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The sorption-corrected multiwell deconvolution method to identify shale gas reservoir containing sorption gas

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A B S T R A C T

In the analysis of the pressure data acquired from a shale gas reservoir, the rate-normalized pressure (RNP) method has been widely used in the shale gas industry due to its simplicity. However, for sharply varying production rate and shut-in of a well, and for pressure-interfered data at a well, the RNP method gives erroneous results in evaluation of the reservoir characteristics. Meanwhile, the deconvolution method can overcome the limit of the RNP method for sharply varying data. However, because the deconvolution method is only applicable to a linear relationship in the pressure-rate data, it is not possible to analyze the pressure data acquired from adsorbed gas-contained shale gas reservoir. This data shows a nonlinear relationship because of the compressibility of desorbed gas which is a strong function of pressure.

In this study, we newly proposed the sorption-corrected multiwell deconvolution method for correctly identifying the shale gas reservoir containing the adsorbed gas. This method was suggested to analyze not only sharply varying production rate but also pressure-interfered data acquired from the multiwell. With the use of this method, we evaluated and compared the effective permeability and the estimated ultimate recovery (EUR) of shale reservoir with RNP method that is currently applied in shale gas industry. From the results, it was concluded that the sorption-corrected multiwell deconvolution method was found to be an excellent methodology comparing to RNP method for analyzing pressure-interfered shale gas production data containing the adsorbed gas.

1. Introduction

In analyzing the production data to identify a reservoir, there are several methods available, such as pressure transient analysis and decline curve analysis. For performing pressure transient analysis, a constant production rate during entire production period is theoretically required, however, the production rate is generally variable over a long period of production because of the low permeability of shale formation (Osholake et al., 2013; Izadi et al., 2014; Kim and Wang, 2014; Jang et al., 2016). Therefore, a variable rate should be converted into a constant rate. To accomplish this task, the RNP and deconvolution methods are generally employed as a converting method. The RNP method is the most widely used due to its simplicity; however, this method cannot analyze sharply varying production data, e.g., the pressure buildup process during the shut-in period (Spivey and Lee, 2013). The deconvolution method can overcome this limitation of the RNP method. However, because the deconvolution method is only applicable to linear relationship in pressure-rate data according to Duhamel's theory, it is not possible to analyze production data acquired from shale gas reservoirs containing sorption gas (Shiyi and Fei, 2008). This production data shows a nonlinear relationship because of the compressibility of desorbed gas which is a strong function of pressure (Gerami et al., 2007; Jarvie, 2012). Therefore, the deconvolution method cannot be directly applied to a shale gas reservoir.

Moreover, in order to economically produce gas from a shale gas reservoir, in general, multiwell pad drilling is essential. In multiwell pad drilling, six to eight horizontal wells generally stem from the same pad, and it can be seen mostly in Eagle Ford, Marcellus, Woodford, and other shale formations. Another important technique in shale gas production is the multi-stage hydraulic fracturing technique as known widely. These two techniques are significantly important for an explosive increase in shale gas production. However, these techniques could cause a critical issue, i.e., the pressure interference caused by hydraulic fractures generated between adjacent horizontal wells. Levitan et al. (2006); Levitan (2007) presented a multiwell deconvolution technique to remove the pressure interference by using the superposition principle. Cumming

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et al. (2014), Thornton et al. (2015) and Tung et al. (2016) conducted a study for the application of the multiwell deconvolution method to actual conventional gas field data.

In the aspect of multiwell production data containing sorption gas, the multiwell deconvolution method implemented with the sorption-corrected pseudopressure was proposed to be able to analyze not only sharply varying production data but also pressure-interfered data obtained from multiwell. From the pressure transient analysis using the sorption-corrected multiwell deconvolution method for a two-well system, we evaluated the effective permeability of the reservoir as well as the estimated ultimate recovery (EUR).

2. Sorption-corrected multiwell deconvolution

Multiwell deconvolution is a technique that enables to reproduce the constant-rate drawdown response from a variable production rate and to remove the pressure interference effect (Levitan et al., 2006). Assuming that there are n numbers of active wells in a reservoir, and these wells are connected to each other by hydraulic fractures. Once the convolution integral is applied to multiwell problem, the bottomhole pressure at observed well #k can be expressed as follows:

$$\Delta m(p)_k = \sum_{j=1}^{n} q(t)_j{}^* g(t)_{kj} = \sum_{j=1}^{n} \int_0^t q(t-\tau)_j \cdot g(\tau)_{kj} d\tau \tag{1}$$

here, $\Delta m(p)$ and $q(t)$ are the measured pseudopressure and flow rate respectively, and $g(t)$ is the unit impulse response function. In which, $g(t)_{kj}$ represents the pressure interference response from well #j at observation well #k.

However, this multiwell deconvolution cannot be applied directly in a shale gas reservoir, because the relationship between $\Delta m(p)$ and $q(t)$ shown in Eq. (1) is nonlinear because of the desorbed gas. To linearize the pressure-rate relationship, first, the following radial diffusivity equation of gas flow can be used:

$$\nabla \cdot (\nabla m(p)) = \beta \frac{\partial m(p)}{\partial t_p} \tag{2}$$

where, β denotes the flow conductivity, and t_p represents pseudotime.

In a multiwell system with n numbers of wells, pseudosteady state approximate solution of Eq. (2) at well #k can be expressed, based on the superposition principle:

$$\Delta m(p)_k = \sum_{j=1}^{n} q(t)_j \cdot \left[\frac{2p_i}{(\mu_g c_t^* Z^*)_i G} t_p \right] + \sum_{j=1}^{n} \left[\frac{1.417 \times 10^6 T}{kh} \left(ln \frac{r_e}{r_{kj}} - \frac{3}{4} \right) \right] \cdot q(t)_j \tag{3}$$

where, Z^* is deviation factor adjusted for desorption and the total compressibility c_t^* is defined as the summation of the free gas compressibility and the desorption gas compressibility c_d. The total compressibility strongly depends on the pressure because of the compressibility of the desorption gas, which causes the nonlinearity of the pressure-rate relationship. Therefore, to linearize the pressure-rate relationship in the deconvolution method, we define the sorption-corrected pseudopressure term $[\Delta m(p)_{corr}]_k$ at well #k by using a variable substitution:

$$[\Delta m(p)_{corr}]_k = \Delta m(p)_k - \sum_{j=1}^{n} q(t)_j \cdot \left[\frac{2p_i}{(\mu_g c_t^* Z^*)_i G} t_p \right] \tag{4}$$

Next, Eq. (3) becomes the following:

$$[\Delta m(p)_{corr}]_k = \sum_{j=1}^{n} \overbrace{\left[\frac{1.417 \times 10^6 T}{kh} \left(ln \frac{r_e}{r_{kj}} - \frac{3}{4} \right) \right]}^{\alpha_j} \cdot q(t)_j \tag{5}$$

where, α is a constant. Therefore, in this equation, the relationship of the sorption-corrected pseudopressure ($\Delta m(p)_{corr}$) and rate ($q(t)$) becomes in a linear form.

Along these lines, when performing a multiwell deconvolution method, the response function $g(t)$ in Eq. (1) should be obtained first. To accomplish this task, in the following objective function $E(g)$, the error between the measured $\Delta m(p)_{corr}^{\boldsymbol{M}}$ and the calculated $\Delta m(p)_{corr}^{\boldsymbol{C}}$ obtained by the convolution of $g(t)$ and rate q should be minimized. The minimization was conducted by using the trust region reflective algorithm. This algorithms is one of the most reasonable numerical optimization algorithm for solving nonlinear problems because it is able to give the appropriate constraints.

$$E(g) = \sum_{k=1}^{n} \left\| [\Delta m(p)_{corr}]_k^{\boldsymbol{m}} - [\Delta m(p)_{corr}]_k^{\boldsymbol{c}} \right\|_2^2 + \sum_{k=1}^{n} \sum_{j=1}^{n} \lambda \| g_{kj} \|_1^2 \tag{6}$$

here,

$$[\Delta m(p)_{corr}]_k^{\boldsymbol{c}} = \sum_{j=1}^{n} g(t)_{kj}{}^* q(t)_j \tag{7}$$

In the objective function of Eq. (6), a smoothing term $\lambda \| g(t) \|_1^2$ is added to prevent large variations in $g(t)$, because the response function $g(t)$ is varied significantly.

Finally, after obtaining $g(t)$ through the above-described objective function, the pressure interference-removed constant-rate drawdown response is then obtained from the following equation:

$$[\Delta m(p)_{corr}]_k^{\boldsymbol{D}} = g(t)_{kk}{}^* q(t)_k + q(t)_k \cdot \left[\frac{2p_i}{(\mu_g c_t^* Z^*)_i G} t_p \right] \tag{8}$$

Thus, the deconvolved pseudopressure $[\Delta m(p)_{corr}]^{\boldsymbol{D}}$ for well #k can be now adequately used in the pressure transient analysis.

In order to confirm the linearized pressure-rate relationship by using the sorption-corrected pseudopressure developed in this work, a comparison was made with the pseudopressure-rate relationship obtained from previous methods. The pressure-rate curve became highly deviated as the rate increases when using the conventional sorption-noncorrected pseudopressure, whereas, the sorption-corrected pressure-rate curve was almost identical to the linear line. Therefore, it can be known that, by implementing the sorption-corrected pseudopressure into the deconvolution method, the pressure transient analysis can be adequately conducted in a sorption-containing shale gas reservoir.

To investigate the effect of the magnitude of adsorbed gas on the pseudopressure derivative, the reservoir simulator was utilized for Langmuir volumes (V_L) of 0, 250 and 350 scf/ton. Fig. 1(a) shows the results of the pseudopressure derivatives without the use of sorption correction. When the adsorbed gas volumes were 250 and 350 scf/ton, the decline in the pseudopressure derivatives $\Delta m(p)'$ was delayed compared with the reservoir that did not contain sorption gas (0 scf/ton). This difference affected the flow regime, which in turn significantly influenced the production data analysis. Meanwhile, Fig. 1(b) shows the sorption-corrected pseudopressure derivatives corresponding to the amount of adsorbed gas. Here, the pseudopressure derivative curves were found to be identical without any delay times, which implies that the sorption-corrected pseudopressure was unique regardless of the magnitude of adsorbed gas.

3. Shale gas reservoir system

A commercial reservoir simulator, CMG-GEM, was used to obtain synthetic production data from the shale gas model in which pressure interference occurs due to the pressure decline resulting from the production of two hydraulically fractured horizontal wells. In the numerical model, the stimulated reservoir volume system represents the primary fractures generated by hydraulic fracturing and secondary fractures