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# The threshold pressure gradient effect in the tight sandstone gas reservoirs with high water saturation

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ABSTRACT

From research and field development, the threshold pressure gradient (TPG) in tight formations is required before the fluid starts to flow. This paper addresses the different factors that affect the TPG in tight sandstone gas reservoirs with high water saturation. First and foremost, the petrophysical properties were obtained through the following tests: X ray diffraction, scanning electron microscope and nuclear magnetic resonance using cores from Sulige gas field in China. Secondly, the TPG experimental investigations were performed using air bubble method, and a TPG correlation was obtained considering the influences of permeability, connate water and movable water. Finally, a gas production model was established with the TPG, slip and diffusion effects taken into account, and its applications were discussed using actual reservoir parameters. The results showed that the cores have plenty of clay minerals and high connate water saturation. Besides, the throat radii from NMR mainly are distributed between 0.0004 and 0.1 μm, with a few between 0.1 and 0.4 μm. The clay depositions decrease the pore and throat diameters, which result in Jamin effect. The experimental results showed that the TPG exists at the connate water saturation, and increase exponentially with either an increase in dimensionless water saturation or decrease in permeability. The IPR curves showed the TPG effect on gas production is very serious i.e. production loss degree decreases especially at high bottom hole pressure, and the production loss degree decreases as the bottom hole pressure decreases. The greater the water saturation or the smaller the permeability, the greater the production loss degree. In addition, the TPG affects the intercept of the abscissa of the flow curve, and the slope of the curve decreases as water saturation increases.

## 1. Introduction

With increased development of tight sandstone gas reservoirs, flow mechanisms at low flow velocity have become of more interest. The threshold pressure gradient (TPG) effect at low velocity, which is closely related to gas production. Fig. 1 shows a typical flow curve of flow rate against pressure gradient. The TPG of a gas reservoir is defined as the minimum pressure gradient that enables the gas to start flowing against viscous forces between solid and gas, and the pseudo threshold pressure gradient (PTPG) is an intercept of the extension line of the linear part to horizontal axis [1–3].

Studies about the TPG effect are fruitful, though some are controversial. Generally, the TPG is obtained experimentally from rock samples in the laboratory, whose value is close to zero. A small number of researchers think it is too hard to happen in actual development. Wang X and Dou H [3,4] thought that the TPG is a misinterpretation of available experimental data, hence the TPG should not be considered in reservoir productivity prediction.

On the other hand, many studies support the existence of TPG effect in tight gas reservoirs. Through a series of experiments, Li A et al. [5–7] observed that the seepage curve does not pass the origin, and there exists a non-linear variation under low flow velocity. With the increase in flow velocity, the curve gradually transits a linear relationship.

Studies showed that the boundary layer between solid (especially quartz and clay) and fluid interaction has an important impact on the TPG. Wu J and Xiong Y [8–10] thought that in the near wall area, a boundary layer is formed due to the attraction of solid wall, which occupies the flow space and thus lowers flow rate. Its thickness declines with the increase of pressure gradient, which results in nonlinear flow characteristics. And the PTPG increases as the mainstream throats get smaller and the movable fluid saturation gets greater [11]. On the basis of an established double boundary model, Liu W [12] found that the dimensionless TPG has a great impact on the external moving boundary than on the internal moving boundary.

Mathematical models analyzing the characteristics and laws of nonlinear flow of the TPG effect are abundant. Pascal H [1] used the TPG

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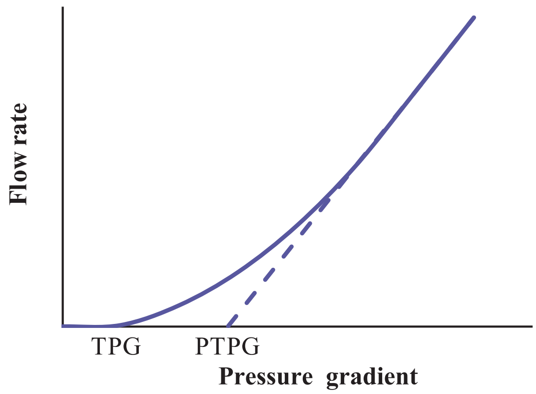


**Fig. 1.** A typical schematic of low-velocity Non-Darcy flow.

relation Eq. (1a), which takes into account the permeability of porous media and yield stress of oil to investigate the TPG effect of oil in non-steady flow through analysis, numerical and integral method. Lu J [2] obtained the analytical solutions to the pressure transient equations of a uniform-flux hydraulically gas well in tight gas formation with TPG, using Green's functions method. Zeng B [13] analyzed the influence of permeability and fluids components on TPG with steady "pressure-velocity" method, and found that the power function is a better function for the TPG (Eq. (1b)), the TPG of different fluids is as follows: Distilled water > Injected water > Formation water > Surfactant solution. Li S and Wu D [14,15] took medium deformation and TPG (Eq. (1b)) into account and proposed the non-linear flow models of single-phase and double-phases of oil and water in low permeability reservoir. Alvaro Prada [16] used brine to flow through the brown sandstone, sandpack and shaly sandstone, and discovered the best least-squares linear fit of experimental data is Eq. (1c), whose coefficient is $R^2 = 0.96$, indicating a relatively strong correlation of the measured data with Eq. (1c). Civan F [17] established a rigorous modeling of flow through hydraulically-fractured shale-gas reservoirs with the transport and TPG effect of gas taken into account, and the TPG correlation he used is also Eq. (1c). Yang Z [7] carried out the experiment in combination with gas bubble method and differential pressure flow method to investigate the TPG and non-linear seepage characteristics of tight sandstone gas, and obtained the related function (Eq. (1d)), which considered the influence of water saturation, but did not distinguish the influences of connate and movable water.

$$\lambda = \frac{\beta\tau_0}{\sqrt{k_a}} \tag{1a}$$

$$\lambda = a_1 k_a^{-b_1} \tag{1b}$$

$$\lambda = a_1\left(\frac{k_a}{\mu}\right)^{b_1} \tag{1c}$$

$$\lambda = a_1 S_w^{b_1}(k_a)^{jS_w^l} \tag{1d}$$

where $\lambda$ is the TPG; $\beta$ is the dimensionless constant determined by experiment; $\tau_0$ is the yield stress of oil; $a_1$, $b_1$, $j$ and $l$ are fitting coefficients; $k_a$ is the absolute permeability; $\mu$ is the viscosity; $S_w$ is the water saturation.

The TPG has a significant impact on production. Huang Y [18] found that when the TPG exists, single well production continues to drop as permeability goes down. Song H [19] believed that inaccurate assessment of well productivity may result if the impact of the TPG in water-bearing tight gas reservoirs is not taken into account, and the stable production time shortens as the initial production rate goes up. Huang G [20] concluded that both the coalbed methane production rate and cumulative production are always less when the TPG is considered because of the sharp decrease of pressure and increase of energy consumption. The study of Wang X [21] showed that in presence of larger TPG, more pressure drop is needed to maintain a constant-rate production.

Although great studies on the TPG effect have been achieved, improvement is needed in many aspects. Feng W [22] established an unsteady seepage mathematical model for gas, but did not consider the influencing factors of TPG. Feng G proposed a plate of well control radius with TPG taken into account and Ding J proposed a TPG model with pore pressure taken into account, both of which ignored the effect of water saturation[23,24]. The study by Zhu W [25] showed that the TPG increases as the permeability decreases or as the water saturation increases, but no definite correlation is proposed. Current TPG correlations, such as Eqs. (1a)–(1d), mainly considered the impact of permeability or viscosity. However, the water saturation is high for tight sandstone gas reservoirs, which affects the TPG. Besides, the influences of connate water and movable water on TPG are different. Therefore, further study of the TPG effect for tight sandstone gas is very necessary.

In this study, firstly the petrophysical properties of cores were obtained through the X ray diffraction (XRD), scanning electron microscope (SEM) and nuclear magnetic resonance (NMR) analyses. Secondly, the TPG and flow experiments were carried out. Thirdly, a TPG correlation was obtained. In addition, the impacts of permeability, dimensionless water saturation and clay minerals on the TPG were discussed. Finally, a gas production model was established with the TPG, slip and diffusion effects taken into account, and its applications using actual reservoir parameters were discussed.

## 2. Experimental

### 2.1. Materials

The natural cores were taken from Sulige gas field, a typical tight sandstone gas reservoir with high connate water saturation ($S_{wc}$) located in northern China. The Core properties are shown in Table 1.The water used in this study was prepared indoor according to the parameters of formation water from Sulige gas field seen in Table 2, which belongs to water type $CaCl_2$. The gas used was methane with a purity of more than 99.99%.

### 2.2. Apparatus

SEM and NMR tests were carried out in S-4800 manufactured by Hitachi Limited, MicroMR12-025 V-12 MHz instrument made by Niumag Limited, respectively.

The schematic drawing of experimental setup is shown in Fig. 2. It mainly includes cylinder, flow controller, U type tube, pressure sensors, core holder, flow meter and ISCO pumps. The traditional U type tube measures the small upstream pressure between 0.00005 and 0.005 MPa.

**Table 1**
The core properties.

| Core number | Diameter, cm | Length, cm | Porosity, % | Permeability, $10^{-3}$ μm$^2$ | $S_{wc}$, % |
|---|---|---|---|---|---|
| 1–1 | 2.54 | 3.66 | 5.13 | 0.19 | 67.78 |
| 1–6 | 2.54 | 4.24 | 17.71 | 1.90 | 48.38 |
| 1–7 | 2.54 | 3.38 | 8.14 | 0.36 | 60.53 |
| 1–10 | 2.54 | 3.68 | 3.03 | 0.13 | 77.02 |
| 1–12 | 2.53 | 4.55 | 15.97 | 0.52 | 57.78 |
| 1–14 | 2.54 | 5.68 | 6.24 | 0.09 | 79.98 |
| 1–16 | 2.54 | 4.06 | 13.63 | 1.02 | 52.71 |
| 1–20 | 2.53 | 4.32 | 9.47 | 0.70 | 55.83 |
| 2–3 | 2.48 | 4.68 | 8.16 | 0.16 | 71.43 |
| 2–4 | 2.48 | 4.72 | 8.28 | 0.18 | 68.55 |
| 2–8 | 2.49 | 4.93 | 8.30 | 0.25 | 63.65 |
| 2–9 | 2.48 | 4.68 | 2.75 | 0.04 | 83.77 |
| 2–12 | 2.48 | 5.00 | 6.81 | 0.06 | 81.88 |