A Numerical Study of the Influence of Nonlinear Fluid Flow Mechanism on Dynamic Production in Tight Oil Reservoirs

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Abstract:

The Fluid flow mechanism in unconventional reservoirs is much more complicated than that in conventional reservoirs mainly because of the co-existing of various sized micro-nano pores and natural / artificial fractures in the same reservoir. Due to the various flow patterns and seepage mechanism among different-sized medium, and also among different production periods in the same medium, the dynamic production is influenced by both the spatial variable and time variable. The capacity of the tight oil reservoirs is also thus greatly influenced. In this paper, numerical simulation is used to automatically identify the flow pattern according to the critical criteria of flow in different medium, and to simulate the dynamic production process with kinetic equations. The simulation is mainly focused on the following characteristics shown in the production process of tight oil reservoirs: I) high-velocity nonlinear, quasi-linear and low-velocity nonlinear flow regimes; II) flow patterns and seepage mechanism among different-sized medium in the same production periods; and III) flow patterns and seepage mechanism among different production periods in the same medium. The simulation results reveal that: a) as the start-up pressure gradient increases, the production gradually decreases; b) the higher the high-velocity non-Darcy coefficient, the lower the production; c) the higher the nonlinear seepage coefficient n value, the higher the production; d)in the same production stage, the flow regime in different locations and porous-fractured media have great differences. Also, at the same location, it changes drastically at different production stages. Based on the above analysis, a better understanding about the influence of the flow state and seepage mechanism on dynamic production and productivity is obtained, which will help optimizing the development method and improving the accuracy of oil well productivity forecasting.

Keywords:

Flow Regime Identification, Nonlinear Fluid Flow Mechanism, Numerical Simulation, Influence Factor Tight Oil Reservoirs.

1. Introduction

The system of pores and the natural/ hydraulic fractures in tight reservoirs are characterized with different scales. There is a big difference for the spatial distribution and geometric scale in the pores and fractures with different scales. Its storage space, percolation capacity and related physical parameters vary greatly. Scales of pores and fractures significantly affect the fluid composition and occurrence state. There is a big difference between flow regime and percolation mechanism in a production process, which causes the difference of oil and gas utilization and contribution to total production in those pores and fractures. Therefore, understanding the influence of flow state and seepage mechanism on production performance and productivity in the production process will help optimize the development mode and improve the accuracy of well productivity prediction.

2. Flow regimes and flow mechanisms

Due to the presence of nano-/-micro/milli- scale pore-fracture media in tight reservoirs, the flow regimes of fluids in different media are different under the same pressure gradient. The flow regimes of fluids at different development stages are different in the same media. The flow regimes of fluids with the different properties in a same media are also different. As [1], [2], and [3] demonstrate, the flow regimes of tight oil can be divided into three types: high-velocity nonlinear flow, pseudolinear flow and low-velocity nonlinear flow.

2.1 High-velocity nonlinear flow and mechanisms

Because of the high oil viscosity and slow flowing behavior of crude oil in tight reservoirs, the pressure gradient required to reach the high-velocity non-linear flow process is high in fracture media. The equation of the high-velocity nonlinear critical pressure gradient is:

$$G_d = 6.0537{w_f}^{-0.571}. \qquad (1)$$

The Forchheimer equation in [4] is usually used to describe the kinetics characteristic of high-velocity nonlinear flow.

$$-\nabla P_p = \frac{\mu_p \bar{v}_p}{K_{F,m}} + 10^{-3} \cdot \beta_{F,m} \rho_p \bar{v}_p |\bar{v}_p| \quad |\nabla P_p| \geq G_{pd} \ . \qquad (2)$$

The high-velocity nonlinear coefficient βF is a key parameter to describe the effect of high-velocity non-linear flow on the fluid flowing behavior. There are some differences between the determination method of high-velocity nonlinear coefficient of matrix and fracture.

The high-velocity nonlinear coefficient in the matrix pore system has been experimentally determined (permeability 0.03 mD to 100 mD) . As [4] and [5] demonstrate:

$$\beta_m = \frac{4.19\times10^{11}}{K_m^{1.57}} \ . \qquad (3)$$

The calculation method of the high-velocity nonlinear coefficient in the fracture can be obtained through the experimental measurement (fracture permeability 0.1mD to 10mD) . As [6] demonstrate:

$$\beta_f = \frac{4.19\times10^{12}}{K_f^{1.176}}. \qquad (4)$$

2.2 Quasilinear flow and mechanisms

When the pressure gradient is higher than the pseudolinear critical pressure gradient and less than the high-velocity nonlinear critical pressure gradient, the flow velocity and the pressure gradient are in a pseudolinear relationship. The flow behavior curve will not pass the coordinate origin and a threshold pressure gradient can be found. The kinetics equation can be expressed as follows,

$$\begin{cases} \overrightarrow{v_p} = -\frac{K_{f,m}}{\mu_p}\nabla P_p & \qquad Linear\ flow \\ \overrightarrow{v_p} = -\frac{K_{f,m}}{\mu_p}\left(\nabla P_p - G_{pc}\right) \quad G_{pb} \leq |\nabla P_p| \leq G_{pd} & \qquad Pseudolinear\ flow \end{cases} . \qquad (5)$$

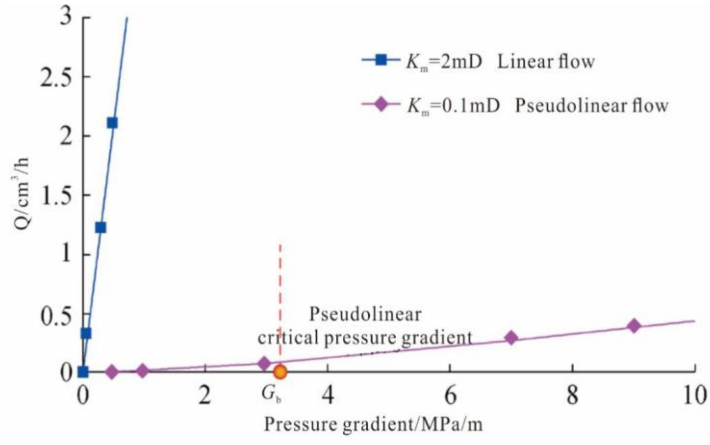

Figure. 1 Pseudolinear flow characteristics of tight oil.

2.3 Low-velocity nonlinear flow and mechanisms

When the pressure gradient is less than the threshold pressure gradient, the fluid cannot balance the additional resistance created by the interface adsorption layer or hydration film and it cannot flow. When the pressure gradient is higher than the threshold pressure gradient and smaller than the pseudolinear critical pressure gradient, the fluid velocity is low. The velocity and pressure gradient deviate from the linear relationship, and it shows the characteristics of low velocity nonlinear flow (Figure 2).

The experimental results show that the fluid flow is significantly affected by the pore structure. Under the low pressure gradient, the fluid cannot flow when the pore throat radius is small. When the pressure gradient is higher than the threshold pressure gradient, the fluids in larger throat will start flow first and then the fluids in smaller throat. As the pressure gradient increases, the fluid regimes in larger throat will convert first (Figure 3). The threshold pressure gradient, the pseudolinear critical pressure gradient and the throat radius show a power function relationship. It can be expressed by

$$G_a = 0.087 \cdot r^{-0.927}, \quad (6)$$

$$G_b = 2.9623 \cdot r^{-0.491}. \quad (7)$$

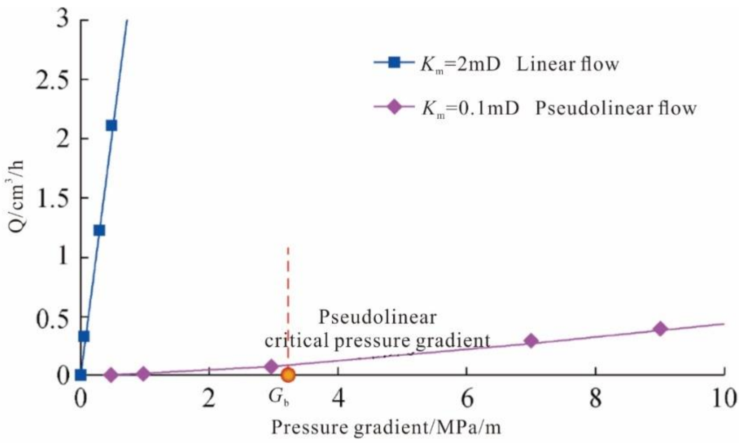

Figure. 2. Low-velocity non-linear flow characteristics of tight oil.

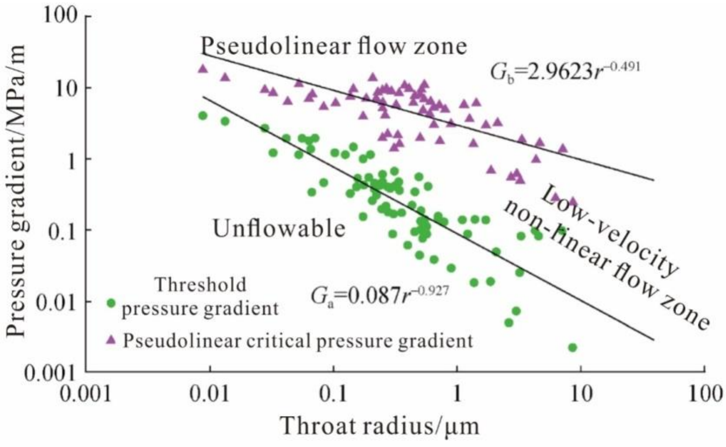

Figure. 3. Low-velocity nonlinear flow limit plate of tight oil.

In tight sandstone reservoirs, there are threshold pressure gradients in both micro-/nano- fractures and matrix pores regardless of oil-water two-phase flow or single oil phase flow. Only when the pressure gradient is higher than the threshold pressure gradient, the fluid can balance the resistance and start to flow. Fluid flow shows the low-velocity non-linear flow. The kinetics equation is

$$\begin{cases} \vec{\bar{v}}_o = 0 & |\nabla P_o| < G_{oa} \\ \vec{\bar{v}}_o = -\frac{K_{f,m}}{\mu_o}(\nabla P_o - G_{oa})^n & G_{ob} \geq |\nabla P_o| \geq G_{oa} \end{cases} . \qquad (8)$$

The threshold pressure gradient is related to reservoir physical properties, pore structure and water saturation. With the permeability decreases, the threshold pressure gradient increases. And the smaller the permeability is, the higher the threshold pressure gradient is. The tighter the reservoir is, the smaller the pore throat is, the higher the water saturation and the threshold pressure gradient. Experimental results show that the pore systems of tight rocks are composed of small-/ nano-pores, and the fluid cannot flow until it balances the threshold pressure gradient. As the pressure gradient increases, the fluid in more pores will start to flow and the core permeability becomes higher. Therefore, the core effective permeability is increasing (Figure 4). The effective permeability of tight rock is

$$K_m = A_m \cdot ln|\nabla P| + B_m, \qquad (9)$$

$$A_m = 0.0326\left(\frac{K_{m\infty}}{\mu_o}\right)^{1.0942}, \qquad (10)$$

$$B_m = 0.3436\left(\frac{K_{m\infty}}{\mu_o}\right)^{1.8427}. \qquad (11)$$

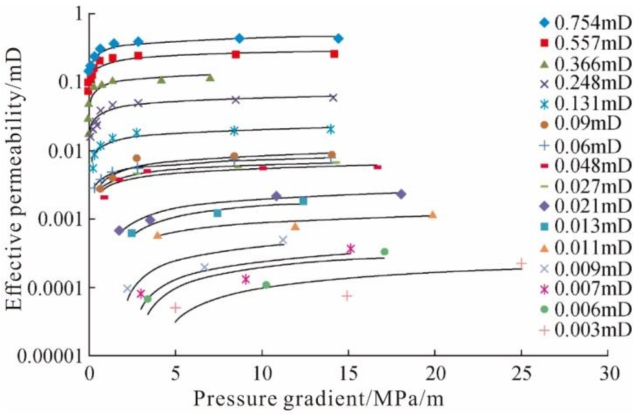

Figure. 4. Change of effective permeability of tight oil with displacement pressure gradient.

3 Adaptive simulation for flow in tight porous media using identification of flow states

Tight oil reservoirs contain different scale porous and fractured media which have different geometric and attribute characteristics. Based on the difference of geometric, attribute characteristics and flow regime between different scale media, the flow regime of flow through different media is identified by flow regime identification standard of tight oil. Based on the identification results, the proper model of flow through media is selected and the identification of flow regimes in different scale media and the self-adaption of complex flow mechanisms are built (as shown in Figure5).

3.1 A numerical model

Detailed steps are as follows:

1. Meshing: The meshing is generated based on reservoirs heterogeneity and conditions of internal and external boundaries.
2. Media division: Each grid is assigned a certain medium (different scale pores and fractures).
3. A parametric model:
   - Assigning geometric parameters (pore radius r_p, the throat radius r, the pore volume V_p, the fracture aperture w_f, and the fracture volume V_f) to each grid.
   - Assigning physical parameters (porosity ϕ, permeability K, saturation S_o) to each grid.
   - Assigning fluid parameters (density ρ_o, viscosity μ_o) to each grid.
   - Assigning the temperature T and the formation pressure P to each grid.

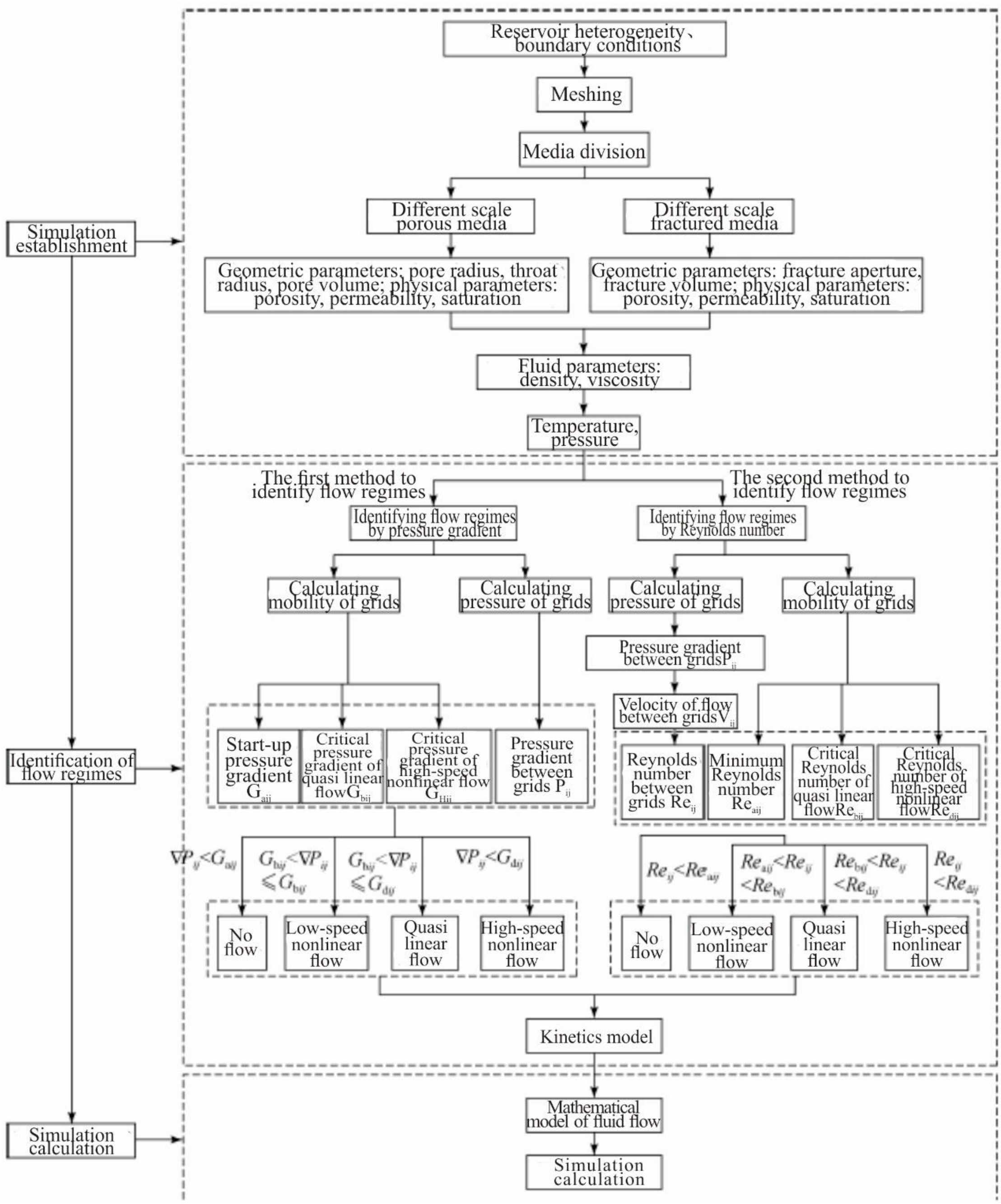

Figure. 5. Adaptive simulation for oil flow in tight porous media using identification of flow states.

3.2 Identification of flow regimes

The flow regime of tight oil flow is the macroscopic flow which can be identified by the pressure gradient or the Reynolds number. The main flow regimes of fluid flow through porous media are low-speed nonlinear flow and quasilinear flow. The main flow regimes of fluid flow through fractured media are low-speed nonlinear flow, quasilinear flow and high-speed nonlinear flow. Based on the flow regime, the proper dynamic model of fluid flow is selected. The detailed information is shown in Table 1.

Table. 1. Flow states and kinetic characteristics within different media.

Media	Pressure gradient	Reynolds number	Flow regime	Kinetic model
Porous media	$\lvert\nabla P_{ij}\rvert < G_{aij}$	$R_{eij} < R_{eaij}$	No flow	$\vec{v}_{ij} = 0$
	$G_{aij} < \lvert\nabla P_{ij}\rvert \le G_{bij}$	$R_{eaij} < R_{eij} < R_{ebij}$	Low-speed nonlinear flow	$\vec{v}_{ij} = -\frac{K_{ij}}{\mu_o}\left(\nabla P_{ij} - G_{aij}\right)^n$
	$G_{bij} < \lvert\nabla P_{ij}\rvert < G_{dij}$	$R_{ebij} < R_{eij} < R_{edij}$	Quasi linear flow	$\vec{v}_{ij} = -\frac{K_{ij}}{\mu_o}\left(\nabla P_{ij} - G_{cij}\right)$
Fractured media	$\lvert\nabla P_{ij}\rvert < G_{aij}$	$R_{eij} < R_{eaij}$	No flow	$\vec{v}_{ij} = 0$
	$G_{aij} < \lvert\nabla P_{ij}\rvert \le G_{bij}$	$R_{eaij} < R_{eij} < R_{ebij}$	Low-speed nonlinear flow	$\vec{v}_{ij} = -\frac{K_{ij}}{\mu_o}\left(\nabla P_{ij} - G_{aij}\right)^n$
	$G_{bij} < \lvert\nabla P_{ij}\rvert < G_{dij}$	$R_{ebij} < R_{eij} < R_{edij}$	Quasi linear flow	$\vec{v}_{ij} = -\frac{K_{ij}}{\mu_o}\left(\nabla P_{ij} - G_{cij}\right)$
	$\lvert\nabla P_{ij}\rvert > G_{dij}$	$R_{eij} > R_{edij}$	High-speed nonlinear flow	$-\nabla P_{ij} = \frac{\mu_o \vec{v}_{ij}}{K_{ij}} + \beta_{ij}\rho_o \vec{v}_{ij}\lvert\vec{v}_{ij}\rvert$

3.3 Numerical simulation

According to the flow regime identification results of different grids, the corresponding mathematical model is selected, and numerical simulation is conducted.

Where G_{cij} is the quasi-start-up pressure gradient between *i*th and *j*th element, $G_{cij} = 0.1518\left(\frac{K_{ij}}{\mu_{ij}}\right)^{-0.659}$, MPa/m.

4 Numerical Simulation

The effects of different flow states and different seepage mechanisms on well production dynamics in tight oil reservoirs are respectively simulated by using multi-medium flow identification and complex flow mechanism adaptive simulation software.

4.1 Simulation with different flow-regime identification parameters and criteria

For the macroscopic flow characteristics of tight oil, the pressure gradient or Reynolds number can be used as identification parameter to identify the flow state. Therefore, two different identification parameters and standards are used in the simulation.

1 Use different pressure gradient criteria to identify the flow state

The pressure gradient is used as a parameter to identify and compare three flow regimes at different scales: (1) Different porous media has corresponding pressure gradient and nonlinear flow parameters; (2) Pressure gradient limit and nonlinear flow parameters corresponding small-scale porous media are used for different media; (3) Pressure gradient limit and nonlinear flow parameters corresponding large-scale porous media are used for different media.

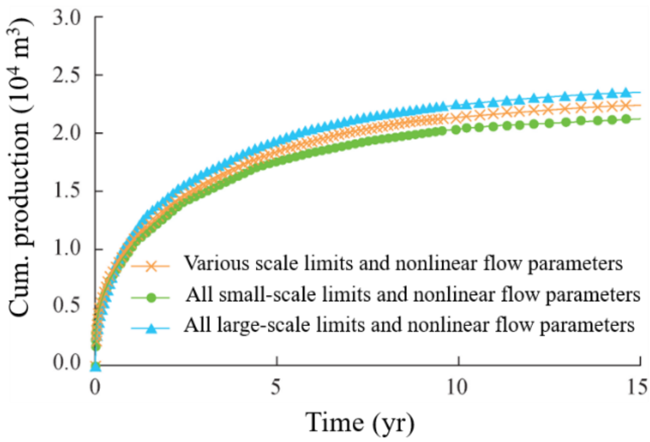

Figure. 6. Effects of pressure gradient limits and non-linear flow parameters on oil production.

It can be seen that when different pressure gradient limits and non-linear flow parameters used for different media, the difference in the flow regimes are obvious and has a large influence on the production dynamics. When different pressure gradient limits and non-linear flow parameters used for the small media, the increase of pressure gradient limits and non-linear flow parameters can enhance the low-speed flow characteristics and decrease the production. When different pressure gradient limits and non-linear flow parameters used for the large media, the decrease of pressure gradient limits and non-linear flow parameters can weaken the low-speed flow characteristics and increase the production (Figure 7).

2 Use different Reynolds Number standards to identify the flow state

The Reynolds Number is used as a parameter to identify and compare three flow regimes at different scales: (1) different porous media has corresponding Reynolds Number limits and nonlinear flow parameters; (2) Reynolds Number limits and nonlinear flow parameters corresponding small-scale porous media are used for different media; (3) Reynolds Number limits and nonlinear flow parameters corresponding large-scale porous media are used for different media.

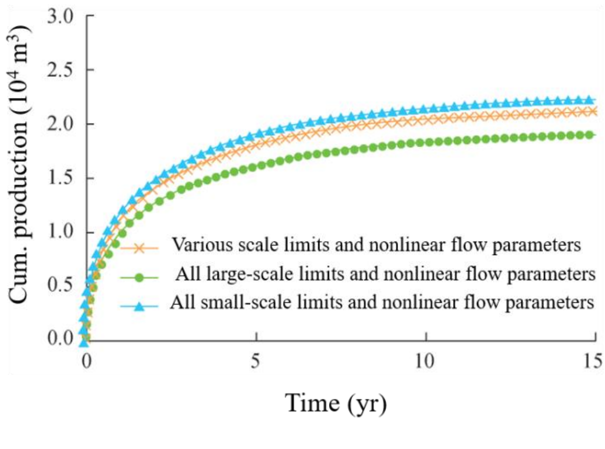

Figure. 7. Effects of pressure gradient limits and non-linear flow parameters on oil production.

It can be seen that when Reynolds Number limits and non-linear flow parameters used for different media, the difference in the flow regimes are obvious and has a large influence on the production dynamics. When different Reynolds Number limits and non-linear flow parameters used for the small media, the increase of Reynolds Number limits and non-linear flow parameters can enhance the low-speed flow characteristics and decrease the production. When different Reynolds Number limits and non-linear flow parameters used for the large media, the decrease of Reynolds Number limits and non-linear flow parameters can weaken the low-speed flow characteristics and increase the production (Figure 8).

It can be seen that, using different identification parameters and criteria can lead to a big difference in the identification results, and the corresponding dynamic equations and nonlinear flow parameters are also different, which affects the production performance.

4.2 Effect of Starting pressure gradient

The starting pressure gradient reflects the flow resistance. To analyse its effect on the production, different starting pressure gradients are simulated (Figure 9).

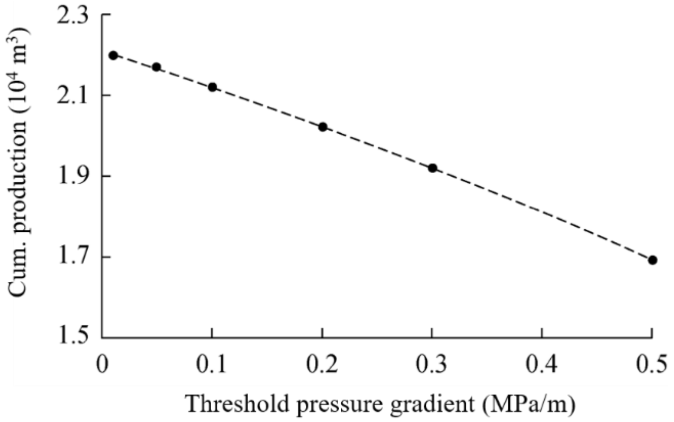

Figure. 8. Effect of starting pressure gradient on the production.

As shown in the figure, as the starting pressure gradient increases, the more resistance the fluid needs to overcome, and the lower the production. When the starting pressure gradient increases from 0.01 to 0.5MPa/m, the corresponding cumulative production decreases from 2.2 to 1.69×10^4 m^3, the production rate declines by 24%.

4.3 Effect of n value on the production

The n value reflects the strength of surface effect and flow resistance. Different n values are simulated to understand its effect on the production (Figure 10).

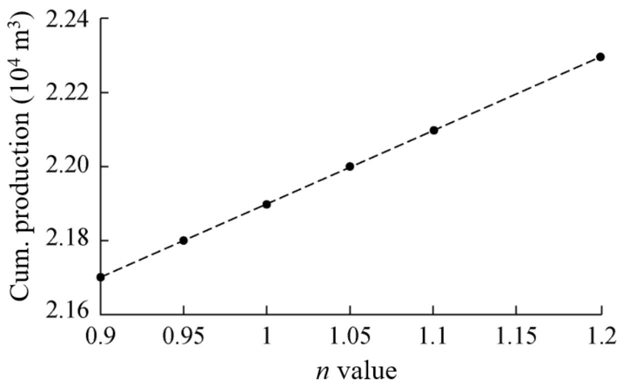

Figure. 9. Effect of n value on the production.

As can be seen from the figure, as the n value increases, the surface effect weakens and the fluid flows more easily, so the production is higher. The reasonable range of n value is usually between 0.9 and 1.2. When it increases from 0.9 to 1.2, the corresponding cumulative production increases from 2.17 to 2.23×10^4m3, and the production rate increases by 2.6%.

4.4 Effect of high-speed non-Darcy turbulence coefficient

The high-speed nonlinear coefficient β reflects the effect of high-speed non-Darcy flow on fluid flow. Simulations were conducted to analyze the effect to different β values on the production (Figure 11).

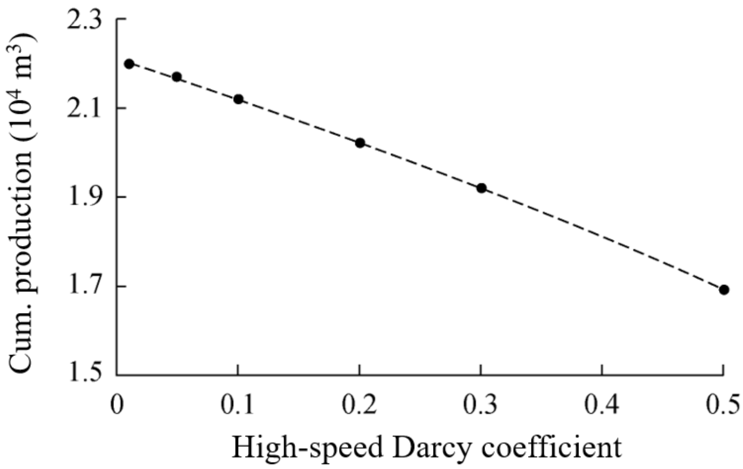

Figure. 10. Effect of high-speed non-Darcy turbulence coefficient on the production.

As can be seen from the simulation results, it is found that as the high-speed non-Darcy coefficient increases, the disturbance of high-speed non-Darcy turbulence flow becomes greater, and the production decreases. The range of high-speed non-Darcy coefficient is usually between 1×10^8~1×10^{11} m^{-1}. When it increases from 1×10^8 to 1×10^{11} m^{-1}, the cumulative production decreases from 2.1 to 1.5×10^4 m^3, and the production rate increases by 28%.

5 Conclusions

(1) Due to the presence of nano-/-micro/milli- scale pore-fracture media in tight reservoirs, the flow regimes of tight oil can be divided into three types: high-velocity nonlinear flow, pseudolinear flow and low-velocity nonlinear flow.
(2) Considering the geometric and attribute characteristics of the media and the flow states within them, the identification of flow states and the adaptive simulation for oil flow in tight porous media are formed by using the identification standards and mathematical modeling.
(3) using different identification parameters and criteria can lead to a big difference in the identification results, and the corresponding dynamic equations and nonlinear flow parameters are also different, which affects the production performance.
(4)Different seepage mechanisms have different effects on the production dynamics of oil Wells. The increase of start-up pressure gradient and high-speed non-Darcy turbulence coefficient leads to the decrease of well production. The increase of n value leads to the increase of well production.

Nomenclature

Letter symbols

G	pressure gradient, MPa / m
K	permeability, mD

∇P pressure gradient, MPa / m
r pore throat radius, μm.
w_f fracture aperture, μm

Greek symbols

$\vec{v}$ fluid flow velocity, m / s
μ fluid viscosity, mPa·s
β high-velocity nonlinear coefficient, m^{-1}
ρ fluid density, g / cm^3

Subscripts and superscripts

a threshold pressure gradient
b pseudolinear critical pressure gradient
d high-speed nonlinear critical pressure gradient
f fracture
g gas phase
i ith element
j jth element
m matrix
o oil phase
w water phase

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