A Well Test Model Study of Multi Fracture-vug Combination for Fractured Vuggy Carbonate Reservoirs

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ABSTRACT

Fractured vuggy carbonate reservoirs usually develop several large-scale caves which are the main storage space of oil-gas. The volume and position of caves are important parameters for production guidance, but there are no effective well test methods of calculating the cave volume of multi-cave reservoirs yet. This paper establishes a multi fracture-vug composite model for fractured vuggy carbonate reservoirs, divides reservoirs into a couple of fracture-vug seepage zones according to the cave distribution, establishes a mathematical model through the coupling of seepage zones, and then obtains analytical solutions of the mathematical model using dimensionless and Laplace transformation. By plotting the standard log-log type curves, this paper analyzes the flow characteristics of the model. It is found that the pressure derivative of the inter-porosity flow segment from caves to fractures is presented as a V-shaped concave, the pressure and pressure derivative curves at the fracture flow segment take on the parallel lines with the slope of 0.5. A parameter sensitivity analysis indicates: the bigger the cave is, the steeper the V-shaped concave goes; the farther the distance between cave and wellbore is, the more hysteretic the V-shaped concave becomes. Finally, the triple fracture-vug model is applied to fit the buildup pressure data of well T40. We calculate that the volumes of cave 1 and cave 2 are 7489 m^3 and 56324 m^3, the cave distances are 25.1m and 189.2m respectively.

Keywords: Fractured vuggy reservoirs, Well test method, Transient pressure analysis

NOMENCLATURE

Symbols	
p_f	fracture pressure, MPa
p_v	cave pressure, MPa
p_w	wellbore pressure, MPa
p_i	initial pressure, MPa
ϕ_f	Fracture porosity, dimensionless
x	Position coordinates, m
K_f	Fracture permeability, D
t	Time, h
μ	oil viscosity, mPa·S
C_{ft}	Fracture compression factor, MPa^{-1}
C_{vt}	Cave compression factor, MPa^{-1}
q_o	total production of the well, m^3/d
B	oil formation volume factor, m^3/m^3
A_f	Fracture cross-sectional area, m^2
C	storage constant, MPa^{-1}
S	skin factor, dimensionless
Superscript	
j	The jth seepage zone
Subscript	
j	The jth cave
D	Dimensionless

1. INTRODUCTION

Carbonate reservoirs play an important role in global petroleum energy resources. According to IHS statistics, carbonate hydrocarbon resources account for about 70% of global oil-gas resources. Proved recoverable reserves account for about 50% of the global total, and production accounts for about 60% of the global total [1].

The fractured vuggy carbonate reservoir is one of the most important types of carbonate reservoir, widely distributed in North America, Middle East, Central Asia and other areas, which develop several large-scale caves and fractures. Caves are the primary storage space, and fractures are great seepage channels connecting caves. Identifying the volume and distance of caves is of great significance for production guidance in the later production period.

Since the 1960s, many scholars have proposed and developed the well test theory of multi-continuum

medium for carbonate reservoirs [2-4]. They think that reservoirs can be regarded as the superposition of several continuous medium systems in space and inter-porosity flow exists in these systems. However, the multi-medium model is based on the continuum assumption, which is not applicable to large-scale fracture-vug reservoirs and fails to explain the cave volume. From the beginning of the 20th century, some scholars take discrete fracture-vug distribution into account and establish well test models that successfully calculate the volume of the large cave [5-7]. Gao holds that the cave flow is Barree-Conway high-speed non-Darcy flow and establishes the numerical well test model for well drilling in a cave [5]. Lu adopts the wave equation to represent the flow in a large-scale cave with an analytical well test model built for well drilling in the cave [6]. And Lin Ran gives a well test analysis for the dual fracture-vug serial-parallel composite model [7]. However, most of the well testing models above focus on one or two caves, which are inapplicable to the multi fracture-vug reservoirs.

In this work, we divide such fractured vuggy carbonate reservoirs into multiple seepage zones and establish a mathematical model for analytical solutions through the coupling of seepage zones, which resolves the well test problem of multi fracture-vug reservoirs.

2. PHYSICAL MODEL AND ASSUMPTIONS

The physical model is shown in Fig 1. The fractured vuggy reservoir with a couple of caves can be Simplified to the physical model.
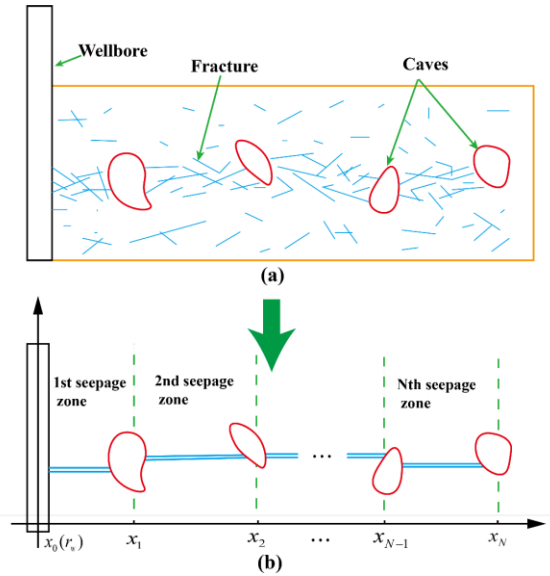

Fig 1 Schematic diagram of the physical model: (a) A fractured vuggy reservoir with a couple of caves. (b) Simplified well test physical model.

In the physical model, several large caves are distributed in the formation along a certain direction, connected in series by large-scale fractures, fracture 1 is in connection with the wellbore. The formation is divided into N fracture-vug seepage ones according to the cave distribution. Physical model assumptions are as follows:

(1)the caves are filled with single-phase oil; (2)The vertical production well is produced at a constant rate; (3)The large scale caves are regarded as equipotential body. (4)In the fracture of every seepage zone, the flow of fluid is isothermal Darcy flow; (5)total compressibility (rock and fluid) is low and a constant; (6)considering the impact of wellbore storage and skin factor, ignoring the impact of gravity and capillary forces; (7) At time t = 0, the pressure is uniformly distributed in a reservoir, equal to initial pressure.

3. MATHEMATICAL MODEL AND SOLUTION

3.1 Mathematical Model

the governing differential equations for the fracture of the jth zone:

$$\frac{\partial^2 p_f^j}{\partial x^2} = \frac{\phi_f^j \mu_f C_{ft}}{3.6 K_f^j} \cdot \frac{\partial p_f^j}{\partial t}$$

$$(x_{j-1} \leq x < x_j)\ (j = 1,2,3...N) \tag{1}$$

Inner boundary conditions:

$$-\frac{86.4 K_f^1}{\mu} \cdot A_1 \cdot \frac{\partial p_f^1}{\partial x}\bigg|_{x=x_0} = q_o B \tag{2}$$

External boundary conditions:

$$-\frac{86.4 K_N}{\mu_N} \cdot A_N \cdot \frac{\partial p_f^N}{\partial x}\bigg|_{x=x_N} = V_N C_{vt} \frac{dp_v^N}{dt} \tag{3}$$

Pressure continuity equation:

$$p_f^j\big|_{x=x_j} = p_f^{j+1}\big|_{x=x_j} = p_v^j \tag{4}$$

Flow continuity equation(Coupling condition):

$$\frac{86.4 K_f^j}{\mu} \cdot A_f^j \cdot \frac{\partial p_f^j}{\partial x}\bigg|_{x=x_j} = \frac{86.4 K_f^{j+1}}{\mu} \cdot A_f^j \cdot \frac{\partial p_f^j}{\partial x}\bigg|_{x=x_j}$$

$$+V_j C_{vt} \frac{dp_v^j}{dt}\ \ (j = 1,2,3,...N) \tag{5}$$

Initial condition:

$$p_f^j\big|_{t=0} = p_v^j\big|_{t=0} = p_i\ \ (j = 1,2,3....N) \tag{6}$$

3.2 Laplace transform of mathematical models

Define dimensionless quantities:

$$x_D = \frac{x}{r_w}, \quad \omega_{(f,v)} = \frac{\phi_{(f,v)} C_{(f,v)t}}{\phi_f C_{ft} + \phi_{vt} C_{vt}}, \quad A_D^j = \frac{A_j}{r_w^2}$$

$$p_{(w,f,v)D} = \frac{86.4 \times K_f^1 r_w}{q_o \mu B}(p_i - p_{(w,f,v)}), \quad V_D^j = \frac{V_j}{r_w^3}$$

$$t_D = \frac{3.6 K_f^1 t}{\mu(\phi_f^1 C_{ft} + \phi_v^1 C_{vt}) r_w^2}, \quad M_1^j = K_f^j / K_f^1.$$

The dimensionless model is omitted in this paper, and the Laplace transform of the dimensionless mathematics model as equation (7)-(11):

$$\frac{d^2 \overline{p_{fD}^j}}{dx_D^2} = \omega_f^j s d \overline{p_{fD}^j} \tag{7}$$

$$(x_D^{j-1} \le x_D < x_D^j)(j = 1,2,3...N)$$

$$\overline{p_{fD}^j}\Big|_{x_D = x_{jD}} = \overline{p_{fD}^{j+1}}\Big|_{x_D = x_{jD}} = \overline{p_{vD}^j} \quad (j = 1,2,3...N-1) \tag{8}$$

$$\frac{d\overline{p_{fD}^1}}{dx_D}\Big|_{x_D = x_{wD}} = -\frac{1}{A_{fD}^1 \cdot s} \tag{9}$$

$$\frac{d\overline{p_{fD}^N}}{dx_D}\Big|_{x_D = x_{ND}} = -\frac{\omega_v^N V_D^N}{A_D^N} s \overline{p_{vD}^N} \tag{10}$$

$$M_1^j \frac{d\overline{p_{fD}^j}}{dx_D}\Big|_{x_D = x_D^j} = M_1^{j+1} \frac{d\overline{p_{fD}^{j+1}}}{dx_D}\Big|_{x_D = x_D^j} +$$

$$\frac{\omega_v^j V_D^j}{A_D^j} s \overline{p_{vD}^j} \quad (j = 1,2,3...N-1) \tag{11}$$

The general solution of equation (7) is:

$$\overline{p_{fD}^j} = B_j e^{\sqrt{\omega_f^j \cdot s} \cdot x_D} + C_j e^{-\sqrt{\omega_f^j \cdot s} \cdot x_D} \tag{12}$$

$$(x_D^{j-1} \le x_D < x_D^j)(j = 1,2,3...N)$$

The B_j and C_j are undetermined constants, Substituting the general solution into the solution equation (8)(9)(10)(11), there are 2N unknown constants and 2N equations, they can be solved by the simultaneous solution. When $x_D^j = x_D^0$, The wellbore pressure can be expressed as:

$$\overline{p_{sD}} = B_1 e^{\sqrt{\omega_f^1 \cdot s} \cdot x_{wD}} + C_1 e^{-\sqrt{\omega_f^1 \cdot s} \cdot x_{wD}} \tag{13}$$

When considering the effects of wellbore storage and skin factor, we can use the following equation derived from Duhamel theory to calculate:

$$\overline{p_{wD}} = \frac{s\overline{p_{sD}} + S}{s + C_D s^2 (s\overline{p_{sD}} + S)} \tag{14}$$

4. TYPICAL WELL TEST CURVES

Taking the triple fracture-vug model as an example, we can get the log-log well test type curves of wellbore pressure and derivative using the Stehfest numerical inversion method, which is shown in Fig 2. There are 8 flowing stages:
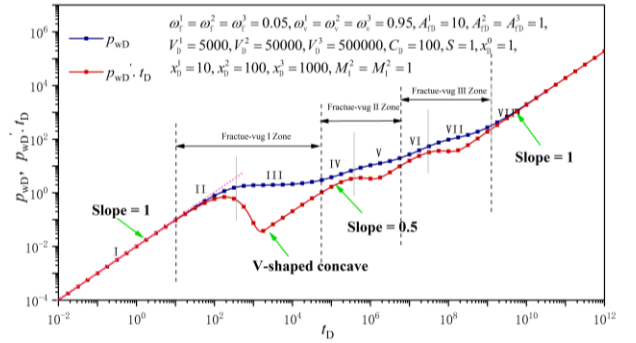

Fig 2 The type curves of the triple fracture-vug model

Stage I: Wellbore storage effect stage, the pressure and derivative curves are straight lines with slope of 1;

Stage II: Fracture linear flowing stage, the pressure and derivative curves are parallel lines with slope of 0.5. This stage usually cannot be observed easily due to the skin effect;

Stage III: Inter-porosity flow stage of the cave in Fractue-vug I Zone, the first cave starts to feed fluid toward fracture I, causing the rapid decrease of derivative curves and the formation of V-shaped concave;

Stage IV: Fracture linear flowing stage in Fracture-vug II Zone where the pressure and derivative curves are parallel lines with the slope of 0.5;

Stage V: Inter-porosity flow stage of the cave in Fracture-vug II Zone and the curve shape is the same as that of Stage III;

Stage VI and Stage VII: Fracture linear flowing stage and the inter-porosity flow stage of the large cave in Fracture-vug III Zone and the curve shape is the same as that of Stage IV and Stage III.

Stage VIII: Pseudo-steady flowing stage of the overall system where the pressure and pressure derivative curves coincide with each other as a straight line with the slope of 1.

5. PARAMETER SENSITIVITY ANALYSIS

We take the dual fracture-vug composite model as the example to analyze the influence of cave volume and distance on the typical curves.

As Fig 3 shows, the volume of Cave 1 increases, the first concave of the pressure derivative curve goes deeper, the inter-porosity flow of Cave 1 increases. the distance between Cave 1 and wellbore increases, the first concave moves right which indicates the response lag of inter-porosity flow of Cave 1. This conclusion applies to the volume and distance of any cave in the multi fracture-vug models.
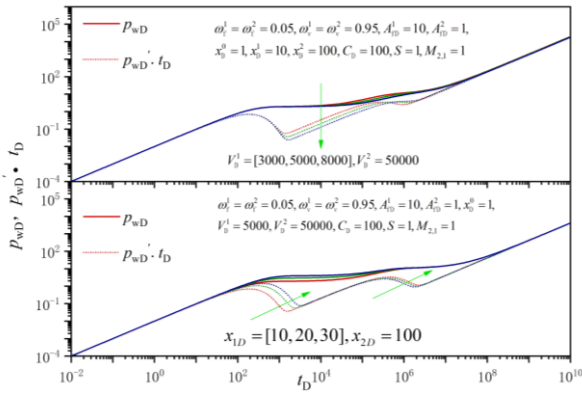
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Fig 3 Effect of the volume and distance of caves

6. FIELD APPLICATION EXAMPLE

Well T40 is a production well of Tahe Oilfield in China. It is drilled in the Ordovician carbonate reservoir with a depth of 7257m. According to well logging and seismic data, the fracture- vug system near the wellbore is well developed, and the far-wellbore may have reservoirs of a certain scale, the total volume of the large caves is between 50,000 and 70,000 m^3. Table 1 lists the reservoir properties of well T40.

Table 1 Reservoir properties of well T40

Parameters	Values	Units
Wellbore radius	0.0914	m
Porosity	0.05	fraction
Oil viscosity	2.1	mPa·S
Oil formation volume factor	1.09	fraction
Compressibility of rocks	0.001	MPa^{-1}

We adopt the triple fracture-vug model to fit the buildup pressure data, and the curve fitting map is shown in Fig 4.
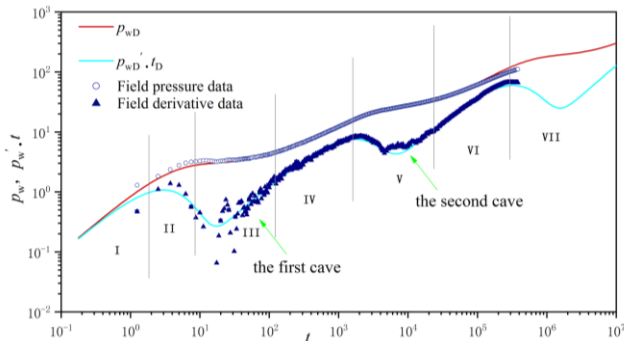

Fig 4 Type curve matching of the T40 well

We calculate that the respective volumes of cave 1 and cave 2 are 7489 m^3 and 56324 m^3, the respective cave distances are 25.1m and 189.2m, which is consistent with the geological data.

7. CONCLUSIONS

(1) A new well test model for fractured vuggy carbonate reservoirs is established. We divide such reservoirs into a couple of fracture-vug seepage zones.

(2) the equations coupling between each seepage zones are presented and the solution of those equations are obtained. the pressure and derivative log-log type curves are plotted to analyze flow characteristics in such reservoirs. The inter-porosity flow segment from caves to fractures is presented as a V-shaped concave, the pressure and derivative curves at the fracture flow segment take on the parallel lines with the slope of 0.5. the bigger the cave is, the steeper the V-shaped concave goes; the farther the distance of the cave is, the more hysteretic the V-shaped concave becomes.

(3) The triple fracture-vug model is applied to fit buildup the data of well T40. We calculate that the respective volumes of cave 1 and cave 2 are 7489 m^3 and 56324 m^3, the cave distances are 25.1m and 189.2m.

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