Journal of Petroleum Science and Engineering 162 (2018) 446–459

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Harmonic pulse testing for well performance monitoring

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ARTICLE INFO

Keywords:
Well testing
Harmonic testing
Well performance monitoring
Horizontal well
Gas storage

ABSTRACT

Harmonic testing was developed as a form of well testing that can be applied during ongoing production or injection operations, as a pulsed signal is superimposed on the background pressure trend. Thus no interruption of well and reservoir production is needed before and during the test.

If the pulsed pressure and rate signal analysis is performed in the frequency domain, strong similarity exists between the derivative of the harmonic response function versus the harmonic period and the pressure derivative versus time, typical of conventional well testing. Thus the interpretation of harmonic well tests becomes very straightforward.

In this paper, we present the analytical models for the most commonly encountered well and reservoir scenarios and we validate the model for horizontal wells against real data of a harmonic test performed on a gas storage well in Italy.

1. Introduction

For decades, well tests have been widely used by the oil industry for evaluation of well productivity and reservoir properties, which provide key information for field development and facilities design (Horne, 1994; Bourdet, 2002; Lee et al., 2003; Kamal, 2009). Recent work has been directed towards complementing conventional well tests with less expensive and/or more environmentally friendly procedures (Hollaender et al., 2002a; Holleander et al. 2002b; Beretta et al., 2007; Verga et al., 2008; Gringarten, 2008; Bertolini et al., 2009; Verga and Rocca, 2010; Verga et al., 2011, 2012, 2015; Rocca and Viberti, 2013; Verga and Salina Borello, 2016). Harmonic well testing is one of those complementing methodologies: it may not replace conventional well testing, but it can be very effective for monitoring purposes. In conventional well tests, equilibrium conditions are required in the reservoir before the test; a single well can be produced at a time, inducing one or more pressure drawdown periods followed by a final pressure build-up which are the object of the interpretation. Conversely, a harmonic test is characterized by a periodic sequence of alternating production rates which can be superimposed on the background pressure trend and thus the test can be carried out during ongoing production or injection operations.

Even if harmonic tests resemble pulse tests (Johnson et al., 1966) because of the sequence of alternating production rates, some major differences exist. Pulse tests aim at assessing hydraulic connectivity between two wells without interrupting production from other wells. In addition to pulse test purposes, harmonic tests aim at assessing well and reservoir properties, such as skin and permeability. To this end, harmonic testing analysis is performed in the frequency domain as opposed to pulse test interpretation, which relies on the pressure and pressure derivative data as in conventional well testing.

The concept of harmonic testing was first proposed by Kuo (1972) and later developed by other authors (Black and Kipp, 1981; Kazi-Aoual et al., 1991; Rosa and Horne, 1997; Hollaender et al., 2002b; Copty and Findikakis, 2004; Despax et al., 2004; Renner and Messar, 2006; Rochon et al., 2008; Ahn and Horne, 2010; Fokker and Verga, 2011; Fokker et al., 2012, 2013; Morozov, 2013; Vinci et al., 2015; Sun et al., 2015; Salina Borello et al., 2017). The main advantage of this testing approach is it does not require the interruption of production nor the knowledge of previous rate history (Hollaender et al., 2002b). In fact, the analysis in the frequency domain allows extraction and analysis of each periodic component of the pressure response in relation to the corresponding periodic component of the rate. The main drawback of harmonic testing is it takes longer to obtain the same information of conventional testing (Hollaender et al., 2002b). For this very reason, harmonic testing is inadequate for exploration and appraisal wells, but it is a valid alternative to conventional well testing for monitoring well performance.

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URL: http://www.polito.it/petroleum

https://doi.org/10.1016/j.petrol.2017.12.053
Received 1 August 2017; Received in revised form 26 October 2017; Accepted 16 December 2017
Available online 20 December 2017
0920-4105/

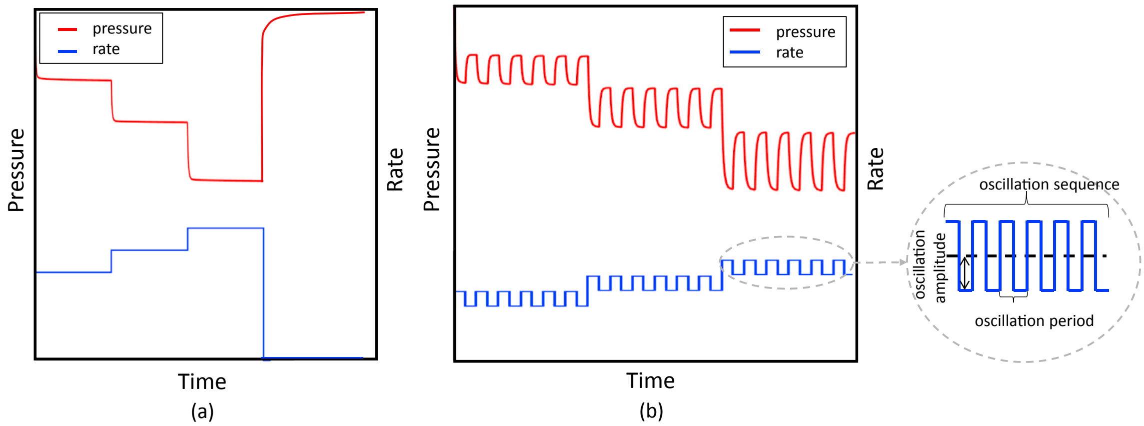

Fig. 1. Schematic of (a) a conventional well test sequence with multiple draw-downs and a build-up, compared to (b) harmonic test.

A qualitative example of conventional well test sequence (with multiple draw-downs and a build-up) compared to a harmonic test is provided in Fig. 1.

The basic concepts of harmonic testing are:

1. If a harmonic rate of given frequency is imposed to a well, the corresponding reservoir pressure response is still harmonic with the same frequency (Kuo, 1972).
2. A square pulse rate is equivalent to a linear superposition of simultaneous harmonic tests each characterized by its own frequency (Fokker and Verga, 2011).
3. The area investigated by harmonic testing is a function of the adopted rate frequencies, which should be selected in order to meet the specific testing targets (Ahn and Horne, 2010).
4. In order to maximize the information provided by harmonic pulse test (HPT) interpretation, pressure data should be adequately preprocessed adopting detrending methodologies (Ahn and Horne, 2010; Viberti, 2016) with the aim of separating pure periodic components of the signal from non-periodic components. Therefore, detrending removes aperiodicity due to temporary test interruption (i.e. well shut-in or significant rate deviation from that of the test design), generated by technical and/or operational issues.
5. Periodicity of rate variation is a basic requirement for harmonic test interpretability. However, the constant rate constraint over each flow period, strictly necessary for a conventional draw-down analysis, is relaxed in harmonic interpretation because rate fluctuations mainly affect the high frequency components (Hollaender et al., 2002b), which are relevant to the near wellbore region.
6. The log-log plot of the absolute value of the amplitude ratio between imposed rate and registered well pressure, and the amplitude ratio derivative, vs. oscillation period ($T = 2\pi/\omega$) is very similar to the conventional log-log diagnostic plot (Hollaender et al., 2002b).
7. Harmonic test response shows a phase shift, which is the relative delay of the pressure cycle with respect to the imposed flow cycle for each frequency. The phase shift can be used to assess the skin (Kuo, 1972) or to identify flow regimes (Hollaender et al., 2002b) since the plot of phase shift vs. oscillation period tends to asymptotic values for specific flow regimes. However, compared to the log-log plot, it does not provide significant additional information (Hollaender et al., 2002b).

2. Harmonic pulse testing type-curves

Harmonic test type curves can be analytically derived for different well and reservoir scenarios by solving the diffusivity equation under the condition of a harmonic rate. Because of the harmonic nature of the imposed rate and induced pressure changes, HPT interpretation involves frequency analysis. Mathematical derivations as well as synthetic validations are reported in the appendix for the reader's convenience.

The log-log plot of the absolute value of the amplitude ratio between imposed rate and registered well pressure and the amplitude ratio derivative vs. the oscillation period ($T = 2\pi/\omega$) provides diagnostic curves which are analogous to the conventional log-log diagnostic type-curves. However, despite the similarity in shape, the conventional time-domain curves are no longer applicable. In fact, a time shift of the derivative characteristic features is observed and differences exist as well between the transition periods from one flow regime to the following.

2.1. *Infinite acting radial flow (I.A.R.F.)*

The dimensionless solution of the diffusivity equation for an infinite-acting homogeneous and isotropic gas reservoir drained by a fully penetrating vertical well, under radial symmetry, was already published by the authors (Salina Borello et al., 2017) in terms of Hankel functions. In the present paper the dimensionless solution is given in terms of modified Bessel functions K_0 and K_1 in a form analogous to Kazi-Aoual et al., 1991:

$$m_D(T_D) = \frac{-K_0(\sqrt{i/T_D}) - S\sqrt{i/T_D}K_1(\sqrt{i/T_D})}{(1 + iSC_D/T_D)\sqrt{i/T_D}K_1(\sqrt{i/T_D}) + iC_D/T_DK_0(\sqrt{i/T_D})} \quad (1)$$

where K_0 and K_1 are the Bessel function and m_D is the dimensionless pseudo-pressure:

$$m_D = \frac{R}{\Lambda} = \frac{1}{\Lambda}\frac{m(p)_{pulser}}{q_{sc}} \quad (2)$$

R is the dimensional amplitude ratio, Λ is a factor to make the pressure over gas rate ratio dimensionless (non-dimensionalization factor):

$$\Lambda = \frac{1}{\pi kh}\frac{T_R p_{sc}}{Z_{sc}T_{sc}} \quad (3)$$

C_D is the dimensionless wellbore storage:

$$C_D = \frac{C}{2\pi\phi c_{ti}hr_w^2} \quad (4)$$

T_D is the dimensionless oscillation period:

$$T_D = \frac{1}{2\pi}\frac{kT}{\mu_i c_{ti}\phi r_w^2} \quad (5)$$

Furthermore, T is the oscillation period; k is the reservoir permeability; h is the pay thickness; ϕ is the porosity; T_R is the reservoir temperature; μ_i and c_{ti} are the gas viscosity and the total compressibility at initial conditions, respectively; Z_{sc} is the gas compressibility factor at standard conditions, which can be approximated to unity; P_{sc} and T_{sc} are