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Discussion on Threshold Pressure Gradient Regarding Flow in Low Permeability Reservoirs

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Abstract : *Oil and gas resources from low permeability reservoirs play a significantly role for many countries like China and America. Flow mechanism in low permeability porous media is thus important. It is widely believed that Darcy's Law have some limitations when applied in low permeability reservoirs. Many researchers especially in China studied the pre-Darcy flow by measuring threshold pressure gradient (TPG) through laboratory tests. Some went further to simulate TPG influences on production prediction in oil and gas development. A lot papers have been published. In this paper, debated concept of TPG and its laboratory measurement in low permeability are critically reviewed. Misunderstanding and erroneous or unnecessary predictions are investigated with considering possible experimental artifacts and flow theory analyzing. After reviewing all the TPG test results in more than 200 references, we find that no obvious trend exists.TPG tested in core flow tests in laboratory is either caused by experimental error, or by low accuracy of instrument, or inadequate test method. NO TPG exists in micro pore low permeability and it is not necessary to give TPG so much attention as many researchers do especially in China. This is well directly verified by high resolution instrument TPG test and further supported by progress in understanding flow mechanism in nano-pores in shale.*

Keywords: *Threshold Pressure Gradient, Low permeability, Experiment, Micropore, Flow mechanism*

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I. Introduction

In low permeability reservoir development, threshold pressure gradient (TPG) is frequently involved and used[1] in well spacing pattern design and production ability prediction. Typical equation including TPG can be seen in Eq. (1a) and (1b)[2].Although the TPG concept[3]was not first put forward in China, a great number of TPG references[4]are published by researchers in China. Many people in China studied the TPG by experiment[5] and numerical simulations[6], however, the existence of TPG has been also strongly questioned[7]. In this paper, typical previous references concerning TPG are critically reviewed, the definition of TPG is discussed, and direct evidences to deny existence of TPG are presented. In the end, some conclusions are given for future study in low permeability reservoir development research.

$u=\frac{q}{A}=\frac{K}{\mu}[\frac{\Delta p}{\Delta L}-\left(\frac{\Delta p}{\Delta L}\right)_{cr}]$,when $\frac{\Delta \mathrm{p}}{\Delta \mathrm{L}}>\left(\frac{\Delta p}{\Delta L}\right)_{cr}$ Eq. (1a)

$\mathrm{u}=0$, otherwise. Eq.(1b)

In Eq.(1a) and Eq.(1b), u, μ, p, denote the volume flux, viscosity, pressure, respectively. K is the permeability of the porous media. q is the flow rate.$\Delta \mathrm{p}$ denotes the pressure difference across the core and $\Delta \mathrm{L}$ is equal to the core length L.

What Is the Accurate TPG Definition? Although threshold pressure gradient (TPG) is frequently used in many publications, its true meaning or accurate definition was seldom given or discussed. Threshold pressure gradient (TPG) definition is necessary to clarity some misunderstand of this concept. In low or ultra-low permeability core flooding permeability test, many researchers found that the flow and pressure does not follow Darcy law when flow or velocity is very low. This phenomenon is well reflected in Figure 1[8]. As can be seen in Figure 1, at point ***a*** and ***b***, the velocity is zero while the gradient pressure is not. This pressure gradient (point **a**) was called threshold pressure gradient (TPG), while point b was called pseudo threshold pressure gradient [9]. Non-linear flow was noticed soon after the Darcy's Law was reported and this force to initiate non-linear flow was named TPG by researchers[10]. From this definition or the description of the non-linear flow phenomenon in porous media, we can see that TPG is a single flow concept that the minimum or minor pressure gradient that makes fluid start to flow in low porous media. In high permeable media, the Darcy Law was well proven and accepted. Thus, there are two key points in this definition: 1) single phase flow [11] 2) in conventional low permeability porous media [12]. As for two phase flow, due to the interfacial tension between two phases and the pore tortuosity, capillary pressure phenomenon was noticed both in low and high permeability porous media. This capillary pressure is actual additional pressure compared to Hagen-Poiseuille's equation [13]. In two phase flow relative permeability test, relative permeability of two phase sum is smaller than unit. That is to say, there are additional resistance force than each single flow resistance. There is no dispute on this additional pressure increase in two phase flow. Hence, this additional force cannot be described as TPG. Although threshold pressure phenomena was reported in 1968[3] or earlier, this two phase threshold pressure is definitely different from typical TPG. However, many researchers overlooked this phenomenon and try to test two phase TPG. Hence, some researchers gave the incorrect two phase TPG results through laboratory tests [14] or field test [15] based on the misunderstanding of TPG. TPG is originally a single phase concept. In other words, some reported existence of TPG in actual oilfield field is actual two phase additional flow resistance which are common both in low and high permeability reservoir, thus is not persuasive [11].TPG is defined for single phase flow rather two phase. This should always be kept in mind.

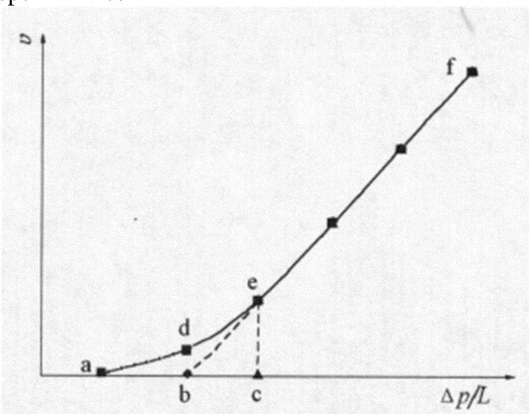

Figure 1 Velocity vs. pressure gradient [8]

Does Non-Linear Flow Necessarily Mean TPG?

Many tests with low permeability cores showed that the phenomenon of non-linear flow [9]. This non-linear flow phenomena were given special attention by researchers in former Soviet Union [12]. Many attributed the non-linear flow in low permeability to TPG [16]. Some researchers investigated the TPG through micro-tubes [17]. Micro scale effect was revealed in gas flowing in micro-tubes [17], and this micro-scale effects that flow does not follow classic fluid mechanism prediction were believed as one cause of boundary layer[18]. Boundary layer was believed to result in TPG [9], although this opinion was also denied [19]. This will be discussed later. However, non-linear flow regimes were well documented [20]and studied, and fluid type, newton or non-newton, mainly accounted for the non-linear flow. No dispute was on non-flow linear flow since different flow regimes in Figure 2[20] was easily verified by fluid mechanics experiments. Different flow regimes are believed to at least partly caused by fluid property determined by molecular structure [21]. Figure 3 describes three typical fluids (Pseudoplastic Fluid, Newtonian Fluid, and Dilatant Fluid) shear stress changed with shear rate. Another typical non-Newtonian fluid is Bingham Fluid [22] which behaves as Newtonian in high rate and no flow in low rate, as can be seen in Figure 4. TPG and non-linear flow are different but easy confused concepts. If a fluid behaves as Pseudoplastic Fluid and Dilatant Fluid, or Bingham Fluid, its low rate flow in porous media, either high permeability or low permeability, is non-linear flow. Only for Bingham Fluid, as can be seen in Figure 4, a possible threshold pressure may be observed. However, this is now true for Newtonian fluid brine or gas. Therefore, non-Linear flow does not necessarily mean TPG.

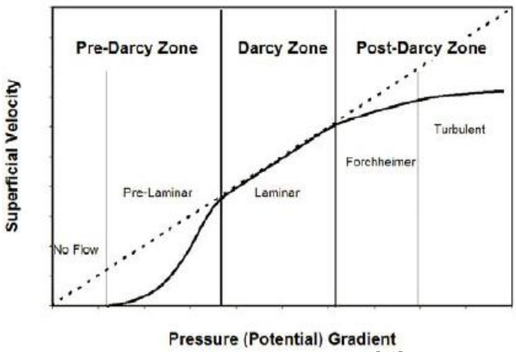

Figure 2 Flow regimes [20]

Direct Evidences To Defy Existence of TPG?

According to low permeability core flow tests[14], a typical curve like Figure 1 can be easily got. These test results are believed evidences of TPG by many or most people in China. However, this is not the truth. First, due to experiment artifacts and the inaccurate instruments used in the low flow rate in low or ultra-low permeability cores, the minor flow at very low pressure gradient was not detected and mistakenly deemed zero flux [11]. After analyzing the publications of TPG test results, few or no introduction was given to the instrument accuracy or error analyses [2]. TPG test most highly depends on high accuracy instrument. TPG supporters never gave a good explaining to this doubt. What is more, one good study [7] with most high accuracy reported up to present made a definite conclusion that no TPG was found in single phase flow experiment in super-low

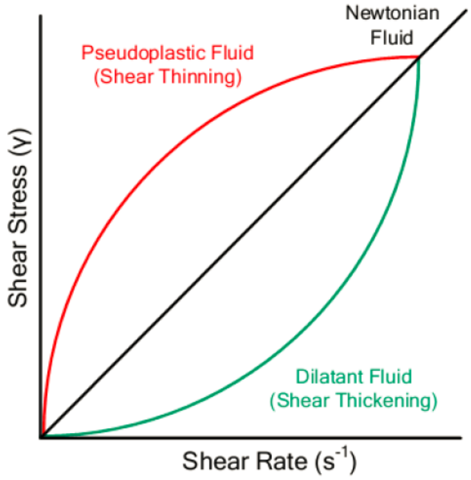

Figure 3 Three typical fluid

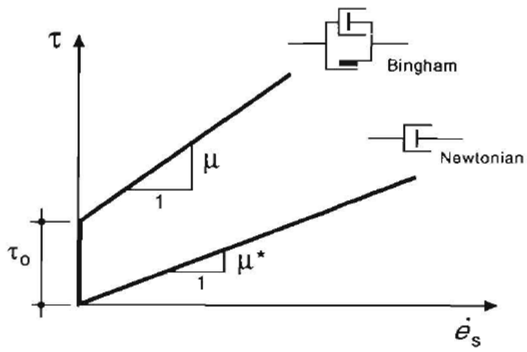

Figure 4 Shear stress vs. shear strain rate response of a Newtonian fluid and a Bingham material [22]

permeability core (kg=0.01mD). Different from other studies, detained information about the instrument accuracy, measures taken to reduce systematic error were carefully introduced and analyzed. A special technique with unsteady state method were adopted, as can be seen in Figure 5[7]. In the test, minor pressure difference was captured by high accurate pressure transducer (range: 0-55.12kPa,0-861.25kPa,0-2239.25kPa, precision:±0.5%) instead of getting flux,which is so minor to catch up easily. Keep upstream pressure constant, and the downstream valve closed, the downstream pressure of core is rising slowing, until finally downstream pressure equals to upstream pressure, which indicates that no TPG exists in 100% single phase (water, kerosene, or oil) saturated ultra-low permeability core [7] . Their tests also verified that much more time is required for pressure wave transmit in lower permeability media. Insufficient time together with no special measures to stop outlet fluid evaporate accounted for failure of getting small flow in many TPG tests [11]. This experiment is currently the best, to the best of our knowledge, direct evidence in China to deny the existence of TPG. Their conclusion was in agreement with foreign researchers' conclusion that no TPG exists for single phase Newtonian fluid (water or brine) flow in tight core (10^{-3}mD)[23]. Another problem is that the TPG value for the same permeability range core varied greatly. For instance, TPG values given in one literature [24] was between 1.86-7.85 MPa/m for Daqing core permeability to brine 0.0347-1.455mD by constant-pressure mercury injection method. While in another constant-rate mercury injection test, TPG was about 0.7 MPa/m for a 1.5mD Daqing core [9]. Even considering the difference between constant-pressure mercury and constant-rate mercury injection method, the difference were so great. In addition, these TPG values are too high to reflect actual condition. In another test, the TPG was between 0.8-0.15MPa/m for cores with air permeability between 0.02-1 mD [25], while in the other test [18]by the same team, TPG was about 0.5 MPa/cm, one hundred times difference. There are many such great different TPG given by different even the same researcher. This reflects that the current TPG tests are either inaccurate or lack of replicability, which should not be accepted in scientific society. What is more important, some reported high TPG values seems impossible to overcome in oilfield development, however, many ultra-low permeability reservoirs in Changqing Oilfield in west China are well effectively exploited. This was well noticed [19]. Second, for low or ultra-low permeability cores, long times are required to detect or read the minor flux [11]. This is easy to understand since it requires time for pressure wave to migrate. Interestingly, this conclusion was questioned by one typical major TPG supporter [26] to argue the doubt toward TPG. Thirdly, the cores that used to test TPG are easily contaminated or plugged the front face through core cutting, as can be seen the schematic diagram Figure 6[11]. This will add to the pressure gradient in test. This phenomena is frequently confronted in laboratory, but also denied by one major TPG supporter [26]. To sum, there is direct evidence from high accuracy instrument test to deny the existence of TPG and the doubt of tests to claim TPG are reasonable.

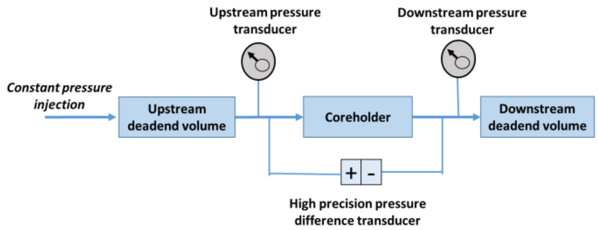

Figure 5 TPG test with highprecision [7]

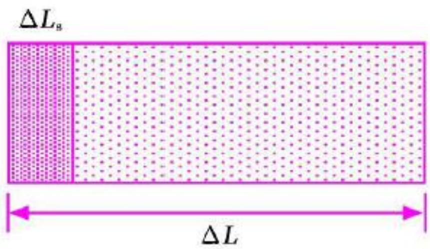

Figure 6 Schematic diagram of plugging core end face [11]

Does Boundary Layer Effect Account for TPG?

Since the average pore and pore-throat is much smaller than high permeable porous media, the scale effect do exist [13]. This was also verified by some micro-tube tests [17]. Some people [12] argue that boundary layer effect, like swelling clays and mobile fines, is the cause of TPG in low permeable porous media. For high permeable porous media and light oil, they argue, the boundary layer is thin and the oil volume fraction in such thin boundary layer is relatively small, thus non-Newtonian property of such oil has little effect on the linear flow in porous media. However, for low permeable porous media or heavy oil, the boundary effect cannot be neglected [25]. This opinion was also doubted. The fluid in boundary layer does not immobilize but flows slowly[11]. The boundary layer thickness or size testing is not well solved yet [19], which implied it is too early to discuss its effect on flow. One test [18] with regard to boundary layer thickness are seriously doubted [19]. Advance in nano-pore research provided us good insight on the boundary effect. Gas permeability in nano-pores is function of pore size and pressure [13]. The smaller the size of pores, the larger difference between apparent permeability and Darcy permeability [13], which does reflect the micro-scale effect. However, pores as small as 1μm show no difference between apparent and Darcy permeability, as can be well seen in Figure 7 [13]. As for most ultra-low permeability formation, the average pores and pore-throat are larger than 1μm. This indicates that Darcy permeability is reliable in low permeability porous media. Therefore, no boundary layer effect should be considered in ultra-low permeability reservoirs. From Figure 7, we can also see that only when pores size drops to nano-scale, gas in such porous media deviates from Darcy permeability. Different gas flow behavior in nano-pores and micropores account for this, as can be seen from Figure 8 [27]. In Figure 8, flow in nano-pores and micro-pores are quite different and the velocity on the pore surface is zero while in nano-pores the velocity on pore surface is non-zero, thus it is obvious that no boundary layer effect exists in micro-pores. Even if some gas molecules gather on the pore wall, since the molecular diameter is nanoscale, the boundary layer due to nanoscale molecular (gas or water) thickness is also nanoscale [27]. Even if the gas or water adsorption on pores wall is multilayer, it is very difficult for nanoscale molecules to form very thick layer by 4 to 5 order of magnitudes times to go to micro-scale. Thus, the claimed boundary effect does not account for TPG in micro-scale low permeability media.

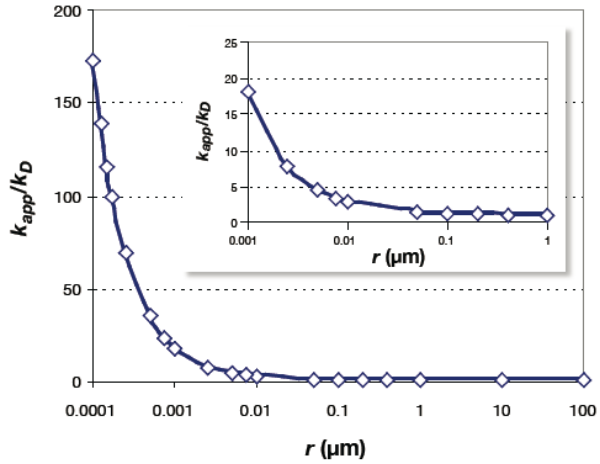

Figure 7 Average pore radius size affected gas permeability in nano-pore[13]

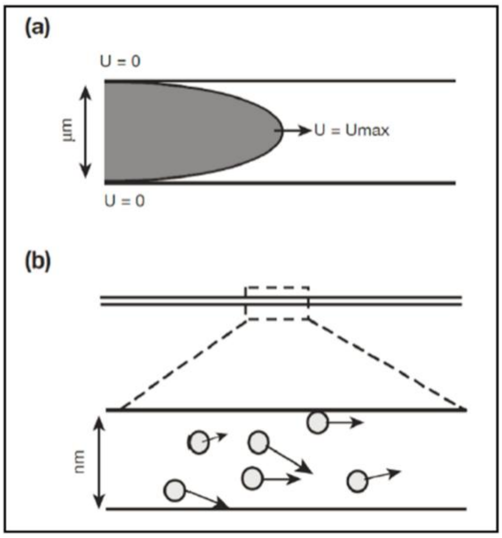

Figure 8 Gas flow difference in micro-pore and nano-pores (a) micro-pores with zero flow velocity at pore walls and (b) nano-pores where gas molecules slip at pore boundary [27]

Is TPG Verified by Field Tests?

Based on the belief that TPG exist, some people reported evidence of TPG in oilfield in China [28]. TPG, even if it exists, is one phase flow result rather than two-phase concept flow which is often misunderstood. In two phase or three phase flow, additional pressure difference are caused by capillary force and phase-phase mutual effect. This is well reflected in relative permeability curves. And there is no dispute on this. The so-called TPG in oilfield are actually caused by skin effects as well as the complex three phase flow in complex heterogeneous layers. Since TPG does not exist, TPG in two phase or three phase is meaningless. Lots of people [29] deduced the production equation and well spacing determination equation based on linear TPG equation without realizing the great difference between single phase linear flow and plane radial flow [30]. In linear flow, TPG is a constant value[2],seen Eq.1.While in plane radial flow, pressure gradient is proportional to the flow but inversely to the radial radius, thus variable[30].Interestingly, one study[30] first believed the existence of TPG and compared the linear flow and plane radial flow and proposed a concept Threshold Flow for plane radial flow to replace TPG in plane linear flow, and gave the conclusion that these two values approach zero, thus can both be neglected. One researcher in strong favor of TPG also argued that TPG should not be considered any longer in low permeability reservoir numerical simulation, well test and production prediction [26] unless formation pressure coefficient is under one. In other words, when formation pressure coefficient is higher than one, it is not necessary to consider TPG [26]. When pressure coefficient is lower than one, TPG must be considered since fluid cannot flow within TPG [26]. Bakken shale play is taken as an example to support this conclusion. Due to volume fracturing g and high formation pressure coefficient, "TPG suddenly disappears"[19]. However, he did not explain how does "TPG suddenly disappear" in the course from matrix to fissure in Bakken. Even according to most conservative TPG value, the TPG in shale must be tremendous high. More importantly, many spontaneous imbibition tests in shale and low permeability core [31] indicate that oil and water can flow in such tight media when the pressure coefficient is much less than one. This denied the belief that TPG should be considered when pressure coefficient is less than one. To conclude, TPG is not verified by field tests, while its nonexistence is verified by shale gas development and spontaneous in tight and low permeable cores. No more effort should be given on TPG.

II. Conclusions

TPG, even if it exists, is one phase flow result rather than two-phase concept flow which is often misunderstood. Well recognized pre-Darcy flow in low permeability is not necessarily related to TPG. Non-Darcy flow is due to fluid property both in high and low permeability reservoir. Claimed existing evidences of TPG are reported with the same method but different value with orders of magnitude even within the same permeability range. Traditional TPG measurement does not or not well answer the doubts of experimental artifacts which include low device accuracy in low even minor velocity and pressure gradient, temperature variations, trapped air influence, and insufficient time. Boundary layer, result of possible interactions between medium & fluid, like swelling clays and mobile fines cannot be

cause of TPG as most TPG supporters claimed because the nanoscale molecular layer is so small comparing to microscale pore radius. All the laboratory measured TPG values are so large that it seems impossible to overcome it in reservoir development. However, success in shale gas and tight oil development overturns this. What is more, many recent spontaneous imbibition tests in ultra-low permeable shale and tight porous media proved no TPG existence even in much more complicated and thinner nano-pore. And imbibition test denied the conclusion that TPG should be considered when pressure efficiency is below one. Non-Darcy flow in low permeability media is not necessarily related with TPG which is frequently misused to characterize non-Darcy flow. TPG is denied existence or proven not unnecessary in low permeability reservoir production prediction and well pattern optimization.

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