The Effect of Vug Density on Fluid Flow

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Abstract—Fractured vuggy reservoirs have long been observed. A thorough understanding of the variability and fluid flow in fractured vuggy carbonates is lacking. Classical theories of fluid flow are not applicable for highly heterogeneous carbonates. Therefore, it is necessary to conduct research on this type of carbonate which is found in many petroleum reservoirs. Single-phase flow in fractured vuggy media is studied by finite element method. The purpose of this study is to obtain phenomenological data (streamlines, velocity and pressure) during flow in a fractured vuggy media to better understand the effect of vug density on flow. Numerical simulation on fractured vuggy model with different vug density are suggested that gravitational impact on flow is more significant in vugs; in identical horizontal plane, velocity in vug is less than velocity in fracture; pressure drop between the both sides of model with bigger vug density is less.

Keywords- vug density; fluid flow; streamline

I. INTRODUCTION

Carbonate rocks often exhibit a wide range of pore sizes because they commonly contain vugs on a scale of one centimeter or larger. The pore level heterogeneity governs to a large extent the flow and transport properties through carbonates. However, modeling the flow and transport through such a system is difficult because of its high level of heterogeneity. Understanding the physics of flow in vuggy carbonates is particularly a challenging problem.

Carbonate rocks commonly exhibit more complex features than sandstone formations because the formation of a carbonate often undergoes two geological processes. The initial process of carbonate sedimentation produces particles with a wide range of sizes and shapes after years of deposition in the ocean environment, where organisms are very active. The post-depositional diagenesis process changes the depositional texture and possibly produces more complicated pore size distribution than the initial carbonate sediments. However, the high level of heterogeneity displayed in the Cretaceous carbonate studied in this research was generated during the sedimentation process. The large vugs (centimeter scale) in the carbonate are the remains of macro organism (such as rudist) that dominated the Cretaceous era. Consequently, the heterogeneities displayed in the vuggy carbonate rocks are often at a centimeter scale or larger.

The study of flow and transport properties of a vuggy system is important for both research and engineering applications for the following reasons. First, studying vuggy porous media will enrich the research on core analysis and modeling because the standard sampling method is on a scale too small to capture the large-scale heterogeneities of the vuggy porous media. The study is also beneficial to modeling because there is no obvious mathematical formalism to accurately model flow through this highly heterogeneous system. Second, developing a better flow model of these multiscale heterogeneities is of both economic and environmental interest for a variety of applications. Fluid flow in carbonates is environmentally important in the movement of groundwater, and economically important in the recovery of hydrocarbons.

II. PREVIOUS RESEARCH

A. Previous flow modeling

Some research on modeling of a 2-Dimensional flow through the vuggy carbonate sample of this research has been previously done. Arbogast applied Darcy- Stokes equations to the vuggy system, in which the matrix was modeled by Darcy’s law and the vug was modeled by Stoke’s law. Arbogast derived a macro-model, which effectively includes the important information of the Darcy-Stokes micro-model. The effective permeability of the entire system can be calculated using the macro-model. Computation studies were performed on this macro-model [1].

It was found from the computational results that the effective permeability depends significantly on the connectivity of the vugs. The effective permeability was found to be in the same order as that of the matrix when the vugs are disconnected. However, it was found to be much larger than the matrix permeability when vugs are connected, and it increases with the vug’s permeability. In addition, the upscaling from fine grids to coarse grids was found to be complicated because the connectivity of vugs is complicated and an inappropriate upscaling technique may not preserve the topology of vug connections. In this paper, vugs in fractured vuggy model are connected.

B. General carbonate core samples studies

Core analysis is necessary for reservoir characterization. Vuggy carbonate core samples were studied by Hidajat [2]. Their samples were less than 3.8cm in diameter and were from a West Texas field. The vugs present in their samples were less than 5 mm across. The vuggy core samples were characterized using routine core analysis methods of mercury capillary pressure, thin section, formation factor, and NMR (nuclear magnetic resonance) T2 measurements. They found that the largest permeability and porosity of the six core samples were 2 Darcy and 21.8% respectively.
Egermann [3] reported a study on vuggy dolomite cores. They found that 1-mm vugs in their samples were disconnected and were embedded in a tight matrix having an average pore-throat radius of 2 microns. A simulation using a pore-network model assuming a homogeneous medium gave reasonable information about water-gas relative permeabilities. It was observed that the imbibition of water in the matrix was slow due to its small permeability.

A relative permeability and wettability study was reported for a Lower Cretaceous carbonate by Okasha [4]. Samples of 1.5 in. (3.8 cm) in diameters were studied. They observed from their samples that the wettability of the Lower Cretaceous carbonate had a wide range, which indicated that the carbonates were heterogeneous. The relative permeability results in their study showed that a significant amount of oil was recovered after water breakthrough.

Waterflooding through a vuggy carbonate core sample at full reservoir conditions was conducted by Dabbouk [5]. Their sample was from a high permeability layer with the presence of rudist shells and debris in a giant Middle East reservoir located offshore in the Arabian Gulf. Rudist shells and debris distributed with a variable density along this layer. The sample had small vugs and macro-pores from dissolution with a porosity of about 27% and a permeability of about 19 md. Small vugs in this sample were scattered inside the rudist fragments of about 1 cm large.

The recovery mechanisms were studied for a vuggy carbonate core by Dehghani and Kamath [6]. Their sample was 10 cm in diameter with a permeability of 1000 md. They showed that the dispersivity of their core sample was greater than 15 cm, the length of the sample, and the tracer breakthrough occurred at 0.2 PVI (pore volume injected). Their experimental results showed that the oil recovery was greatly enhanced during a steamflood/blowdown process. The mechanism involved was that the low permeability regions were heated by the vuggy and high permeability regions during high temperature steamflooding, which allowed displacing more oil from the low permeability regions.

In this paper, the model fractured-vuggy medium used in the experiments is a model of the fracture-and-vug type. The model parameters (fracture aperture, vug diameter and vug density) can be adjusted to the desired values. The length of model is 10 cm with fracture aperture of 200μm, vug diameter of 2 cm. The vug densities of fractured-vuggy models are 10/m, 20/m and 30/m, respectively.

III. MATHEMATICAL MODEL

Fractures can be either fluid-flow conduits or fluid-flow barriers. When a fracture is formed, the void space within the fracture serves as a fluid-flow conduit. After the void space is filled with minerals, the fracture becomes a barrier to the fluid flow. In this study, we assumed that there isn’t any mineral in fractures and vugs. Fluid flow in fractured vuggy media is characterized by the Navier-Stokes Equations.

With the Navier-Stokes equation, the vector $\vec{u}$ covers velocities $u$, $v$, and $w$ in the x-, y- and z-direction. The nonlinear system described in equation (1) consists of three coupled equations in 2D and four in 3D. The application mode consists of a momentum balance plus a continuity expression,

$$-\nabla \cdot \eta \left[ \nabla \vec{u} + \left( \nabla \vec{u} \right)^T \right] + \rho u \cdot \nabla \vec{u} + \nabla p = \vec{F}$$

$$\nabla \cdot \vec{u} = 0$$

The dependent variables in this equation are the velocities, $\vec{u}$, and the fluid pressure, $p$. The density, $\rho$, and the viscosity, $\eta$, are the fluid properties. $\vec{F}$ is a vector of directional forces.

In this study, $\vec{F}$ is the vertical force of the fluid weight, $\rho \cdot g$, to model gravitational impacts on flow.

The equation

$$\vec{u} \bigg|_{x=0} = \vec{u}_0$$

specifies the velocity vector at the boundaries, while the equation

$$p \bigg|_{x=L} = 0$$

$L$ in equation (3) denotes the length of model.

IV. RESULTS AND DISCUSSION

The numerical simulation was performed at ambient conditions (25°C). The fluid system used in the experiments is water. The fluid was very carefully chosen and prepared. Fluid density is 998 kg/cm3. The viscosity of water is 0.96 mPa.s.

The model is first saturated with water. Then water is injected at a different rate. The fluid pressure at the outlet corresponds to atmospheric pressure. The pressure drop between the inlet and outlet is recorded.

One common approach that has been taken in all previous models is the finite-element method (FEM). The FEM gained immediate popularity because of its systematic formulation, ability to handle irregularly shaped boundaries [7,8]. Equation (1) was solved by finite element method. Figure 1 shows the flow chart of numerical simulation.

Figure 2 shows a comparison between the different models. The direction of fluid flow change when fluid flows from fracture into vug. The density of streamlines is bigger in the direction of fracture, was analyzed.

In order to study the effect of vug density on flow, the data of velocity and pressure in symmetrical axis, which is parallel to the direction of fracture, was analyzed.

Figure 3, 4 and 5 show that (1) velocity in vug decreases with the position when fluid flow in the first half part of vug, and increase with the position when fluid flow in the second half of vug; (2) velocity in fracture maintains constant.
For the fractured vuggy system, Reynolds number follows the equation

$$Re = \frac{\delta \mu \rho}{\eta}$$  \hspace{1cm}(4)$$

$\delta$ is the fractured vuggy media properties, which depends on hydraulic diameter $D_h$. Hydraulic diameter of fracture is

$$D_{hfracture} = \frac{wb}{2(w+b)}$$  \hspace{1cm}(5)$$

In equation (5), $b$ is aperture of fracture, and $w$ denotes the width of fracture ($w \gg b$). Then, hydraulic diameter of fracture can be simplified

$$D_{hfracture} = \frac{b}{2}$$  \hspace{1cm}(6)$$

Hydraulic diameter of vug is.

$$D_{hvug} = \frac{\pi(D_x/2)^2}{\pi D_x} = \frac{D_x}{4}$$  \hspace{1cm}(7)$$

In equation (7), $D_x$ is the diameter of section which is vertical with flow direction.

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During the numerical simulation, Reynolds number is a constant. Hydraulic diameter of vug, $D_{hvug}$ is bigger than hydraulic diameter of fracture, $D_{hfracture}$. From equation (4) we can see that the velocity will decrease when fluid flows into vug.

Figure 7 illustrates the relationship between pressure and position. From this figure we can see that (1) in identical horizontal plane, pressure in vug maintains invariant, the value of pressure decreases with vug density increasing; (2) fluid flow in fractured vuggy model with bigger vug denisty need less pressure drop. For example, as vug density=10/m, $\Delta p=2.27$Pa, while as vug density=30/m, $\Delta p=1.18$Pa.

V. CONCLUSIONS

The following conclusions have been drawn on the basis of the analysis presented in this paper.

(1) Gravitational impact on flow is more significant in big vugs.

(2) In identical horizontal plane, velocity in vug is less than velocity in fracture; velocity in the middle of vug decreases with vug density increasing.

(3) The existence of vug is advantageous in fluid flow. Pressure drop between the both sides of model with bigger vug density is less.

REFERENCES


Figure 1. Flow chart of numerical simulation

Input Data:
Sample Volume: Center, Dimension and Orientation
Fluid System: Density, Viscosity

Generate Fractured-Vuggy Model

Exert Boundary Conditions

Generate Mesh

Calculation

Output Data: Velocity, Pressure

End
Vug density=10/m

Vug density=20/m

Vug density=30/m

Figure 2 Streamlines in fractured-vuggy models

Figure 3 Velocity in fractured vuggy model with vug density=10/m

Figure 4 Velocity in fractured vuggy model with vug density=20/m

Figure 5 Velocity in fractured vuggy model with vug density=30/m

Figure 6 Pressure in fractured vuggy models