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Analytical modeling dynamic drainage volume for transient flow towards multi-stage fractured wells in composite shale reservoirs

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ABSTRACT

This paper presents an analytical solution to predict the expansion of drainage volume for a composite transient linear flow system consisting of stimulated-reservoir volume (SRV) and unstimulated reservoir volume. Correct prediction of dynamic drainage volume (DDV) is essential in production data analysis and well space evaluation. With the prediction of DDV, we can calculate the average pressure and average saturation with different time, which can assist designing different exploitation scenarios.

The compound linear flow solution within both SRV and unstimulated matrix is derived under constant-flowing-bottomehole-pressure (FBHP) and constant-rate boundary conditions. Laplace transform and numerical inversion are implemented to obtain the analytical solution. The location of pressure front is calculated using the impulse response concept, which is the maximum rate of pressure response. A multi-variable regression method is applied to determine an empirical equation indicating the relationship between DDV and the square root of time; the empirical equation includes conductivities of both SRV and unstimulated matrix volume, fracture length, and fracture spacing.

The results suggest that the DDV demonstrates a linear relationship with square-root-of-time for both linear flow regime within SRV and the compound linear flow in composite fractured reservoirs. The advancement of DDV within stimulated-reservoir volume is much faster than unstimulated matrix, which is approximately 100 times in general. To verify the accuracy of newly derived DDV equations, we analyze the synthetic production data from series of fine-grid numerical simulations. Finally, we make a sensitivity analysis of hydraulic fracture spacing with respect to DDV, which can be implemented to evaluate the fracturing design. In practice, the solution derived can be used to determine optimal fracture spacing.

1. Introduction

Production of shale gas (referring to natural gas in fine-grained rocks, i.e., organic-rich shales, mudstones, siltstones, and fine sandstones interlaid with shales, muds and carbonate rocks) in North America/Asia has increased significantly as a result of multi-stage fracturing and horizontal drilling (Clarkson, 2013; Yuan et al., 2015a).

Typically, it is critical to make accurate reservoir/fracture characterizations and well performance predictions for the evaluation of unconventional reservoirs. In shale reservoirs, a wide range of complex reservoir/fluid properties (i.e., gas desorption, non-Darcy, and multiphase flow; ultra-low permeability, stress-dependent porosity, and dual-porosity/dual-permeability etc.) and macro/micro fracture network distribution lead to conventional evaluation methods not accurate enough (Zhao et al., 2015a). But it is still possible to develop some analytical, semi-analytical, and numerical models to present pressure transient and production behaviors in tight gas (Yuan and Wood, 2015). The tri-linear flow model presented by Ozkan et al. (2009), Brown et al. (2011) takes into account of the key characteristics of complex flow of multiple transverse fractures with finite conductivity of horizontal wells. Stalgorova and Mattar (2012) then developed the tri-linear flow model to a five-region flow model, which incoperates the fluid supplement from partially stimulated reservoir volume and matrix. Apaydin et al. (2012) developed the analytical tri-linear flow model with composite blocks to describe the effect of microfractures on matrix permeability. Zhao et al. (2014) also extended the conventional multiple hydraulically fractured horizontal well (MFHW) into a composite model to describe the stimulated reservoir volume (SRV). Despite obvious advantages of "tri-linear" and "five-region" models, there are still some drawbacks of them. In fact, it is not possible for uniform density of micro-fractures distributed in the formation, due to fracturing effects, the properties quality of micro-fractures (aperture, density and conductivity) near horizontal wells would be better than those fractures away from the wells. Yuan et al. (2015b) developed a

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Nomenclature

C_{RD}	dimensionless reservoir conductivity
c_{tO}	total outer reservoir compressibility, psi^{-1}
c_{tI}	total inner reservoir compressibility, psi^{-1}
h	reservoir thickness, ft
k_I	permeability of the inner reservoir, md
k_O	permeability of the outer reservoir, md
p	pressure, psi
q	production rate, STB/day
q_1	rate at day 1, STB/day
s	Laplace parameter
s_o	Parameter defined in trilinear flow model
t	time, days
t_e	end time of linear flow regime within SRV, days
t_D	dimensionless time
x	x coordinate, ft
x_D	dimensionless x coordinate, ft
x_F	hydraulic fracture half-length, ft
y	y coordinate, ft
y_e	half of distance between two hydraulic fractures, ft
y_D	dimensionless y coordinate, ft
y_{eD}	dimensionless half of fracture spacing
α	Parameter defined in trilinear flow model
η_I	inner-reservoir diffusivity, ft^2/h
η_O	outer-reservoir diffusivity, ft^2/h
η_{OD}	outer-reservoir diffusivity ratio, ft^2/h
μ	fluid viscosity, cp
ϕ_I	inner-reservoir porosity, fraction
ϕ_O	outer-reservoir porosity, fraction
G_p	cumulative production, STB

multi-linear flow solution considering the variant fracture densities versus the distance to wellbores (primary hydraulic fractures, secondary fractures and then the partially open but not fully connected natural fractures).

Along with these analytical models for a multi-stage fractured horizontal well to evaluate well production, the objectives of production data analysis (PDA), including straight-line analysis, type-curve methods, analytical/numerical solutions and empirical methods, are to obtain: (1) reservoir and well stimulation characterization, (2) evaluation of dynamic drainage efficiency, and (3) forecast of reservoir performance and development planning (Sun, 2015; Yuan et al., 2015a). As noted by Yuan et al. (2016), for shale and tight reservoir, the understanding on the propagation of distance-of-investigation (DOI) (or DDV in view of volume) of transient linear flow is essential to apply production analysis techniques to evaluate or predict well performance. The concept of DOI or DDV have been demonstrated as a useful tools for designing well testing, rate-transient analysis (Nobakht, 2014), identification of infill drilling, and optimization of well fracturing. (Datta-Gupta et al., 2011) investigated the impacts of DOI or DDV on production analysis during transient linear flow by calculating the average pressure within dynamic drainage volume in stress-dependent reservoirs.

So far, a variety of authors have developed different concepts or models to estimate the distance of investigation, and for defining the stabilization time (time reaching pseudo-steady or steady state). For example, Tek et al. (1957) proposed the drainage radius at that point where the fluid flowing is 1% of the fluid flowing into the wellbore. Jones (1962) defined the drainage radius as the distance at which the pressure changes only by 1%. van Poollen (1964) equated the Y function of infinite and finite reservoirs that allows calculating the radius of investigation. Aguilera (1987) extended van Poollen's equation to the case of naturally fractured reservoirs that are represented by dual porosity systems. Sobbi and Badakhshan (1996) and Aguilera (2006) published a radius of investigation equation for well test analysis with pseudo-steady state inter-porosity flow for both dual-porosity finite and infinite reservoirs. Wattenbarger et al. (1998) proposed a new equation of DOI by indicating the end of the half-slope line in type curves. Kuchuk (2009) presented a comprehensive study on the DOI for radial flow. In shale reservoirs, the dominant flow regime for multi-stage fractured horizontal wells is transient linear flow, which can last for several years. In addition to some empirical models for DOI, only within the SRV an analytical formulation of DOI was recently employed to evaluate the dynamic drainage volume (DDV) for the linear flow system. Behmanesh et al. (2015) apply two different approaches to calculate the DOI, which are the maximum rate of pressure response method, and the trainsent-boundary flow intersection method. However, in view of production from both SRV and unstimulated shale/tight sand matrix, the DOI (or DDV in view of volume) of transient linear flow in compound multi-stage fractured reservoirs has not been determined yet. Moghanloo et al. (2015) proposed an empirical equation of DDV based on its asymptotical relation with production time. Nobakht and Clarkson (2012) ignored the production contribution outside the stimulated-reservoir volume (SRV); therefore, it is assumed that there is only transient linear flow within SRV. However, as the assumption of the trilinear flow model from Brown et al. (2011), and the continuing production of multi-stage fractured horizontal well after linear flow, there would be compound linear flow (Song et al., 2011) regime, where both SRV and unstimulated reservoirs near SRV can contribute fluid productions.

This paper presents an analytical solution calculating the pressure and dynamic drainage volume (DDV) of both linear flow within SRV and that of the compound linear flow; our analytical solution for DDV is derived under the constant-flowing-pressure and constant-production-rate condition. The pressure front is calculated implementing the impulse responce concept, which is the maximum rate of pressure response. A multi-variable regression method is applied to propose an empirical equation indicating the relationship between DDV and square root of time considering the effects of different diffusivities within SRV and unstimulated matrix, hydraulic fracture length, and fracture spacing. A synthetic simulation case is used to validate our new equation of DDV for a multi-stage fractured horizontal well. Finally, we perform a sensitivity analysis of hydraulic fracture spacing, which can be implemented to find the optimal fracture spacing that could help the project economics.

2. Model and methodology description

The tri-linear flow model (Brown et al., 2011) is specifically applicable to a multi-stage fractured horizontal well (MFHW) in unconventional reservoirs with ultra-low matrix permeability. The premise of this flow model is that linear flow regime is dominant in both SRV and unstimulated reservoir volume for a long time while producing from a MFHW. With the assumption in this paper, the transient flow response of many identical transverse hydraulic fractures of a horizontal well can be modeled via considering a single fracture and the rectangular area around it (Fig. 1). Meanwhile, it assumes that there is not skin factor nor well storage effect. For the derivation of the outer reservoir, the boundary condition will be regarded as infinit acting flow. The total production rate of the horizontal well is the accumulation of the production of each single symmetric fracture. Similarly, as sketched in Figs. 1 and 2, the total DDV of the horizontal well is the DDV summation of each identical symmetry element. Our analytical solution is derived from considering one-quarter of a hydraulic fracture and its corresponding DDV. We