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Fracture network numerical well test model based on the discrete-fracture model

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Abstract

Based on the characteristics of fractures in naturally fractured reservoir and the discrete-fracture model, a fracture network numerical well test model was developed, which incorporated the fractures explicitly in the spatial domain. In two-dimensional problems, fractures were represented as one-dimensional line element and matrix space was discretized into linear triangular elements. Bottom hole pressure response curves and pressure field were obtained by solving the model equations with finite-element method. Through analyses of the bottom hole pressure curves and the fluid flow in pressure field, seven flow stages can be recognized on the curves, i.e. wellbore storage, transition, fracture linear flow, fracture network flow, matrix to fractures flow, system radial flow and boundary-dominated flow. Effects of reservoirs parameters, such as fracture conductivity, matrix permeability, fracture density and permeability anisotropy were studied. The analysis results demonstrated that fracture conductivity played a leading role in the fluid flow. Matrix permeability influenced the beginning time of flow from matrix to fractures. Fractures density was another important parameter controlling the flow. The fracture linear flow was covered under large fracture density. The pressure propagation was slower in the direction of larger fracture density. The same situation happened in the permeability anisotropy cases.

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*Keywords:*discrete-fracture model; fracture network; numerical well test; finite-element method; conductivity; fracture density; permeability anisotropy

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1. Introduction

Naturally Fractured Reservoirs hold a significant amount of the world's hydrocarbon reserves. This kind of reservoirs can be considered as two mediums, rock matrix and fractures. In 1963, Warren and Root[1] presented the homogeneous orthotropic dual medium model, which is currently the most widely used dual medium model. The assumptions that fracture and matrix system exist in the same point does not tally with the actual. The dual media theory is not suitable for describing the flow in poor developing fracture system. Noorishad and Mehran[2] and Bacal[3] used finite-element method to simulate single-phase flow in fractured reservoirs which incorporates the fractures explicitly in the spatial domain and provides a new way to describe fractured reservoir. In 2011, Moinfar[4] compared the accuracy between dual-permeability and discrete-fracture model. Other scholars study on the comparison and integration of the dual-media model and discrete-fracture model. In this paper, a numerical well test model for fracture network based on discrete-fracture method is developed.

Nomenclature

d_1,d_2	dimension of matrix block
w	fracture aperture
K_f	permeability of fractures
K_m	permeability of matrix
ϕ_f	porosity of fracture
ϕ_m	porosity of matrix
p_f	pore pressure of fracture
p_m	pore pressure of matrix
p_i	initial pressure of reservoirs
p_w	pressure of well bottom hole
μ	fluid viscosity
C_t	total compressibility
B	volume factor
C	wellbore storage
q	wellbore production rate

2. Physical model

The transient flow toward a well surrounded by fracture network was studied. The following assumptions were considered.

(1). Fracture network develops from x and y direction in a rectangle reservoirs. The fractures split the matrix as small rectangles of $d_1\times d_2$. The well bore is in an intersection of fractures.

(2). The fractures permeability isK_f and the aperture is w.

(3). The porous medium contains a slightly compressible fluid of viscosity, μ and compressibility C.

(4). There is no damage zone surrounding the well bore and the effects of gravity, temperature, and other physical and chemical effects are ignored.

The system above defined is shown in Fig.1.

3. Mathematical model and numerical method

3.1. Mathematical model

The governing equation of this problem are obtained by combining Darcy's law and mass conservation based on the discrete-fracture model description. For matrix, the transient equation of pressure can be written as

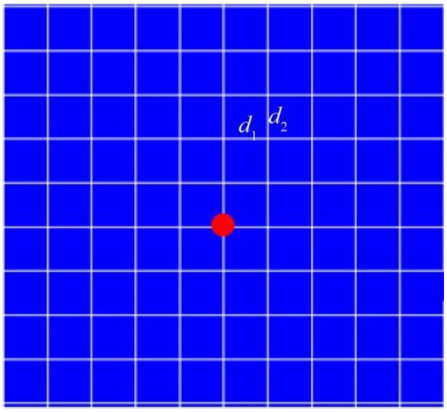


Fig.1 Sketch of fracture network model

$$\frac{K_m}{\mu}\frac{\partial^2 p_m}{\partial x^2}+\frac{K_m}{\mu}\frac{\partial^2 p_m}{\partial y^2}=\phi_m C_t\frac{\partial p_m}{\partial t} \tag{1}$$

For fractures, the transient equation of pressure based on the discrete-fracture model can be written as

$$\frac{K_f}{\mu}\frac{\partial^2 p_f}{\partial l^2}=\phi_f C_t\frac{\partial p_f}{\partial t} \tag{2}$$

Initial conditions for this problem are as follows:

$$p_m = p_i , p_f = p_i \tag{3}$$

The constant production rate boundary conditions around wellbore are as follows:

$$\sum_{j=1}^{N} L_j h\frac{K}{\mu}\frac{\partial p_j}{\partial n}\bigg|_{\Gamma_i}=Bq+C\frac{dp_w}{dt} \tag{4}$$

$$p_j = p_w \tag{5}$$

Constant pressure at reservoir outer boundary is given by:

$$p\big|_{\Gamma_o} = p_i \tag{6}$$

or no flow condition:

$$\frac{\partial p}{\partial n}\bigg|_{\Gamma_o}=0 \tag{7}$$

3.2. Numerical method

The Galerkin weighted residual method and finite-element discretization is used to solve equation (1) and (2).

The weak form of these equations can be written as

$$\iint_A\left(\frac{K_m}{\mu}\frac{\partial p_m^e}{\partial x}\frac{\partial\delta p_m^e}{\partial x}+\frac{K_m}{\mu}\frac{\partial p_m^e}{\partial y}\frac{\partial\delta p_m^e}{\partial y}+\phi_m C_t\frac{\partial p_m^e}{\partial t}\delta p_m^e\right)dA=\int_s\delta p_m^e\frac{K_m}{\mu}\frac{\partial p_m^e}{\partial n}ds \tag{8}$$

and

$$\int_l \left(\frac{K_f}{\mu} \frac{\partial p_f^e}{\partial l} \frac{\partial \delta p_f^e}{\partial l} + \phi_f C_t \frac{\partial p_f^e}{\partial t} \delta p_f^e \right) \delta p_f^e dl = \delta p_f^e \frac{K_f}{\mu} \frac{\partial p_f^e}{\partial l} \Bigg|_1^2 \tag{9}$$

The final finite element equations for matrix can be written as

$$\begin{aligned} & A\left(\frac{K_m}{\mu} b_i^2 + \frac{K_m}{\mu} c_i^2 + \frac{\phi_m C_t}{6\Delta t} \right) p_{mi}^{e,n+1} + A\left(\frac{K_m}{\mu} b_i b_j + \frac{K_m}{\mu} c_i c_j + \frac{\phi_m C_t}{12\Delta t} \right) p_{mj}^{e,n+1} + \\ & A\left(\frac{K_m}{\mu} b_i b_k + \frac{K_m}{\mu} c_i c_k + \frac{\phi_m C_t}{12\Delta t} \right) p_{mk}^{e,n+1} - \frac{L}{3} \frac{\partial p_{mi}^{e,n+1}}{\partial n} - \frac{L}{6} \frac{\partial p_{m(j,k)}^{e,n+1}}{\partial n} = \\ & \frac{\phi_m C_t}{6\Delta t} p_{mi}^{e,n} + \frac{\phi_m C_t}{12\Delta t} p_{mj}^{e,n} + \frac{\phi_m C_t}{12\Delta t} p_{mk}^{e,n} \end{aligned} \tag{10}$$

For fractures as

$$\left(\frac{K_f}{\mu} \frac{1}{L} + \frac{\phi_f C_t}{3\Delta t} \right) p_{fi}^{e,n+1} + \left(-\frac{K_f}{\mu} \frac{1}{L} + \frac{\phi_f C_t}{3\Delta t} \right) p_{fj}^{e,n+1} = \frac{\phi_f C_t}{3\Delta t} p_{fi}^{e,n} + \frac{\phi_f C_t}{6\Delta t} p_{fj}^{e,n} \tag{11}$$

4. Result and discussion

4.1. Bottom hole pressure response curve and pressure field

The bottom hole pressure response curve of fracture network model is presented in Fig.2.

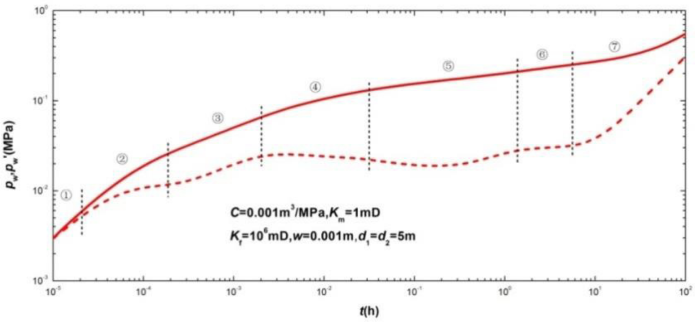
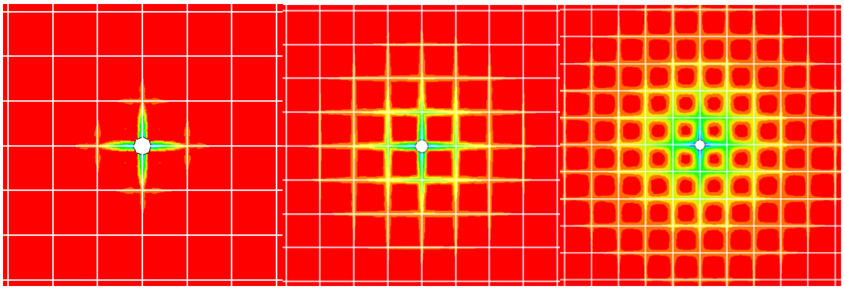


Fig.2 Bottom hole pressure response curve of fracture network model

As can be seen from Fig.2, the bottom hole pressure response curve can be divided into 7 stages. The first part is wellbore storage stage with a straight line of slope 1. The second is transition stage. The third stage is fracture (bi)linear flow stage(Fig.3-(a)). Because of high permeability of fractures, the flow occurs firstly in the fractures which are connected directly with wellbore. This stage is similar with the bilinear flow in the vertical fractured well[8, 12]. In this stage, the pressure and pressure derivate curve are parallel line. However, the line slope is not the same as that in the vertical fractured wells, which are 1/2 or 1/4 because there are 4 fractures connected with wellbore. The fourth is fracture network flow stage (Fig.3-(b)). When the pressure expands to the fractures perpendicular to the fractures which are connected directly with wellbore, formation presents fracture network flow. The fifth stage is transformation from matrix to fractures stage (Fig.3-(c)). With the decrease of fractures pressure, fluid flows from matrix to fractures under the pressure difference. In this condition the pressure derivate curve goes down and forms a concave because of the pressure supply of the matrix. Then, the sixth stage is the radial flow stage which reflects a horizontal pressure derivate. The last stage is boundary dominated flow stage with line of slope 1.



(a)fracture linear flow (b)fracture network flow (c)matrix transformation flow

Fig.3 Pressure field of fracture network model

4.2. Compare with dual porosity model

Fig.4 presents the result of porosity model and this paper. As can be seen, they can be matched well except the (bi)linear stage, as the fractures are not dealed explicitly in the dual porosity model.

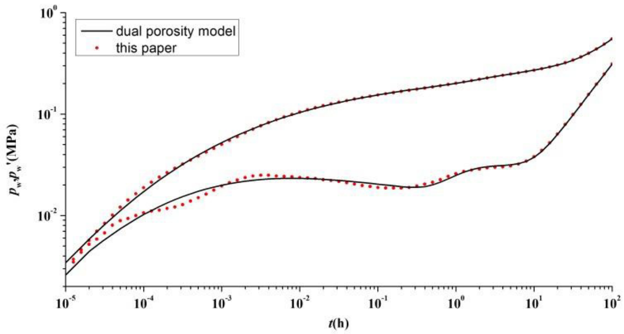


Fig.4 Compare between dual porosity model and this paper

5. Conclusion

(1) A fracture network numerical well test model was developed based on the discrete-fractured model. The model equations were solved by finite-element method and obtained the bottom hole pressure response curve which can be divided into 7 stages according to the curve type and pressure field.

(2) The result of the model agrees well with the dual porosity model expect the (bi)linear stage at early time

Acknowledgements

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