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Discussion of liquid threshold pressure gradient

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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.

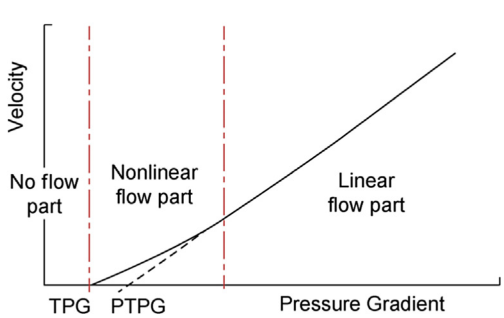

Fig. 1. A typical schematic of low-velocity Non-Darcy flow [7].

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 pressure gradients to overcome in order to flow. When the pressure gradient increases, more small pores will begin to flow. However this is just a hypothesis, and in one phase flow, there is no capillary pressure. Wang et al. [22,23] simulated the oil transport through inorganic nanopores in a shale model using molecular dynamics. By using equilibrium molecular dynamics and nonequilibrium molecular dynamics, their study shows that the oil in nanochannels consists of two parts: absorbed oil and free oil in 7.8 nm nanopores. With the decrease of the pore size to 1.62 nm, the percentage of the absorbed layer increases from 36.9% to 100%, but almost all the absorbed layer is movable given a pressure gradient. Unfortunately, the velocity in the study is high and the molecular dynamic method cannot simulate low velocity flow because of the immense computational cost in low fluid velocity. Jin et al. [24] studied the effect of interfacial layer on water flow in nanochannels using the Lattice Boltzmann method. They found that both the permeability of nanochannel and the water velocity in the nanochannel dramatically decrease when increasing the thickness of the interfacial layer. However, in their study, the boundary layer is simply set to be unchangeable and unmovable like a solid at different pressure gradients.

In sum, the percentage of boundary fluid layer, caused by the rock fluid interacting forces, is much higher in tight and shale oil reservoirs than in conventional reservoirs. The properties within the boundary fluid are different from the inner free fluid, which makes the fluid mechanism different from the Darcy flow in conventional bigger pores. That is the cause of low-velocity non-Darcy flow. However, the fluid in the boundary layer can still flow at given a pressure gradient. By also considering the heterogeneous distribution of pore diameters, there is always a flow even at a very low pressure gradient. Therefore, TPG does not exist.

3. Existing formulas of low velocity non-Darcy flow

In this section, we present several formulas to describe the low velocity non-Darcy flow in order to fit the schematic curve in Fig. 1. No analytical derivation has ever been done on any of these formulas.

PTPG equation. This equation is introduced in early studies [9,10], and the biggest advantage is its simplicity, even though this equation lacks the nonlinear flow part.

$$\begin{cases} v = 0 & \nabla p \le G \\ v = -\dfrac{k}{\mu}\nabla p\left(1 - \dfrac{G}{|\nabla p|}\right) & \nabla p > G \end{cases} \tag{1}$$

where v is flow velocity, k is permeability, mD; μ is fluid viscosity, cP; ∇p is pressure gradient, G is the PTPG, MPa/m.

Xu equation. There are several similar nonlinear equations [7,15,18,25], one equation presented by Xu et al. [18] is

$$\begin{cases} v = 0 & \nabla p \le a - b \\ v = -\dfrac{k}{\mu}\nabla p\left(1 - \dfrac{a}{|\nabla p| + b}\right) & \nabla p > a - b \end{cases} \tag{2}$$

Both a and b are positive values. All three flow parts in Fig. 1 are considered in equation (2). The TPG value is $a - b$. If $b = 0$, then equation (2) will be the same with equation (1). If $a \le b$, there will be no TPG but just the nonlinear flow part. However, compare with equation (1), the coefficients of a and b are more difficult to determine.

Using equation (1), a lot of research has been done in order to study the pressure distribution and production performance affected by PTPG. When the pressure gradient is less than PTPG, there will be no flow. So including PTPG in flow analysis is a moving boundary problem. Within the boundary the flow will occur, beyond the boundary the flow rate will be zero, but the boundary is moving all the time. Ignoring the moving boundary issue will help us get the analytical solution easily but loose the true physical phenomenon. Pascal [26] first solved the moving boundary problem while studying non-Newtonian fluid flow problems by using an integral method, an approximate but concise method. Wang et al. [27] solved this moving boundary problem by defining new dimensionless variables and obtained the pressure solution and moving boundary equation using Laplace transformation method. Lu [28] presented an analytical solution to the pressure transient equations of a uniform-flux hydraulic fractured gas well in tight gas formation considering threshold pressure gradient. These solutions are obtained using the Green's functions method with numerical approximations. A method to determine the location of the moving boundary front is also presented in his work. However, until now there has been no analytical solution when using equation (2) to more accurately describe the non-Darcy flow. As for a numerical solution, finite difference method is mostly used. Li and Liu [29] improved the numerical method to successfully solve the moving boundary problem of radial unsteady flow while considering the PTPG equation. Xu et al. [18] solved the nonlinear flow model numerically, and believed that the nonlinear model can more effectively model the low-velocity non-Darcy phenomenon. Guo et al. [30] experimentally and numerically studied the production performance of hydraulic fractured tight sandstone reservoirs by using Xu equation while considering the non-Darcy flow.

4. Justification of non-existence of threshold pressure gradient

A typical and much more accurate experimental data is given by Xiong et al. [21] c.f. Fig. 2. PTPG cannot describe a complete region of a non-Darcy flow. Therefore, researchers used quadratic equations to fit the experimental data. However, quadratic equations will underestimate the value of velocity when the pressure gradient is small. In this way a TPG point will be found by extending the quadratic curve to the X axis. However when we use a cubic equation, there is a much smaller TPG value compared to the quadratic equation, and the fitting result is better for this example data in terms of the values of R^2 (c.f. Table 1). This means that the TPG values can be caused by fitting the experimental data by using quadratic equations. Note that the fitting processes are performed using MATLAB curve fitting

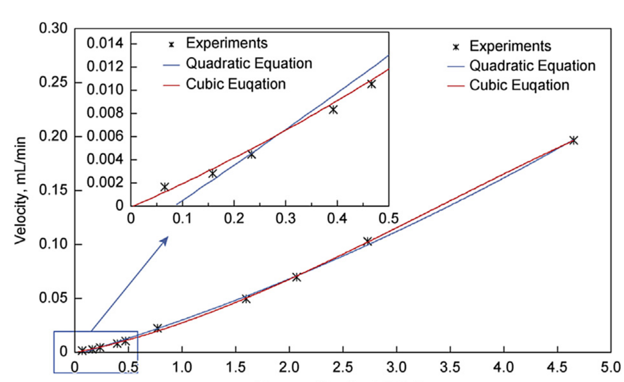

Fig. 2. A typical experimental data of volume flux vs. pressure gradient by Xiong et al. [21] and the corresponding quadratic and cubic fitting curves.

Table 1
Curve fitting results.

Quadratic equation		Cubic equation	
$q = 0.0029(\nabla p)^2 + 0.0295\nabla p - 0.0025$		$q = -0.0089(\nabla p)^3 + 0.0090(\nabla p)^2 + 0.00196\nabla p - 0.000134$	
TPG = 0.086		TPG = 0.009	
R^2	0.9991	R^2	0.9997

Table 2
PTPG and TPG values when permeability is 0.01 *mD* and fluid viscosity is 1 *cP*.

Equations	PTPG, MPa/m	TPG, MPa/m
(3)	439.19	
(4)	45.85	
(5)	12.80	
(6)	29.63	
(7)		0.855
(8)		0.577

toolbox based on the least square method. Whether there is TPG or not cannot be determined simply by fitting the data using a quadratic equation and extending the curve, because usually TPG is caused by the underestimation of the velocity at small pressure gradient.

Several TPG or PTPG correlations are reported in similar studies using quadratic equations to get TPG and using straight line equations to get PTPG. Some of them are listed as follows [9,12–14,25,31].

$$\mathrm{PTPG} = 11.03\left(\frac{k}{\mu}\right)^{-0.8} \tag{3}$$

$$\mathrm{PTPG} = 0.5\left(\frac{k}{\mu}\right)^{-0.9813} \tag{4}$$

$$\mathrm{PTPG} = 0.0747k^{-1.117} \tag{5}$$

$$\mathrm{PTPG} = 0.4k^{-0.9348} \tag{6}$$

$$\mathrm{TPG} = 0.00965\, k^{-0.9738} \tag{7}$$

$$\mathrm{TPG} = 0.0252\, k^{-0.68} \tag{8}$$

where PTPG is the pseudo threshold pressure gradient, MPa/m; TPG is the threshold pressure gradient, MPa/m.

If the reservoir permeability is 0.01 *mD*, and the fluid viscosity is 1 *cP*, then the values of the PTPG and TPG are listed in Table 2. The pressure gradients are in the range of 0.577 MPa/m to 439.19 MPa/m. No such pressure gradient can happen in field conditions, which means that the TPG or PTPG values are too big to exist. Note that in a radial flow to a production well, the pressure gradient far away from the well are much smaller than that in the near wellbore region. In other words, only in a small part of the reservoir area near the well bore can the fluid flow because of TPG or PTPG. After the well produces for several months, an interesting thing happens if we shut the well. No matter how long time is taken, the bottom hole pressure will not build up to the initial pressure because of TPG, and there would be a logarithmical pressure drop (c.f. Fig. 3) which is obviously not the fact in the field situation. The only explanation is that TPG does not exist.

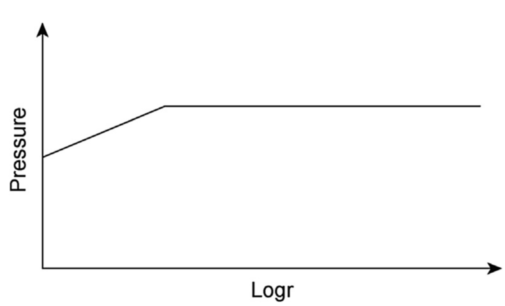

Fig. 3. Final pressure distribution of a producer given TPG.

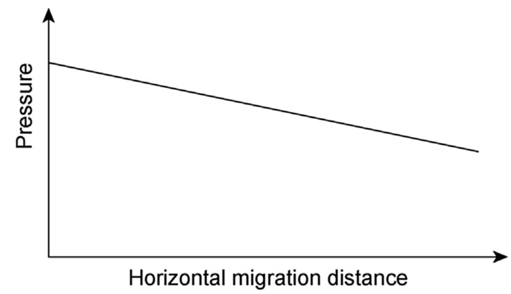

Fig. 4. Schematic of initial pressure distribution given TPG at the same depth.

Besides, there are other field facts which cannot be explained by the existence of TPG, for example, fluid distribution in a reservoir. Fluid distribution in a reservoir follows the gravity segregation. The gravity force gradient is small compared to the TPG values, so the fluid re-distribution or migration process cannot happen. In real reservoirs, the fluids are actually distributed according to the gravity segregation. So, the TPG cannot exist [32].

Another example is the initial pressure distribution given TPG. Suppose there is enough force for hydrocarbon migration to overcome TPG and form a shale or tight reservoir. Given TPG, what will happen to the initial reservoir pressure? Due to TPG, the ultimate initial reservoir pressure will not be the same for the same depth. The schematic is shown in Fig. 4. The slope in the figure represents a TPG value. This situation is obviously not fact for a shale or tight reservoir, further indicating that TPG cannot exist.

5. Conclusions

The significance of liquid threshold pressure gradient in tight and shale oil reservoirs stimulated this study. Based on our review and discussion on the subject, the following conclusions may be drawn.

(1) Published studies using quadratic equations to fit experimental data underestimate the velocity at the small pressure gradient region. This is one of the reasons that cause the misinterpretation of the existence of TPG by extending the curve of velocity vs. pressure gradient to the gradient axis.

(2) The existence of threshold pressure gradient (TPG) in tight and shale reservoirs is due the misinterpretation of the experimental data and/or due to the fact that instruments used in laboratory cannot measure so low velocity and pressure gradient.
(3) The values of TPG estimated from existing correlations are so large that they cannot explain some of real facts. Some of the counter examples demonstrate that TPG cannot exist. Instead, the low-velocity non-Darcy flow may exist that consists of linear flow part and nonlinear flow part.
(4) Low-velocity non-Darcy flow exists in the reservoirs when the pressure gradient is very low.
(5) The low-velocity non-Darcy flow may be due to the boundary effect, or even by the flow nature itself in tight and shale reservoirs.

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