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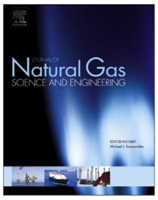

Pressure-buildup analysis method for a post-treatment evaluation of hydraulically fractured tight gas wells

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ABSTRACT

Tight gas reservoirs have a very low permeability, usually approximately <0.1 md. Consequently, a fractured horizontal well drawn from these reservoirs will encounter difficulty reaching a radial flow regime after completion. The effective reservoir permeability and the effective fracture half-length cannot be determined using short-term well test data. In addition, the wellbore storage effect tends to obscure early flow regimes in hydraulic fractures, thereby hampering the calculation of fracture conductivity. Fitting well test curves in the absence of early flow regimes in the fracture and middle radial flow regime is not sufficient. In this paper, a deconvolution-based pressure buildup analysis method amended with a modified Schroeter deconvolution model is proposed. The proposed method utilizes short-term pressure buildup and long-term flow rate data to recover the true reservoir pressure response. A synthetic case is presented to demonstrate that the proposed deconvolution model and algorithm can eliminate the wellbore storage effect and recover the fracture linear flow and formation radial flow regimes. A field case in the East China Sea is further presented to demonstrate the feasibility of the proposed method. This study demonstrates that a short-term pressure buildup test data can still be used to calculate the fracture and reservoir dynamic parameters of tight gas wells. Thus, the hydraulic fracturing treatment can be quantitatively evaluated.

1. Introduction

Completion of a horizontal well with a multistage hydraulic fracturing treatment has become an effective means to produce gas from tight gas reservoirs (Kang and Luo, 2007; Dai et al., 2012). These reservoirs exhibit a low permeability, usually no more than 0.1 md, which results in a long period of transient flow in fractured horizontal wells. In the last ten years, many studies have focused on mathematical models and the pressure transient response of fractured horizontal wells. Ozkan et al. (2009), Denney (2010), Yao et al. (2013), and Wang et al. (2014) proposed mathematical models and analytical solutions for multistage fractured horizontal wells. Al-Kobaisi et al. (2006) focused on the pressure transient response during the early flow stage of a horizontal well intercepted by multiple transverse fractures. The early flow stage is defined as a transient flow period prior to fracture interference, which indicates a flow state under the control of fracture storage, including fracture radial flow, radial linear flow, and bilinear flow. Zerzar et al. (2004), Luo et al. (2010), and Cheng (2011) studied the pressure transient response in subsequent stages (after the fracture storage dominated stage), including the formation linear flow, pseudo-radial flow, composite linear flow, infinite-acting radial flow, and boundary-dominated pseudosteady state flow or steady state flow. Song et al. (2011) introduced the concept of pseudo-pseudosteady state flow to describe a flow regime between pseudo-linear flow and composite linear flow, which is also called exhaustion flow in a stimulated reservoir volume. Wang et al. (2013) utilized numerical simulations to present the six flow regimes of a hydraulically fractured horizontal well and the corresponding pressure-transient-response type curve (Fig. 1). The flow regimes follow the sequence: fracture flow obscured or masked by wellbore storage effect, formation linear or bilinear flow, pseudo-pseudosteady state flow, composite linear flow, formation radial flow, and pseudosteady state flow. For a tight gas reservoir with 0.01 md permeability, a fractured horizontal well usually takes a decade to reach the formation radial flow regime.

Well test analysis is an effective method to define flow regimes, as well as quantify reservoir and well-completion parameters

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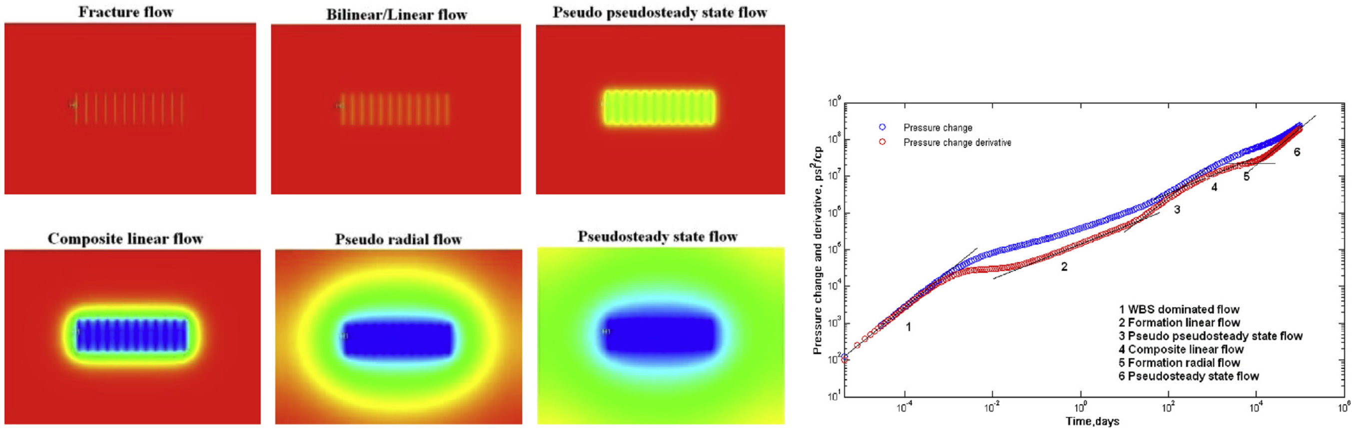

Fig. 1. Flow regimes of a simulated hydraulically fractured horizontal well and corresponding pressure-transient-response type curve (Wang et al., 2013).

(Bourdet, 2002; Gringarten, 2005; Du, 2007; Ehlig-Economides et al., 2009; Clarkson, 2009). Short-term well tests (pressure buildups or drawdowns) are not practical or useful for the quantitative evaluation of a hydraulic fracturing treatment for fractured horizontal tight gas wells because the extraction of the effective fracture half-length, which is a key well-completion parameter, from the recorded transient pressure requires an estimate of the reservoir's effective permeability. Effective permeability can only be precisely estimated directly from a buildup or drawdown test if data from the formation radial flow regime reflecting this parameter were recorded. However, this flow regime occurs only after long shut-in or flowing times because of the extremely low permeability of the tight gas reservoir. Several months are required to test the well, and allowing the well to reach the radial flow regime is not economically feasible to producers. Meanwhile, the early flow regime in hydraulic fractures is usually obscured by the wellbore storage effect. This leads to a failure calculating the fracture conductivity, which is another key well-completion parameter, if early fracture flow is not recovered.

Well test deconvolution is a new breakthrough in the well test field (Gringarten, 2010). A calculation using the deconvolution can yield the true reservoir pressure transient response during whole flow periods. Thus, the superposition effect caused by variable flow rates is avoided, and additional information about the reservoir is obtained and compared with data from a relatively short test duration. Well test deconvolution can be divided into two categories, i.e., deconvolution in the spectral domain and time domain. The former (Scott et al., 1991; Iseger, 2006; Al-Ajmi et al., 2008) transforms the convolution operation in the time domain into multiplication in the spectral domain by applying the Laplace or Fourier transform, and it converts the obtained transient pressure response to the time domain by the Stehfest numerical inversion. The latter (Baygu et al., 1997; von Schroeter et al., 2004; Levitan, 2005; Llk et al., 2006; Onur and Kuchuk, 2010; Onur et al., 2011) can be further divided into linear, restrained linear, and nonlinear solutions, in which the deconvolution considers the majority of errors and possesses a stable solution. However, Schroeter's decovolution process has not eliminated the wellbore storage effect. Therefore, the early flow regime in the fractures still cannot be recovered using their decovolution models.

In this study, we propose a modified Schroeter deconvolution model specially designed to analyze the short-term pressure-buildup test data from hydraulically fractured horizontal wells in tight gas reservoirs. The wellbore storage effect can be eliminated, and the fracture linear flow and formation radial flow regimes can be recovered using the proposed analysis method. Consequently, several well-reservoir parameters, such as reservoir effective permeability, hydraulic fracture half-length, and conductivity, can be determined. A numerical well testing synthetic study was performed to demonstrate the analysis procedures. A field application was then conducted to prove the feasibility of the proposed method.

2. Modified Schroeter deconvolution model and algorithm

2.1. Modified Schroeter deconvolution model

Duhamel's principle in a single-well system states that the pressure drop is the convolution product of flow rate and reservoir response as a function of time (van Everdingen and Hurst, 1949).

$$\Delta p(t) = p_i - p(t) = \int_0^t q(\tau) g(t - \tau) d\tau \tag{1}$$

The first step in well test analysis is to solve the Bourdet logarithm derivative. For the case of a single-flow period with a constant flow rate, the numerical differentiation of the pressure data in Eq. (1) with respect to the logarithm of time is equal to the product of the reservoir impulse response g and time t as follows (Bourdet et al., 1989):

$$\frac{d\Delta p}{d \ln t} = tg(t) \tag{2}$$

To maintain physical significance, Eq. (1) should meet the following constraint requirements to ensure that the flow rate and impulse response are greater than or equal to 0:

$$q(\tau) = \begin{cases} 0, \tau \le 0 \\ 1, \tau > 0 \end{cases} \tag{3}$$

The following equation can be obtained according to the definition by von Schroeter et al. (2004):

$$u(\sigma) = \ln\{tg(t)\}, \sigma = \ln t, t \in [0, T] \tag{4}$$

Thus, Eq. (1) can be transformed as follows:

$$\Delta p(t) = \int_{-\infty}^{\ln t} e^{u(\sigma)} q_{sc}(t - e^{\sigma}) d\tau \tag{5}$$

Eq. (5) is the Schroeter deconvolution model, in which q_{sc} is the