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Discussion of liquid threshold pressure gradient

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ABSTRACT

Some authors believe that a minimum pressure gradient (called threshold pressure gradient (TPG)) is required before a liquid starts to flow in a porous medium. In a tight or shale oil formation, this TPG phenomenon becomes more important, as it is more difficult for a fluid to flow. In this paper, experimental data on TPG published in the literature are carefully reviewed. What we found is that a very low flow velocity corresponding to a very low pressure gradient cannot be measured in the experiments. Experiments can only be done above some measurable flow velocities. If these flow velocities and their corresponding pressure gradients are plotted in an XY plot and extrapolated to zero velocity, a non-zero pressure gradient corresponds to this zero velocity. This non-zero pressure gradient is called threshold pressure gradient in the literature. However, in the regime of very low velocity and very low pressure gradient, the data gradually approach to the origin of the plot, demonstrating a non-linear relationship between the pressure gradient and the velocity. But the data do not approach to a point of zero velocity and a threshold pressure gradient. Therefore, the concept of threshold pressure gradient is a result of data misinterpretation of available experimental data.

The correct interpretation is that there are two flow regimes: nonlinear flow regime (non-Darcy flow regime) when the pressure gradients are low, and linear flow regime (Darcy flow regime) when the pressure gradient is intermediate or high. The nonlinear flow regime starts from the origin point. As the pressure gradient is increased, the curve becomes a straight line demonstrating the linear flow regime. We have verified our views by first analyzing the causes of non-Darcy flow, and then systematically analyzed typical experimental data and correlations in the literature. We conclude that TPG does not exist. We also use several counter examples to support our conclusion.

1. Introduction

With the development of tight and shale oil reservoirs, more attention has been paid to the flow mechanisms in micro-, and even nano-pores at low fluid velocities. The low-velocity non-Darcy flow phenomenon is believed to exist, but there is a lack of systematic studies. Low-velocity non-Darcy flow occurs when the pores are small and the fluid flow rate is low. This phenomenon has to be studied carefully in order to understand fluid flow in shale and tight oil reservoirs. This flow is quite different from the classical Darcy's law in conventional reservoirs.

In the microfluidics, some researchers believe liquid slip flow happens [1,2] when water transport though carbon nanotubes. But whether the concept of slip length can be used to interpret practical reservoir flow is a question, as there are many core flooding studies showing that the liquid measured permeability is lower than Klinkenberg corrected gas permeability [3–5]. Generally, the smooth surface of the nanotubes is believed to be one of the main causes for liquid slip. Recently, Secchi et al. [6] measured the liquid slip length using ionic transport measurements and electron microscopy methods. They found that significant water slip flow happened in carbon nanotubes; however, there was no slip in boron nitride nanotubes. Both nanotubes

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have quite similar surface structure and wettability for water. Secchi et al. believe this stark difference is caused by different electronic structures of carbon nanotubes and boron nitride nanotubes. For carbon nanotubes, the surface is really smooth and the electronic structure are much stable, which lead to the significant liquid slip flow. These conditions are lacking in practical shale and tight porous medium. We do not believe there is such liquid slip flow in practical shale and tight formations as some laboratory experiments [3–5] exhibited. Therefore, we only focus on the low velocity non-Darcy flow in this paper.

A typical schematic of low-velocity non-Darcy flow is given by Huang et al. [7] as shown in Fig. 1. When the pressure gradient is large enough, there is a linear relationship between the fluid velocity and pressure gradient. However, when the pressure gradient is small, there is no flow rate. As the pressure gradient becomes larger than a certain value called threshold pressure gradient (TPG), the flow occurs. As the pressure gradient is further increased, the flow rate increases and finally a linear relationship occurs, similar to Darcy's law. There are three flow regimes (parts): the no flow part, the nonlinear flow part, and the linear flow part (c.f. Fig. 1).

Using a normal experimental setup, the nonlinear flow part is not measurable. We can only measure flow rate and pressure gradient at some levels in practice. If we extend the straight line of the linear flow part to the X axis (pressure gradient), it intersects with the X axis at a non-zero point (with a positive value). The flow phenomenon is quite similar to the Bingham fluid property. This is contrary to Darcy's law, which states that a zero flow velocity should correspond to a zero pressure gradient. The intercepted positive value is known as the pseudo threshold pressure gradient (PTPG), and this phenomenon has been presented in earlier studies. PTPG is also called Threshold Pressure Gradient (TPG), because in early studies, the nonlinear flow part was not recognized. We use the proper term, PTPG, in this paper. Miller and Low [8] first studied the non-Darcy flow phenomenon in low permeability clay systems. The interacting forces between the fluid and the rock are believed to be the cause of the threshold pressure gradient. This phenomenon did not gain much attention until the late 1990s, when low permeability reservoirs became our development attention. Prada and Civan [9] studied this phenomenon using brine, and concluded that the PTPG increases with the decrease of fluid mobility. They discovered that the higher rock permeability, the smaller the PTPG is, and the higher fluid viscosity, the smaller the PTPG is. Based on their discovered correlation, a value of PTPG can be too large to be practical. Other similar experimental studies concluded the same results, but presented different PTPG correlations [10–14]. In those studies, the PTPG values cannot be easily determined because of the difficulties in accurately measuring small flow rates and low pressure gradients.

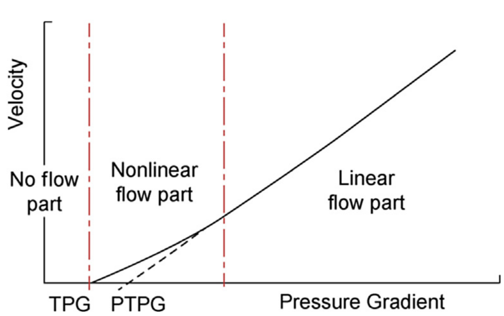

Fig. 1. A typical schematic of low-velocity Non-Darcy flow [7].

With higher accuracy of experimental instruments, lower pressure gradients and lower velocities can be measured. Nowadays, the nonlinear flow part is well recognized and the nonlinear flow part is believed to be the mainly flow regime in tight or shale oil reservoirs. This means that the nonlinear flow part needs to be carefully studied. Many studies have been done, and different experimental results and developed correlations have been reported [15–18]. The non-Darcy flow behaviors in those studies are the similar to that shown in Fig. 1. According to the studies cited above, there is a trend showing that the newly measured TPGs are much smaller than those published earlier, and it is difficult to determine whether there is TPG or not, because too low rates or pressure gradients cannot be accurately measured.

In this paper, we first carefully review the cause of low-velocity non-Darcy flow and summarize the existing non-Darcy formulas and corresponding study results. Using the previously published experimental data and correlations, we verify that TPG does not exist. Finally, we refer to several counter examples to support our conclusion.

2. The cause of low-velocity non-Darcy flow

The boundary effect between the rock and fluid is believed to be the main cause of low-velocity non-Darcy flow. For fluids in shale and tight oil reservoirs, the interfacial force between fluids and rocks is large enough that needs to be considered compared to the pressure gradient driving force. The lower the permeability, the more obvious the boundary effect is. The fluid molecules distribute unevenly due to this force. Huang's [10] study shows that the percentage of resins and asphaltenes is bigger near the fluid rock boundary than in the pore center, in other words, the density near the boundary is higher than in the pore center. In addition to this, the viscosity is also higher in the boundary layer. It can be understood that it is more difficult for the fluid near the pore wall to flow than the fluid in the pore center. Some authors [7,10,19] divided the fluid in the pores into two parts: the boundary absorbed fluid and the inner free fluid. In the shale and tight reservoirs the percentage of boundary fluid is much bigger than in the conventional reservoirs. This phenomenon is more obvious. If we assume such two layers exist, and even if all the pores have the same diameter, there should not exist a threshold pressure gradient, as a low pressure gradient cannot drive the fluid near the walls, but can drive the fluid in the pore centers. In practical reservoirs, there are a wide range of pore diameters, a very low pressure gradient can always drive the fluid from some relatively large pores or pore centers, and thus a low flow rate exists. Because of the boundary effect, the flow rate will be lower than the Darcy flow rate without the boundary effect. Thus the relationship between the flow rate and the pressure gradient may not follow the linear Darcy equation. As a result, the relationship becomes a curve which is below the linear line for Darcy flow, showing the low-velocity non-Darcy flow. Although the flow rate is lower than the Darcy flow rate, the flow rate cannot be zero at some low pressure gradient. Again, the threshold pressure gradient does not exist.

Yang et al. [19] and Xu and Yue [20] studied the flow in micro tubes. The diameters of the tubes are 5 μm and 2 μm. The experiments show that the flow mechanism in micro tubes is just like that shown in Fig. 1. Xu and Yue [20] were able to measure a flow rate as low as 3.25×10^{-5} μL/s at a pressure gradient of 0.21 MPa/m. They had a doubt about the existence of TPG. Xiong et al. [21] believed that the non-Darcy flow is caused by the different diameters of the pores in tight and shale oil reservoirs. Different diameters of the pores will have different threshold