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RESEARCH PAPER

Production prediction for fracture-vug carbonate reservoirs using electric imaging logging data

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Abstract: Considering the fluid flow non-darcy characteristics in fracture-vug carbonate reservoirs, a new multi-scale conduit flow model production prediction method for fracture-vug carbonate reservoirs was presented using image segmentation technique of electric imaging logging data. Firstly, based on Hagen-Poiseuille's law of incompressible fluid flow and the different cross-sectional areas in single fractures and vugs in carbonate reservoirs, a multi-scale conduit flow model for fracture-vug carbonate reservoir was established, and a multi-scale conduit radial fluid flow equation was deduced. Then, conduit flow production index was introduced. The conduit flow production index was calculated using fracture-vug area extracted from the result of electrical image segmentation. Finally, production prediction of fracture-vug carbonate reservoir was realized by using electric imaging logging data. The method has been applied to Ordovician fracture-vug carbonate reservoirs in the Tabei area, and the predicted results are in good agreement with the oil testing data.

Key words: Tarim Basin; Ordovician; carbonate; fracture-vug carbonate reservoir; electric imaging logging; conduit flow model; production index; production prediction

Introduction

The Ordovician fracture-vuggy carbonate reservoirs in the Tarim Basin contain almost no primary pores; fractures and vugs are the main fluid flow channels and storage and seepage space[1–3]. For fracture-vuggy carbonate reservoirs, fluid flow is mainly influenced by pore structure and pore size. The production prediction model based on Darcy flow does not apply to the fracture-vuggy carbonate reservoirs[4].

Production prediction researches based on logging data fall into two categories. The one based on Darcy flow theory, in which the corresponding stratigraphic model is built, the corresponding production prediction formula deduced, and then the production predicted by using parameters calculated from the logging data[5–8]. Because the storage and seepage space of fracture-vuggy carbonate reservoir is made up of fractures and vugs, and the fluid flow in fractures and vugs is non-Darcy flow, this method based on the Darcy flow theory does not apply to fracture-vuggy carbonate reservoirs. The other category calculates the reservoir characteristic parameters with logging data, and then is coupled with the well test result to establish empirical relationships to predict the production via artificial intelligence, pattern recognition or other methods[9–15]. This kind of method relies heavily on regional experience, and without a priori theory, it requires a large amount of data to build model.

Electric imaging logging is a logging method that measures the conductivity of the formation near the borehole. Due to the different electrical conductivities of different geologic bodies, electric imaging logging data can reflect the geological phenomena such as fractures, vugs and bedding in the formation near the borehole wall in images. In fracture-vuggy carbonate reservoirs, image segmentation technique[16–17] can be used to extract fracture-vug parameters from electric imaging logging data to characterize the effectiveness of fracture-vuggy carbonate reservoir. So far, there is no report about wellbore production prediction using the fracture-vug parameters extracted from electric imaging logging data in light of fracture-vuggy carbonate reservoir fluid flow characteristics.

Since the fluid flow in fractures and vugs of fracture-vuggy carbonate reservoir is conduit flow, a multi-scale conduit radial fluid flow formula in fracture-vuggy carbonate reservoirs has been deduced based on the Hagen-Poiseuille law. Then, conduit flow production index was introduced and calculated with fracture-vuggy area extracted from the electrical image segmentation. And a new multi-scale conduit flow production prediction method for fracture-vuggy carbonate reservoirs has been worked out, and applied to the northern Tarim Basin

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fracture-vuggy carbonate reservoirs. The application results verify the reliability of the method.

1. Formula for multi-scale conduit radial fluid flow in fracture-vuggy carbonate reservoirs

1.1. Fluid flow in fracture-vuggy carbonate reservoirs

The main storage and seepage space of Ordovician fracture-vuggy carbonate reservoirs is composed of fractures and vugs. The section of wellbore and fracture-vuggy carbonate reservoir formation around wellbore after drilling is shown in Fig. 1a. Fluid flow in fractures and large-scale vugs follows the Navier-Stokes equation of viscous incompressible fluid[18–19]. In the wellbore, in wider fractures (e.g., a fracture over 2 mm wide), the fluid flow can be approximately equivalent to a constant laminar flow in finitely long and infinite extension flat polar plates. The constant laminar flow in finitely long and infinite extension flat polar plates is approximate to irregular shaped Hagen-Poiseuille flow[20–21]. Vugs in fracture-vuggy carbonate reservoirs usually take a long time to form by dissolution of fresh water and thus have long dissolution paths. The dissolution path of a vug is much larger than the diameter of the vug (a pore with a diameter of less than 2 mm and a vug with a diameter greater than 2 mm), so the flow of fluid in the vugs can be approximately equivalent to the conduit flow. In oil production, the flow velocity of the fluid in vugs is not high, and the fluid flow is approximate to laminar flow. The Hagen-Poiseuille flow is the solution to the Navier-Stokes equation of viscous incompressible fluid of thin conduit laminar flow problem[22]. Put together, the fluid flow into wellbores through vugs of different sizes and finite long fractures is uniformly equivalent to the flow of the fluid in thin conduits with different cross-sectional areas.

The flow equation for the Hagen-Poiseuille law that describes the incompressible Newtonian fluid flow in one thin conduit is

$$Q=\frac{\pi\Delta pR^4}{8\eta\Delta L}=\frac{\Delta pA^2}{8\pi\eta\Delta L} \tag{1}$$

Equation (1) shows that the flow of incompressible Newtonian fluid through the thin conduit is proportional to the pressure gradient of the thin conduit, and proportional to the square of the cross-sectional area of the thin conduit as well. The differential form of equation (1) is

$$Q=\frac{A^2}{8\pi\eta}\frac{\mathrm{d}p}{\mathrm{d}L} \tag{2}$$

1.2. Multi-scale conduit radial fluid flow formula

The fluid flow in dissolution fractures and vugs is simplified as conduit flow, which is different greatly from the fluid flow in granular sandstones. In the following derivation, it is assumed that the Hagen-Poiseuille law can be used to describe the fluid flow in individual fractures and vugs of fracture-vuggy carbonate reservoir. By equivalizing the fractures and vugs into multiple conduits with different cross-sectional areas, a multi-scale conduit flow model for fracture-vuggy carbonate reservoirs is established.

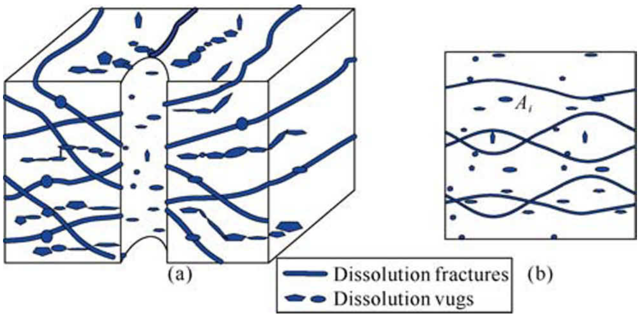

Fig. 1. Fracture-vuggy carbonate reservoir model (a) and cross-sectional distribution of fractures and vugs in borehole wall (b).

A_i is the cross-sectional area of the ith equivalent thin conduit at the borehole wall (Fig. 1b), and $\frac{\mathrm{d}p_i}{\mathrm{d}L_i}$ is the effective capillary pressure gradient of the ith equivalent thin conduit. For multi-scale conduit flow model of fracture-vuggy carbonate reservoir, the differential form of the fluid flow formula is

$$Q=\sum_i\frac{A_i^2}{8\pi\eta}\frac{\mathrm{d}p_i}{\mathrm{d}L_i} \tag{3}$$

It is assumed that the flow of formation fluid from the depth of formation to the wellbore is radial fluid flow, the pressure difference only exists in the radial direction of the wellbore, and there is no series flow at different depths (Fig. 2). The radial flow in the wellbore is symmetrical about the borehole center. In the cylindrical coordinate system, the flow of fluid in the wellbore can be expressed as

$$Q=\sum_i\frac{A_i^2}{8\pi\eta}\frac{\mathrm{d}p_i}{\mathrm{d}r_i}=\frac{\sum_i A_i^2}{8\pi\eta}\frac{\mathrm{d}p}{\mathrm{d}r} \tag{4}$$

Thus equation (4) is rewritten as

$$Q\mathrm{d}r=\frac{\sum_i A_i^2}{8\pi\eta}\mathrm{d}p \tag{5}$$

Computing the integral along supply radius, we have

$$\int_{r_\mathrm{w}}^{r_\mathrm{e}}Q\mathrm{d}r=\frac{\sum_i A_i^2}{8\pi\eta}\int_{p_\mathrm{w}}^{p_\mathrm{e}}\mathrm{d}p \tag{6}$$

Multi-scale conduit radial fluid flow formula in fracture-

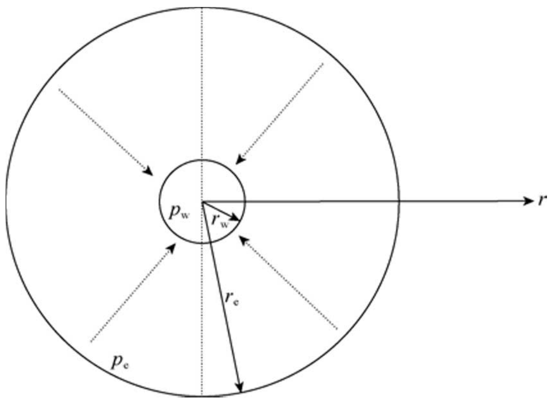

Fig. 2. The radial fluid flow model of bore hole.