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Full Length Article

A practical method for production data analysis from multistage fractured horizontal wells in shale gas reservoirs

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HIGHLIGHTS

- A comprehensive method is proposed for production data analysis from shale gas wells.
- Both adsorption mechanism and fracture networks are considered in this method.
- New type curves are developed to make type curve fit more accurate and convenient.
- Production data is processed considering desorption and compressibility nonlinearity.

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ABSTRACT

Shale gas reservoirs are characterized by gas adsorption in matrix and complex fracture networks after hydraulic fracturing stimulation, and the properties of which cannot be measured through existing methods. Many linear flow models have been proposed to interpret these properties, however the nonlinearity of desorption and gas compressibility is often neglected when analyzing production data. Moreover, the production rate and bottom hole pressure (BHP) are usually variable, while the control mode in analytical models is either at constant production rate or BHP. Therefore, the nonlinearity should be considered when interpreting production data, and the problem of variable rate and BHP remains to be solved. In this paper, a comprehensive method for analysis of production data with variable rate for multistage fractured horizontal wells in shale gas reservoirs has been put forward, in which the nonlinearity of desorption and compressibility is considered. The classical tri-linear flow model is modified by incorporating desorption in the matrix. New type curves are developed incorporating normalized rate, integration of the rate and derivative of the integration against pseudo-time. To analyze production data with nonlinear desorption and compressibility, modified material balance equation and material balance time are applied to process production data. If the production data of a real shale reservoir is given, the half-length and the permeability of the hydraulic fractures, the permeability of the stimulated reservoir volume can be determined with this method. Finally, a field case is used to demonstrate this method for production data analysis.

1. Introduction

Shale reservoirs are normally regarded as self-sourcing reservoirs and the shale matrix is typically observed with very low permeability and rich of organic matter with much gas adsorption [1]. The economical production of shale gas reservoirs normally requires technologies of drilling horizontal wells and multistage fracturing stimulation, which forms a stimulated reservoir volume (SRV) comprised of shale matrix and many induced fractures around the main hydraulic fractures [2,3]. Many numerical and semi-analytical models have been proposed to incorporate the nonlinear desorption in the matrix [4–6] and the complex morphology of the fracture network [7–9]. However, many parameters of the fracture network cannot be directly measured through core analysis, well logging or microseismic mapping. Fortunately, the complex fracture networks and the matrix in the SRV are treated as an equivalent medium in linear flow models, which are proved to be versatile enough to incorporate the fundamental petrophysical characteristics of shale reservoirs, including the properties of the unstimulated region and the SRV [10–14]. And computational convenience of the linear flow solution makes it a practical alterna-

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Nomenclature

A_{cw}	cross sectional area to flow, m^2
B_g	formation volume factor, rm^3/sm^3
h	formation thickness, m
k_m	matrix permeability, md
k_I	permeability of the inner reservoir, md
k_O	permeability of the outer reservoir, md
k_F	fracture permeability, md
C_g	gas compressibility, MPa^{-1}
C_t	total compressibility, MPa^{-1}
C_{tm}	total compressibility of the matrix, MPa^{-1}
C_{tF}	total compressibility of fractures, MPa^{-1}
C_d	desorption compressibility, MPa^{-1}
P_m	matrix pressure, MPa
P_F	fracture pressure, MPa
P_I	pressure in the inner reservoir, MPa
Z	gas compressibility factor, dimensionless
P_O	pressure in the outer reservoir, MPa
P_{sc}	pressure at standard condition, MPa
p_i	initial pressure, MPa
p_L	Langmuir pressure, MPa
q_{sc}	wellbore gas rate, sm^3/day
q_N	normalized rate, m^3/day/MPa^2 (mPa s)
t	production time, days
t_a	pseudo-production time, days
t_{ca}	material balance time, days
T	formation temperature, K
T_{sc}	temperature at standard condition, K
y_F	half-length of the hydraulic fracture, m
V	absorbed gas volume, sm^3
V_L	Langmuir volume, m^3/m^3
v_m	gas flow velocity in the formation, m/day
M	molecular weights of gas, kg/kmol

Greeks

L_F	fracture space
Ψ_m	pseudo-pressure in the matrix, MPa^2/mPa s
Ψ_F	pseudo-pressure in the fracture, MPa^2/mPa s
Ψ_{wf}	wellbore pseudo-pressure, MPa^2/mPa s
η_D	diffusivity ratio, dimensionless
Ψ_O	pseudo-pressure in the outer reservoir, MPa^2/mPa s
Ψ_I	pseudo-pressure in the inner reservoir, MPa^2/mPa s
λ_{IF}	interporosity flow coefficient between inner reservoir and fracture, dimensionless
λ_{IF}	interporosity flow coefficient between inner reservoir and outer reservoir, dimensionless
ω_F	the width of the hydraulic fracture
Φ_m	formation porosity, m^3/m^3
Φ_F	fracture porosity, m^3/m^3
ρ	gas density, kg/m^3
μ	fluid viscosity, mPa s
∂	differential operator

tive to more rigorous but computationally intensive and time-consuming solutions when interpreting production data. However, the nonlinearity of desorption and gas compressibility is neglected when analyzing production data with linear flow models.

There are three analytic methods to analyze production data from hydraulically fractured horizontal wells in shale gas reservoirs proposed by previous scholars. The first method is flow regimes analysis using linear flow models [10–12,15–19], because many hydraulically fractured horizontal wells have been observed to exhibit a long-time transient linear flow regime, which is characterized by a one-half slope on log-log plots of rate against time, and $\sqrt{k_m}x_f$ can be calculated through the slope of the matrix linear flow. However, other parameters are difficult to obtain with this method, because sometimes the regime dominated by matrix drainage is the only flow regime that can be identified. The second method is type curve fitting, which is widely used to analyze production data from vertical wells in conventional gas reservoirs. To analyze production data from multistage fractured horizontal wells in shale gas reservoirs, Moghadam et al. [20] and Abdulal et al. [21] proposed new type curves to analyze production data by defining a modified dimensionless rate and time. But this type curve can be only used to analyze linear flow regime dominated by inner reservoir. The third method is to match the production data with the analytical or semi-analytical model solution by the means of iterations of unknown parameters [12,14]. However, the method can lead to multi-solution because of the uncertainty of many parameters in the model. In conclusion, the linear flow models provide a very practical method for production data analysis, but the nonlinearity of desorption and gas compressibility is neglected when analyzing production data, and the problem of variable rate and BHP still remains to be solved.

To analyze production data with variable rate and BHP, the normalized rate and material balance time are adopted to process production data in conventional gas reservoirs [22,23]. But desorption in the matrix is not considered in production data analysis, so this method remains to be modified. The derivative of normalized rate or pressure is also analyzed to make type curve fitting efficient [2,14,24,25]. However, the derivative of normalized rate is noisy most of the time, because the derivative is sensitive to production data which is always fluctuant and with errors. Therefore, it is not practical to analyze the derivative of normalized rate.

Therefore, in this paper, a comprehensive method is presented for analysis of production data from multistage fractured horizontal wells. The classical tri-linear model proposed by Brown et al. [12] is modified by considering the nonlinearity of desorption and gas compressibility. Desorption compressibility and pseudo-time are adopted to solve the nonlinearity in the equation. And the modified material balance equation, normalized rate and material balance time are applied to process production data with variable rate, then new type curves are developed which incorporate normalized rate, integration of the rate and derivative of the integration. If the production data of a real shale reservoir is given, the fracture parameters and the production performance can be predicted with the production data analysis method.

2. Methodology

2.1. Physical model

As shown in Fig. 1, the hydraulic fracture at each stage is assumed as biwing transverse fracture in this study. And complex fracture networks comprised of many induced fractures are formed around the hydraulic fractures during hydraulic fracturing stimulation. Microseismic measurements and other geophysical evidence suggest that the creation of complex fracture networks during fracturing treatments may be a common occurrence. But the fracture networks around hydraulic fractures are so complex that the relative parameters, such as the numbers of induced fractures, the ori-