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# Micro-flow kinetics research on water invasion in tight sandstone reservoirs

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ABSTRACT

The tight sandstone gas is a very critical unconventional gas resource. Nevertheless, liquid invasion may result in reduction of well productivity during the exploitation of tight gas. At present, the research on micro-flow kinetics in tight porous media is not very detailed, and there is no mathematical model for accurate description of liquid invasion in tight sandstone reservoirs. In this study, based on the micro-flow kinetics, the liquid invasion process is divided into two successive phases where the initial stage dominated by capillary and the pseudo steady stage influenced by pore pressure; a simplified kinetic model is proposed. The study shows that (i) the initial invasion stage is a transient process; (ii) during pseudo steady state, the key parameter becoming pore pressure drawdown, which should be considered in analysis of invasion in tight sandstone; (iii) the factor of permeability and static contact angle significantly influence invasion process, while viscosity has less impact on it.



## 1. Introduction

Liquid invasion is an important transport mechanism in many geophysical and environmental applications, such as carbon sequestration (Juanes et al., 2006), enhanced oil recovery (EOR) (Morrow and Mason, 2001). That is, fluid enters into porous media due to capillary force and mechanical pressure or injection pressure. It's important to study the fluid flow in order to enhance comprehensive understanding of the transport phenomena.

Tight sandstone gas (TGS) is a major type of unconventional gas (Economides and Wood, 2009). TGS refers to low permeability sandstone reservoir that can't be produced at economic flow rates after stimulation treatments (Holditch, 2006). For tight sandstone reservoirs, extraneous fluid invasion is the primary factor of formation damage (Odumabo et al., 2014; Wang et al., 2012; Zhao et al., 2009), which will reduce well deliverability appreciably. Thus, understanding the invasion in tight sandstone reservoirs is important for effective exploitation of tight gas.

Up to know, a great number of complementary studies utilizing Scaling group (Li and Horne, 2004; Mattax and Kyte, 1962; Schmid and Geiger, 2012; Standnes, 2010a,b), Lucas–Washburn model (Cai et al., 2010a,b,c; Lucas, 1918; Washburn, 1921), Handy model (Cai et al., 2012; Handy, 1960; Li and Horne, 2001), the normalized recovery model (Aronofsky et al., 1958; Civan, 1998; Standnes, 2010a,b), and the fractal model (Cai et al., 2010a,b,c) to deal with the transport phenomena have been proposed. These researches can be broadly divided into two categories: the approach of using Lucas–Washburn model and the use of a Darcy-scale model (Masoodi and Pillai, 2012). These researches have contributed to analyzing invasion by extraneous fluids into a permeable bed. Although the two-phase immiscible flow in non-tight porous media is well understandable, most of them concentrate in naturally fractured reservoirs developed by water injection. The study of extraneous fluids invasion is relatively limited (Parn-anurak and Engler, 2005; Windarto et al., 2012). Moreover, these researches may be restricted to qualify the invasion length of extraneous fluids due to neglecting the effect of pore pressure drawdown in the near wellbore area. In fact, once a permeable formation is penetrated by the bit, the near wellbore region will be subjected to a pore pressure drawdown induced by fluid production. Namely, the flow resistance will increase with increasing invasion length.

In this paper, analyzing the balance between driving forces (capillary force and down-hole fluid column pressure) and resistance forces (viscous force and pore pressure and inertial force) when extraneous fluids invade into tight porous media. The effect of pore pressure drawdown is investigated both experimentally and numerically. Furthermore, analogy to N. Fries and M. Dreyer's research (Fries and Dreyer, 2008), the invasion process is divided

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into two successive stages, and the related mathematical model is established.

## 2. Liquid invasion in tight sandstone reservoirs

### 2.1. Characteristics of tight sandstone reservoirs

Tight sandstone reservoirs are generally characterized by low porosity, low permeability, fine pore throat (Walls, 1982; Zou et al., 2012a,b), and thus are vulnerable to the damage from extraneous fluids (Bahrami et al., 2012). In this paper, the lab samples used in the research come from Upper Triassic Xujiahe ($T_3x$) tight sandstone gas reservoirs in the Western Sichuan basin, China, which is widely used as a model rock in tight gas research (Kang et al., 2012). The tight gas reservoirs are mainly composed of micro-scale pores and throats (Holditch, 2006), with some nano-scale pores and throats present (Zou et al., 2012a,b). However, limited by the experimental condition, this paper only investigates micro-scale pores and throats in tight sandstone.

### 2.2. Liquid invasion into tight sandstone

In this section, a physical simulation experiment (Fig. 1) was conducted by using a transparent micro model. By utilizing laser etched method, the flow network was generated based on the real thin section from a tight gas reservoir in the Western Sichuan basin, China. Due to the limitation of fabrication ability, the average pore throat radius was amplified to 100 μm. Length of micro model was 11 cm and it had 8 cm width, as shown in Fig. 2.

In our experiments, air and water represented the Non-wetting phase and Wetting phase, respectively. The deionized water was dyed with red to enhance visual observation and to facilitate image analysis. Table 1 lists the properties of the liquid. Experiment condition was set at room temperature (25 ± 0.5 °C). The first step before starting the experiment was to fire the micro model at 100 °C for 24 h. Then the deionized water was injected through the inlet and collected at the outlet. To simulate the effect of pore pressure drawdown during invasion, the initial injection pressure was approximately 0.001 MPa (a water head of 0.1 m) and subsequently no longer replenishment of water. Therefore, the driving force gradually reduced toward the outlet.

The images taken during invasion through microscope camera are displayed in Fig. 3.

At early stage of the trial ($t = 1–5$ s), the initial injection pressure and capillary force were the potential to cause fast water invasion into the model. After 5 s, the invasion distance was $8.743 \cdot 10^{-3}$ m. Very distinct fingers were observed (Fig. 3, $t = 5$ s).

In the middle stage of the test ($t = 6–15$ s), as viscosity resistance increased and driving force generated by fluid pressure decreased, the liquid velocity rapidly slowed down. After 10 s, the invasion distance was $10.72 \cdot 10^{-3}$ m. After 15 s, the invasion front already reached the outlet of the model. At this time, water almost occupied all pores and throats.

In the later stage of the experiment ($t = 16–35$ s), the flow ability of invading water was lower. Finally, the invasion process reached a pseudo steady state and some water remained in single or small clusters of pores, as shown in Fig. 3. It can be seen that the invasion front was not initially piston like. After approximately 10 s, a piston like front was established. This corresponded to approximately 2/3rd of the total model length. Some scholars have confirmed that liquid advances with a piston-like front in sandstone (Cai and Yu, 2012; Fernø et al., 2013), which is consistent with our experimental observations. Based on the observations, we can apply the capillary model to study the invasion in tight sandstone.

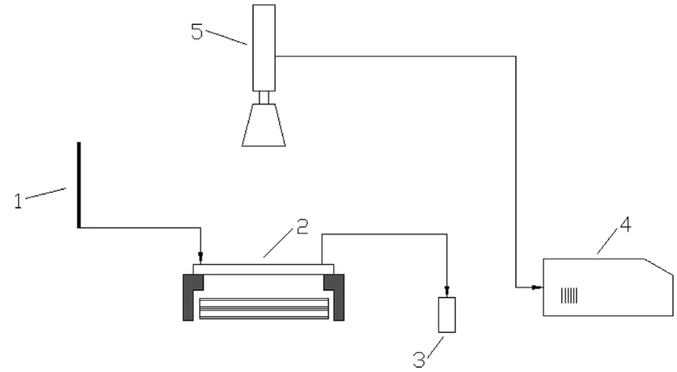


**Fig. 1.** Schematic diagram of the experimental setup. 1. Level controller, 2. Micro model, 3. Liquid collector, 4. Computer, 5. Microscope camera.

During drilling operations, mud filtrate will invade the porous media developing a damaged zone around the wellbore zone (Bennion, 1999). During the invasion, the effect of gravity can be omitted. Thus, there is capillary force, viscosity resistance, inertial force and external force (owing to the difference between downhole fluid column pressure and in situ pore pressure) acting on the system. At the beginning, the driving force (generated by capillary force and pressure differential) is the highest, thus the mud filtrate invades a permeable zone with high velocity. As time proceeds, invasion is gradually approaching the pseudo steady state. It's known that the dominate force is different in different time periods (Fries and Dreyer, 2008). Aim at filtration in tight sandstone, at the initial stage, the viscous resistance can be neglected due to tiny quantities of invading fluids. Thus the capillary, inertial and external forces are dominant. As the invasion front progresses further into the reservoirs, the invasion rate slows down fast owing to the effect of viscous and external forces, which play a key role in this period. It should be noted that the external force is no longer a fixed value due to the effect of pore pressure drawdown. During the later stage, invasion approaches the pseudo steady state, which is the result of competition between driving force and resistance. At this time, the length of fluid travel passing through rock media can be defined as critical invasion distance.

The early and late times can be referred to as "transient" and "pseudo steady" states. Also, the interim interval between these two periods can be called as "late transient" state (Saboorian-Jooybari et al., 2012). Since the first two states are almost instantaneous, they are collectively called as the initial stage in this paper.

## 3. Mathematical model

The model development uses the following assumptions:

(1) The tight porous media (tight sandstone) are comprised of a bundle of tortuous capillaries, all with the same equivalent radius $r_e$, and neglecting wall roughness.

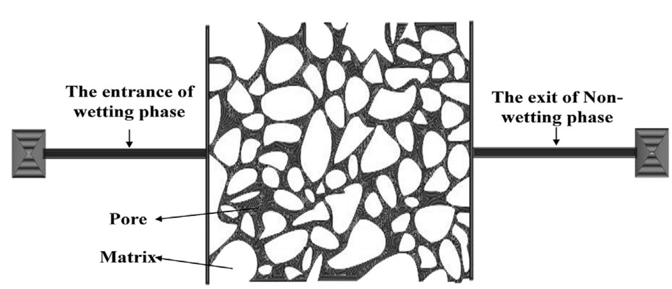


**Fig. 2.** Schematic diagram of micro model for invasion mechanisms.