test data with the analytical method is based on simple infinite acting reservoir equations and homogeneous formations. As shown in Fokker and Verga (2011), the harmonic interpretation of pulse tests, based on the analytical solution of flow equations in the frequency domain, can be successfully applied to multiphase flow in anisotropic formations. Ahn and Horne (2010) developed an analytical solution for harmonic testing that accounts for radial multi-composite reservoirs. However, since the analytical approaches for the interpretation are based on simple infinite acting reservoir equations, they prevent reliable results to be obtained in more complicated heterogeneous systems. As an example, the evaluation of the average permeability between the pulser and the responder is based on the assumption that the length of the flow path, or the distance travelled by the pressure disturbance, is the same as the well distance. This assumption implies an underestimation of the intra-well permeability should the pressure disturbance travel along a winding flow channel instead of along the straight line connecting the two wells.

In this paper we report on a numerical simulator in the Fourier space, which we built for the interpretation of harmonic well tests in strongly heterogeneous reservoirs. We have applied the simulator to two synthetic cases: one comprising a channelized reservoir and the other representing a field with a permeability barrier. We also used the simulator to perform the interpretation of a pulse test on a gas storage field case.

2. Numerical solution in the Fourier space

In complex reservoir systems, such as fields characterized by wells close to the reservoir boundaries or by macroscopic heterogeneities, axial symmetric analytical solutions are no longer applicable and a numerical solution is needed. Only a restricted number of frequencies in the pressure and rate pulsing signal are meaningful, therefore, for the interpretation of harmonic tests, a numerical simulation in the frequency domain would be much more efficient in terms of computational time than a numerical formulation in time (Fokker and Verga, 2011).

A heterogeneous reservoir containing a slightly compressible fluid, in which the permeability k was space-dependent, was considered. Assuming almost constant values for the fluid viscosity μ, the total compressibility c, and the porosity ϕ, the flow is described by the diffusivity equation:

$$\phi c\mu \frac{\partial p}{\partial t} = \nabla\cdot(k\nabla p) \tag{1}$$

where p is pressure and t is time. For oil, with nearly constant parameters, the diffusivity equation is linear. For gas reservoirs, the equation holds in terms of pseudo-pressure $m(p)$:

$$\phi c\mu \frac{\partial m}{\partial t} = \nabla\cdot(k\nabla m) \tag{2}$$

Eq. (2) is not linear; however, if the pressure disturbances are assumed to be small, it can be treated as such. Since a pressure drop of a few bars is sufficient to apply the methodology, the assumption of linearity is reasonable. As an example, in the considered real case the maximum pressure drop was four bars, which influences the PVT properties only at the third significant digit.

Under the assumption of linearity, the combined pressure solution of a reservoir with many wells producing with variable production rates and a harmonic rate imposed in one of them, can be treated as a superposition of the individual contributions. Thus the response to each harmonic component can be considered independently and, if the rate q is decomposed in the harmonic components q_ω with angular frequency ω (defined as $2\pi/T$), then the following applies:

$$q(t) = \sum_\omega q_\omega = \sum_\omega Q_\omega e^{i\omega t} \tag{3}$$

The pressure response of the reservoir is harmonic with the same cycle time T. The pressure can thus be expressed as:

$$p(r,t) = \sum_\omega p_\omega(r,t) = \sum_\omega P_\omega(r) e^{i\omega\omega} \tag{4}$$

where p_ω is the response to the angular frequency ω. The non-oscillating frequency ($\omega = 0$) term in Eq. (4) corresponds to the constant background p_i to comply with the initial condition. To satisfy the undisturbed outer boundary condition all the oscillating components have to be null for x, $y \to \infty$. In the pulser the pressure drop is determined by the pulsing rate. Then, the problem can be formulated for each angular frequency component as:

$$\begin{cases} \mu c\phi \dfrac{\partial P_\omega e^{i\omega t}}{\partial t} = \nabla\cdot\left[k\nabla P_\omega e^{i\omega t}\right] \\ \left[P_\omega e^{i\omega t}\right]_{(x,y)\to\infty} = 0 \\ \left[\nabla P_\omega e^{i\omega t}\right]_{(x,y)_{pulser}} = \dfrac{\mu B}{k2\pi r_w h} Q_\omega e^{i\omega t} \end{cases} \tag{5}$$