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Seepage features of high-velocity non-Darcy flow in highly productive reservoirs

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ABSTRACT

Reservoir seepage characteristics are complex under high production rate conditions, especially in the near-wellbore region. The motion pattern of seepage changes due to its high flow velocity, leading to a nonlinear relationship between the pressure gradient and the kinematic velocity, as well as leading to the high-velocity non-Darcy flow characteristics of the fluid flow. Aimed at determining the non-Darcy flow-generating mechanism and the seepage law for reservoirs with high and extra high production rates, we performed steady 'pressure gradient-flow rate' core displacement experiments by displacing the typical cores with simulated oil and with the formed water. By analyzing the displacement experiments, we determined the basic rule and influencing factors of high and extra high production reservoirs. With the application of the dimensionless analysis method to analyze the experimental data, we investigated the value and variation range of the Reynolds number that determines whether a non-Darcy flow will occur. By introducing the Forchheimer equation, we established the calculation method of the non-Darcy coefficient and achieved an accurate characterization of the seepage law of high and extra high production reservoirs. Finally, by applying this method to the data from typical high production wells in West Africa, we found that the calculation results of the new model were in accordance with the measured values, which indicates that the new method and model presented in this study can be used for actual well test analysis and deliverability evaluation of high and extra high production reservoirs.

1. Introduction

Currently, with the continued development of oil and gas exploration and new technologies, the production of oil and gas from deep-water reservoirs is increasing, and its proportion is continuing to grow. Deep-water oil and gas fields have the characteristics of abundant oil and gas resources and large reserves with high production rates. However, compared with other offshore and onshore reservoirs, higher technical requirements, financial risks and operational difficulty are involved in the development of deep-water reservoirs. Considering the space and working life of the platform, to recover the investment as soon as possible, the production rate of most wells in deep-water reservoirs must remain very high. Under this high production condition, reservoir seepage characteristics are complex, especially near the wellbore.

There is abundant evidence that a high-velocity non-Darcy flow occurs in many subsurface systems, such as the flow near wellbores of gas or oil production and gas waste (CO_2 sequestration) injection wells. The effects of non-Darcy or high-velocity flow regimes in porous media have been observed and investigated for decades (e.g., Tek et al., 1962; Scheidegger, 1972; Katz and Lee, 1990; Wu, 2002; Wu et al., 2011; Zhang et al., 2014). The motion pattern of seepage changes due to its high flow velocity, which also leads to a deviation from linearity between the pressure gradient and kinematic velocity. The fluid flow shows high-velocity non-Darcy flow characteristics. The fluid flow behavior of high production reservoirs and extra high production reservoirs cannot be accurately described with traditional models, which has led to the slow growth of relevant development theory and technology, such as reservoir engineering and deliverability evaluation. It is necessary to understand the flow behavior distribution and deliverability evaluation for the complicated seepage patterns of high production and extra high production reservoirs.

The core displacement experiment is the most traditional method to study the complex phenomena of seepage. An experimental study on high-velocity non-Darcy flows mainly concentrates on sand-packed models or artificial core drives. Moreover, the realization of a stable and large pump capacity required to

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generate a non-Darcy flow is a key problem of non-Darcy flow experiments. An experimental simulation of seepage under high velocity conditions has been performed, and the high-velocity seepage of water in artificial sandstone has been studied (Belhaj et al., 2002). In addition, the inertial flow in porous media has been investigated, and it has been proposed that both the Forchheimer equation and the Izbash equation offer good descriptions of the experimental process of larger velocity ranges (Moutsopoulos et al., 2009). One-dimensional homogeneous earth column experiments have been conducted on quartz sand of two different particle sizes, and the experimental data were fit using the Forchheimer equation (Li and Engler, 2001; Barree and Conway, 2004; Zeng and Reid, 2006). Furthermore, researchers have also studied the flow of fluid in porous media through sand-packed model experiments. The sand-filling test method has been used to evaluate the fluid flow properties in porous media (Yamada et al., 1979). The properties of coarse gravel were initially studied, and then tiny particles were gradually added to change the properties of the porous medium. Aljalahmah (2014) experimentally investigated the effect of a non-Darcy flow through fracturing sand and irregular-shaped materials.

According to the experiments in the literature, there are several concerns that must be addressed. A single fluid may not be able to capture the effect of the fluid properties under a non-Darcy flow. Under the condition of a high velocity flow, the pore structure of porous media is easily changed due to its poor compaction, which may cause uncertainties in experiments. The cementation of artificial sandstone with higher permeability is loose, which could lead to particle migration during displacement and affect the experimental results.

Regarding the studies on high-velocity non-Darcy flow, the nonlinear flow was thought to be the result of the increase of the drag force (Firoozabadi, Katz et al., 1979) on the pore wall or the increase of the viscous force (Hassanizadeh and Gray, 1987) when the velocity is high. The flow cross section was constantly changing, and the additional pressure drop was caused by streamline bending. The contraction and expansion of the pore and throat induced the acceleration and deceleration of the fluid, causing an additional pressure drop (Kalaydjian et al., 1996).

The deviation from Darcy's law under high velocity flow is due to the microscopic inertial effects (Scheidegger, 1960; Bear, 1988; Barak, 1987; Ma et al., 1993). Barak thought that with the increase of the flow velocity, a local vortex of fluid and a bending of the streamline would be generated. He attributed the nonlinearity to a microscopic inertial force. Ruth and Ma believed that the Forchheimer number could be used to describe a non-Darcy flow. The parameter of permeability should be one of the key factors in determining the non-Darcy coefficient. They concluded that the non-Darcy effect occurs because microscopic inertial effects alter the velocity and pressure fields.

Due to the importance of the non-Darcy effect, we need to determine whether and when non-Darcy flow occurs in reservoirs. This requires determination of the critical transition point from a Darcy flow to a non-Darcy flow. There are two primary types of criteria to estimate the non-Darcy effect in porous media: the Reynolds number and the Forchheimer number (Blick and Civan, 1988; Du Plessis and Masliyah, 1988; Andrade et al., 1999). Velocity distribution in porous media has been studied experimentally (Dybbs and Edwards, 1982). High-velocity nonlinear flow was thought to be similar to turbulent flow in pipelines (Chilton, 1931). The Reynolds number for identifying turbulent flow in a pipeline was employed to describe a non-Darcy flow in porous media. A high-velocity nonlinear flow has also been proven to occur when the Reynolds number is greater than 0.1 (Skjetne, 2001). The Forchheimer number was proposed for use as the critical parameter to estimate the transition from Darcy to non-Darcy flow (Ruth et al., 1992).

However, the current research on high-velocity non-Darcy flows is inferior to systematic studies that comprehensively consider the pore structural features, fluid properties and pressure gradient due to the inconsistencies of the research objectives and the different definitions of the characteristic length. Therefore, these studies cannot be easily applied to general conditions in high production reservoirs.

In this study, which is based on the non-Darcy flow-generating mechanism in high production reservoirs and extra high production reservoirs, we performed steady ‘pressure gradient-flow rate’ core displacement experiments by displacing the typical cores with simulated oil and with the formed water. We analyzed the experimental data using a dimensionless analysis method and determined the seepage characteristics of a non-Darcy flow along with its influencing factors. Through the introduction of a non-Darcy coefficient, we were able to accurately characterize the seepage patterns in high production reservoirs and extra high production reservoirs. The result was also applied to the typical high production wells of deep-water reservoirs in West Africa.

2. Experiments

Currently, high-velocity non-Darcy seepage experimental studies have concentrated on sand-packed models and artificial cores. The value of the non-Darcy coefficient is determined only by measurements of individual cores or sand-packed models, making the application of the results difficult to apply to general cases. The properties of the fluid in an actual high production reservoir are different, such as the viscosity and density. Therefore, it is necessary to study the effects of the reservoir characteristics and fluid properties on the seepage rules and the flow pattern distribution in high production reservoirs. The experimental process is briefly described as follows. Initially, we performed the experiment with low discharge, and then we observed the simultaneous increase in the flow rate and the pressure until non-Darcy flow occurs. The pump should have a large capacity and should be able to continuously work for a long period.

The fluid flow in porous media is influenced by many factors that are related to the physical parameters of the fluid (viscosity, density, etc.), the geometric parameters of the porous media (porosity, permeability, etc.), and all of the types of forces (viscous force, capillary pressure, gravity, additional pressure gradient due to non-Darcy effect, etc.). Therefore, during the processes of experimental design and test result analysis, the key factors that should be systematically considered are the viscosity, density and movement velocity of the fluid, the porosity and permeability of the core, and the experimental temperature.

(1) Porous media selection:

Because the experimental fluid must flow at a high velocity, the permeability of the selected porous media should be high. If the compaction is not sufficiently strong for a sand-packed model, then particle migration and a change in the pore structure will occur that could lead to uncertain experimental results. A high-permeability natural core that is loosely cemented is also unsuitable. Therefore, we selected a natural outcrop core that has a suitable permeability and good cementation. Thus, no particle migration will occur, even under high velocity flow conditions.

(2) Core preparation:

Along the horizontal direction of the bedding of the rock