Fuel 193 (2017) 444–459

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Semi-analytical modeling of shale gas flow through fractal induced fracture networks with microseismic data

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ARTICLE INFO

Article history:
Received 28 September 2016
Received in revised form 5 December 2016
Accepted 18 December 2016
Available online 3 January 2017

Keywords:
Shale gas flow model
Fractal induced fracture network distribution
Hydraulically fractured horizontal well
Microseismic
Gas adsorption
Percolation theory

ABSTRACT

Hydraulic fractures connecting to the adjacent induced fracture network significantly promote the productivity of unconventional gas reservoirs. Precise characterization of the fracture network in stimulated reservoir volume (SRV) is particularly important in modeling shale gas flow mechanisms. The objective of this work, based on available microseismic information of fracture density and field production data, is the integrated modeling of shale gas production with time-dependent pressure, pressure-dependent gas properties, and scale-dependent heterogeneous induced-fracture properties.

This paper presents a Fractal Induced Fracture Network Distribution (FIFND) model to characterize SRV heterogeneity. The model consists of a novel fractal induced-fracture density distribution and a fractal permeability/porosity distribution. The FIFND model can accurately estimate the induced fracture permeability and porosity when only the microseismic data of fracture density are available. This is highly useful since microseismic fracture density data are more frequently available than permeability and porosity data. A semi-analytical Fractal Transient Shale Gas Flow model (FTSGF) is then derived for the multi-stage hydraulically-fractured horizontal wells. The FTSGF model is coupled with the FIFND model to better describe the fracture network heterogeneity in the SRV. The transient flow contribution from the matrix is modeled by apparent matrix porosity with the presence of adsorbed gas. The fractal transient flow features are ultimately transformed into a characteristic function of the fractal matrix-fracture flow transfer.

The FIFND model is validated though the upscaled microseismic geological data for a Barnett shale well. Fracture density distribution, which is regulated by the Hausdorff dimension, is more significant on well productivity than fracture permeability, which is mainly subject to the fracture tortuosity index. The FTSGF model is verified by the field production data in Barnett shale. The robustness of the FTSGF model is justified by a good fit with the Power Law Exponential Decline model (PLE) and alignment with realistic values of multiple physical parameters, including average induced-fracture apertures. Our model is also validated for predicative robustness using fewer months of production data.

Finally, we propose and implement a workflow for the integrated semi-analytical modeling of shale gas production. The workflow provides an effective tool for characterization, history-matching, and forecasting reservoir/well performance of hydraulically-fractured horizontal wells in shale reservoirs. The limitations of the proposed models and potential future expansions are discussed.

1. Introduction

In the evaluation of well performance in unconventional reservoirs, semi-analytical/analytical flow models honor well/reservoir physics and are favored for flexibility and reliability in model tuning, reservoir characterization, and matching production history.

Fig. 1 is the top view of a multi-stage hydraulically-fractured horizontal well. A hydraulically-stimulated well consists of hydraulic fractures (HF), stimulated reservoir volumes (SRV), and unstimulated reservoir volumes (USRV). The USRVs are unstimulated matrices where induced fractures have not extended and formation permeability remains in the order of nano-Darcy for typical shales. Two types of USRV are discussed here: (1) USRV region beyond the hydraulic fracture tip (denoted by USRV-A). (2) USRV region at the SRV boundary between two hydraulic fracture stages (denoted by USRV-B). The SRV region is composed of induced fracture networks (with natural fractures) and matrix. The activated

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http://dx.doi.org/10.1016/j.fuel.2016.12.059

Nomenclature

B_g	gas formation volume factor, ft^3/SCF
B_{gi}	gas formation volume factor at the initial pressure, ft^3/SCF
c_m, c_f, c_{HF}	compressibility of matrix, fracture network, and hydraulic fracture, 1/psi
c_{mt}, c_{ft}, c_{HFt}	total compressibility of matrix, fracture network, and hydraulic fracture, 1/psi
c_g	isothermal gas compressibility, 1/psi
C_D	dimensionless wellbore storage constant
$C_1 \ldots C_8$	coefficients
D_∞	decline constant at the infinite time
$\widehat{D}_i$	decline constant
E	Euclidean dimension
F_{CD}	dimensionless hydraulic fracture conductivity
$F(s)$	characteristic function of dual porosity/permeability model in the fractal SRV
G	original gas-in-place, BCF
G_p	cumulative gas production, BCF
h_m	average matrix slab thickness, ft
$\overline{h}_f$	average induced-fracture aperture, ft
h_{mt}, h_{ft}	total matrix slab thickness and total fracture aperture, ft
h_R	pay zone half-thickness, ft
h_D	dimensionless thickness
Δh	single gridblock thickness in the microseismic geo-model, ft
H	Hausdorff dimension
J	productivity index, MMSCF/day-psi
k_m, k_f, k_{HF}	permeability of matrix, fracture network, and hydraulic fracture, mD
$\overline{k}_m$, $\overline{k}_f$, $\overline{k}_{f0}$	bulk permeability of matrix, induced fracture, and induced fracture at $y = w_{HF}$, mD
K_a	adsorption coefficient, ft^3 gas/ft^3 rock
M_g	molar mass of dry gas, lb/lb-mole
M_s	the month when bottomhole pressure starts to stabilize
n	time exponent
N_f	number of induced fractures, fracs
N_t	total number of induced fractures, fracs
N_{HF}	number of hydraulic fracture stages
N_k	number of gridblocks (in z-direction) in the upscaled microseismic geo-model
p_i	initial reservoir pressure, psi
p_U, p_m, p_f, p_{HF}, p_{wf}	pressure in USRV, SRV matrix, SRV fracture network, hydraulic fracture, and wellbore, psi
p_{UD}, p_{mD}, p_{fD}, p_{HD}, p_{wD}	dimensionless pressure in USRV, SRV matrix, SRV fracture network, hydraulic fracture, and wellbore in time domain
$\overline{p}_{UD}$, $\overline{p}_{mD}$, $\overline{p}_{fD}$, $\overline{p}_{SD}$, $\overline{p}_{HD}$, $\overline{p}_{wD}$	dimensionless pressure in USRV, SRV matrix, SRV fracture network, SRV, hydraulic fracture, and wellbore in Laplace domain
p_L	Langmuir pressure, psi
$\overline{p}_R$	average reservoir pressure, psi
p_{wfc}	bottomhole pressure constraint, psi
Δp	differential pressure, psi
q_{gL}, q_{gR}	a quarter of gas production rate from the left or right induced fracture half-cluster, MSCF/day
q_t	total gas production rate of a multi-stage hydraulically fractured horizontal well, MSCF/day
q_{PLE}	gas rate estimated by the PLE model, MSCF/day
$\hat{q}_i$	flow rate intercept, MSCF/day
s	Laplace operator
S_{wi}	initial water saturation, fraction
t	production time, days or months
t_D	dimensionless time
T	reservoir temperature, °F
v	order of Bessel function
V_a	adsorbed gas volume fraction
V_p	volume of adsorbed gas per mass of rock, SCF gas/ton rock
V_L	Langmuir volume, SCF gas/ton rock
V_{sc}	molar gas volume at standard condition, SCF/lb-mole gas
w_{HF}	hydraulic fracture half-aperture, ft
w_D	dimensionless hydraulic fracture aperture
x_{HF}	hydraulic fracture half-length, ft
x_D	dimensionless distance in x-direction
y_c	critical location (also the effective SRV width), ft
y_e	hydraulic fracture half-spacing (also the outer boundary of USRV-B), ft
y_D	dimensionless distance in y-direction
y_{cD}, y_{eD}	dimensionless distance of critical location and hydraulic fracture half-spacing
y_{D2}	dimensionless distance in y-direction, where $y_{D2} = y_D/w_D$
z_D	dimensionless distance in z-direction
Z, Z^*	original and corrected gas deviation factor, dimensionless
Z_i, Z_i^*	original and corrected gas deviation factor at the initial pressure, dimensionless
α, β, γ	parameters in the modified Bessel equation
ζ	flow region, or media denotation
η_m, η_f, η_{f0}, η_{HF}	diffusivity in matrix, fracture network, fracture at $y = w_{HF}$, and hydraulic fracture, ft^2/day
η_{UD}, η_{HD}	dimensionless diffusivity in USRV, and hydraulic fracture
θ, $\overline{\theta}$	tortuosity index and average tortuosity index
λ	interporosity flow coefficient
μ_g	gas viscosity, cp
ρ_a	mass of adsorbed gas per rock volume, lb gas/ft^3 rock
ρ_b	rock density, ton rock/ft^3 rock
ρ_f	induced fracture density, fracs/ft
ρ_g	free gas mass density, lb/ft^3 gas
ϕ_m, ϕ_f, ϕ_{HF}	porosity of matrix, induced fracture, and hydraulic fracture, fraction
$\overline{\phi}_{am}$	apparent matrix porosity, fraction
$\overline{\phi}_m$, $\overline{\phi}_f$, $\overline{\phi}_{f0}$	bulk porosity of matrix, fracture network, and fracture at $y = w_{HF}$, fraction
ω	storativity ratio
α_c	unit conversion factor

fracture network largely enhances the original formation permeability and therefore, governs dominant flow paths to the hydraulic fractures.

Researchers investigated the role of USRV-A. Anderson et al. [3] found that when matrix permeability is below 10 nD, the USRV-A is insignificant in terms of a 20-year estimated ultimate recovery (EUR). Stalgorova and Mattar [32] showed a similar result in numerical simulation and then abandoned the USRV-A to develop their trilinear flow model. Fan [14] and Fan and Ettehadtavakkol [15] demonstrated that the USRV-A's effect is negligible compared to the SRV, since the flowing capability in unstimulated matrix is limited by ultra-low permeability. With respect to the 20-year EUR, the contribution from the USRV is less than 1%. To address the dominance of fracture network in flow rate, Fan and Ettehad-