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A semi-analytical model for the flow behavior of naturally fractured formations with multi-scale fracture networks

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SUMMARY

This paper presents a semi-analytical model for the flow behavior of naturally fractured formations with multi-scale fracture networks. The model dynamically couples an analytical dual-porosity model with a numerical discrete fracture model. The small-scale fractures with the matrix are idealized as a dual-porosity continuum and an analytical flow solution is derived based on source functions in Laplace domain. The large-scale fractures are represented explicitly as the major fluid conduits and the flow is numerically modeled, also in Laplace domain. This approach allows us to include finer details of the fracture network characteristics while keeping the computational work manageable. For example, the large-scale fracture network may have complex geometry and varying conductivity, and the computations can be done at predetermined, discrete times, without any grids in the dual-porosity continuum. The validation of the semi-analytical model is demonstrated in comparison to the solution of ECLIPSE reservoir simulator. The simulation is fast, gridless and enables rapid model setup.

On the basis of the model, we provide detailed analysis of the flow behavior of a horizontal production well in fractured reservoir with multi-scale fracture networks. The study has shown that the system may exhibit six flow regimes: large-scale fracture network linear flow, bilinear flow, small-scale fracture network linear flow, pseudosteady-state flow, interporosity flow and pseudoradial flow. During the first four flow periods, the large-scale fracture network behaves as if it only drains in the small-scale fracture network; that is, the effect of the matrix is negligibly small. The characteristics of the bilinear flow and the small-scale fracture network linear flow are predominantly determined by the dimensionless large-scale fracture conductivity. And low dimensionless fracture conductivity will generate large pressure drops in the large-scale fractures surrounding the wellbore. With the increasing of the interporosity flow parameter, flow exchange between the matrix and the small-scale fracture network will be advanced and may mask the pseudosteady-state flow period. The duration of flow exchange increases and the dip caused by the interporosity flow gets deeper with the decreasing of the storability ratio. Finally, an appropriate choice of the pseudosteady or transient dual-porosity model to idealize the small-scale fracture networks with the matrix depends entirely on a better understanding of the geological evidence supporting either model.

1. Introduction

The flow behavior in naturally fractured formations has been extensively investigated due to their importance in safe storage facilities for captured CO_2, geothermal and petroleum resource recovery. Owing to the complex configure of geological heterogeneity and multi-scale length in porous media, fluid flow in these fractured rocks is mainly controlled by the characteristics of fractures that develop (length, location, hydraulic conductivity, etc.), and show complex interconnected situation (Sahimi, 1995; Berkowitz, 2002). Currently, there are three major kinds of approaches used for modeling fluid flow in naturally fractured formations: continuum models, discrete fracture network models and hybrid models.

The continuum models use the well-known spatial averaging approach based on the representative elementary volume (REV) method to conceptualize fracture networks and porous blocks as continuum occupying the entire domain. One classical type of continuum models is the double-porosity model introduced by Barenblatt et al. (1960). The dual-porosity model represents a fractured medium by two completely overlapping continua, porous

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Nomenclature

B	liquid formation volume factor, m^3/m^3
$\tilde{c}_{tf}$	total small-scale fracture bulk compressibility, Pa^{-1}
c_{tF}	total large-scale fracture compressibility, Pa^{-1}
$\tilde{c}_{tm}$	total matrix bulk compressibility, Pa^{-1}
C	wellbore-storage coefficient, m^3/Pa
C_D	dimensionless wellbore-storage coefficient
h	formation thickness, m
h_m	thickness of matrix slabs, m
$\tilde{k}_f$	small-scale fracture bulk permeability, m^2
k_F	large-scale fracture permeability, m^2
$\tilde{k}_m$	matrix bulk permeability, m^2
L_F	total length of large-scale fracture, m
L_i	matrix-block dimension in i-direction, m
N_s	number of large-scale fracture segments
N_w	number of fracture segments connected to wellbore
p_f	small-scale fracture pressure, Pa
p_F	large-scale fracture pressure, Pa
p_i	initial formation pressure, Pa
p_m	matrix pressure, Pa
p_w	wellbore pressure, Pa
q_F	flux per unit length entering the fracture, m^2/s
q_w	well production rate, m^3/s
r_w	wellbore radius, m
s	Laplace variable
s_c	skin factor for flow choking
t	time, s
t_D	dimensionless time
$T_{Di,j}$	dimensionless transmissibility between fracture segment i and j
$T^*_{Di,j}$	dimensionless transmissibility between fracture segment i and j after star-delta transformation
$T_{Dw,i}$	dimensionless transmissibility between fracture segment i and wellbore
w_F	large-scale fracture width, m
x	x-coordinate, m
x_i	x-coordinate of midpoint of fracture segment i, m
x_{Di}	dimensionless x-coordinate of midpoint of fracture segment i
y	y-coordinate, m
y_i	y-coordinate of midpoint of fracture segment i, m
y_{Di}	dimensionless y-coordinate of midpoint of fracture segment i
ΔL_{Fi}	length of large-scale fracture segment i, m
ΔL_{FDi}	dimensionless length of fracture segment i

Greek symbols

α_D	Parameter used in large-scale fracture network flow model
γ_{Di}	dimensionless transmissibility between fracture segment i and interface
ε	direction of large-scale fracture, m
ζ	reference length in the system, m
η_F	large-scale fracture diffusivity, m^2/s
η_{FD}	dimensionless large-scale fracture diffusivity
θ_i	angle of fracture segment i to the x-axis
λ	interporosity flow parameter
μ	fluid viscosity, Pa s
σ	matrix shape factor, m^{-2}
$\tilde{\phi}_f$	small-scale fracture bulk porosity, fraction
ϕ_F	large-scale fracture porosity, fraction
$\tilde{\phi}_m$	matrix bulk porosity, fraction
ω	storativity ration

Superscripts

–	Laplace transform
∼	bulk property

Subscripts

D	dimensionless
f	small-scale fracture
F	large-scale fracture
i	fracture segment index
m	matrix
w	wellbore

matrix, and fractures. Then, this model was developed by Warren and Root (1963) to represent the naturally fractured formation as an idealized system formed by matrix blocks, separated by uniform and orthogonal fractures. Accounting for mass transfer between the two continua, exchange functions are defined based on a pseudosteady-state interporosity flow concept (Warren and Root, 1963) or transient interporosity flow concept (Kazemi et al., 1969; de Swaan, 1976; Najurieta, 1980; Serra et al., 1983; Pruess, 1985; Noetinger et al., 2001). Furthermore, a more practical approach called triple-porosity model was developed by Wu et al. (2004) to consider the interaction between matrix, small-fracture, and large-fracture continua recently. Because of their conceptual simplicity and computational efficiency, the continuum models have been widely used for fluid flow through fracture formations in petroleum, geothermal engineering and groundwater hydrogeology. If the formation develops some large-scale fractures controlling the principle pathways for fluid flow, the flow behavior may be captured more rigorously by considering these fractures explicitly.

The discrete fracture network (DFN) model is, in principle, a more rigorous model. The approach simulates the fractures explicitly and often adopts fully numerical methods. In the model, the fractures are usually represented by refined grids with high permeability (Palagi and Aziz, 1994; Li et al., 2003; Cipolla et al., 2011) or lower dimension elements than that of the matrix (Noorishad and Mehran, 1982; Beca and Arnett, 1984; Granet et al., 2001; Juanes et al., 2002; Karimi-Fard et al., 2003). Furthermore, the hybrid models are proposed to incorporate naturally hierarchical, scale-dependent properties by combining the discrete fracture models and the continuum models. In these models, large fractures are often considered explicitly. Small and medium fractures are modeled through a network block (Clemo and Smith, 1997) or nonfractured zones with enhanced effective permeability (Lee et al., 2001; Li and Lee, 2008). By use of the detailed knowledge of fracture and matrix properties, the DFN and hybrid approaches can effectively deal with the anisotropy of the fractured rocks. However, due to the complexity of the discrete fracture models and associated limitations of numerical computation, these approaches may introduce the heaviness of model setup and the increased computational time for the case with a large number of cells and small time step to obtain sufficiently accurate results.

To develop petroleum and geothermal resource efficiently in fractured reservoirs, people often create induced fracture networks by the technology of hydraulic fracturing to reduce the flow resistance in the region near production well. These fractures often behave as large-scale fractures which dominantly control fluid