Study on unsteady seepage characteristics and production decline of tight channel sandstone gas reservoirs

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Abstract. Tight channel sandstone gas reservoirs are mainly characterized by low porosity and permeability to ultra-low porosity and permeability, strong heterogeneity, and slow energy supply rate in the later stage, resulting in small gas well control reserves, and fast decline rate of gas well pressure and production. Therefore, it is urgent to carry out targeted research on production decline. In this paper, from the perspective of percolation mechanics, a mathematical model of low-velocity non-Darcy unstable percolation in tight channel sandstone gas reservoir is established, a diagram of the relationship between non-Darcy effect, flow boundary characteristics, and dynamic bottom-hole flow is established, and the dynamic influencing factors of bottom hole flow are analyzed. From a seepage mechanics point of view, this paper establishes a tight sandstone gas reservoir river unstable low-speed non-darcy seepage flow mathematical model of non-darcy effect and flow boundary characteristics and the relationship between the bottom hole flow dynamic chart and analysis of bottom hole flow dynamic influence factors, research shows that start-up pressure gradient, skin factor, the closed boundary of tight sandstone gas reservoir river bottom hole flow dynamic effect is bigger, The research content of this paper has certain guiding significance for realizing the effective development of tight channel sandstone gas reservoir.

1. Preface

Tight channel sandstone gas reservoirs are mainly sandstone lithologically closed gas reservoirs. Although the sand body is distributed in contiguous areas, it has poor connectivity and strong heterogeneity and is characterized by low porosity, low permeability, and extra-low porosity, and extra-low permeability[1]. The production of gas Wells declines rapidly in the early stage and slowly in the middle and late stage[2], which makes development difficult.

To realize the stable, high, and effective development of tight channel sandstone gas reservoir, a mathematical model of low-speed non-Darcy unstable seepage in tight channel sandstone gas reservoir is established based on the basic principles of percolation mechanics, and the influencing factors of production decline are analyzed. The research shows that the larger the dimensionless starting pseudo-pressure gradient is, the faster the decline rate is. The larger the skin coefficient is, the greater the decrease of flow rate is. The larger the radius of the outer boundary is, the longer the time for the pressure wave to reach the boundary is, and the velocity of flow decrease is faster. The results of this study are
of great significance for stable and high yield and enhanced oil recovery of tight channel sandstone gas reservoirs.

2. The establishment of the mathematical model
Assumptions: (1) A well in a homogeneous low permeability gas reservoir is produced at a fixed bottom hole pressure; (2) There is a starting pressure gradient in the flow of fluid; (3) The horizontal thickness of the reservoir is equal, the upper and lower layers are well separated, and the formation pressure distribution is uniform under the original conditions; (4) Ignoring the influence of gravity and capillary force; (5) Isothermal seepage; (6) Skin effect exists near the bottom of the well [3-4].

Therefore, according to the theory of seepage mechanics, the mathematical model of the effective well diameter of low permeability gas well with constant bottom hole pressure production considering the influence of skin effect can be established as follows:

Basic equation:
\[
\frac{1}{r_{De}} \frac{\partial}{\partial r_{De}} \left[ r_{De} \frac{\partial \psi_D}{\partial r_{De}} \right] + \frac{1}{r_{De}} \lambda_{qBD} e^{-S} = \frac{\partial \psi_D}{\partial t_D} \tag{1}
\]

Initial conditions:
\[
\psi_D(r_{De}, t_D = 0) = 0 \tag{2}
\]

Internal boundary conditions:
\[
\begin{align*}
\psi_D(r_{De} = 1, t_D) &= 1 \\
q_D &= -\frac{\partial \psi_D}{\partial r_{De}} \bigg|_{r_{De} = 1} - \lambda_{qBD} e^{-S} \\
Q_D &= \int_0^1 q_D dt_D
\end{align*} \tag{3}
\]

Outer boundary conditions:
\(2\) The closed formation with instantaneous pressure wave propagation:
\[
\frac{\partial \psi_D}{\partial r_{De}} \bigg|_{r_{De} = R} = 0 \tag{4}
\]

Type in the \(\psi_D\) —— Dimensionless quasi pressure;
\[
\psi_D = \frac{\psi - \psi_i}{\psi_i - \psi_{\text{wf}}} \tag{5}
\]

q_D —— Dimensionless yield;
\[
q_D = \frac{0.01273 T q_w}{kh(\psi_i - \psi_{\text{wf}})} \tag{6}
\]

\(\lambda_{qBD}\) —— Dimensionless starting pseudo pressure gradient;
\[
\lambda_{qBD} = \frac{r_w}{\psi_i - \psi_{\text{wf}}} \lambda_{qBD} \tag{7}
\]

3. Solution of the mathematical model
Using a similar method, the Laplacian space solution of low-velocity non-Darcy unstable seepage in closed low permeability gas reservoirs can be obtained [5]:
\[
\tilde{q}_D = be^{-S} \sqrt{g} F(r_{De} = 1) - M(r_{De} = 1) - e - \lambda_{qBD} e^{-S} / g \tag{8}
\]
\[
\bar{Q}_D = \frac{be^{-s} \sqrt{g} F(r_{De} = 1) - M(r_{De} = 1) - e - \frac{\lambda_{vbd} e^{-s}}{g}}{g}
\]

Type in:

\[
F(r_{De}) = -I_1 \left( e^{-s} \sqrt{g} r_{De} \right) K_1 \left( e^{-s} \sqrt{g} R_{De} \right) + K_1 \left( e^{-s} \sqrt{g} r_{De} \right) I_1 \left( e^{-s} \sqrt{g} R_{De} \right)
\]

\[
M(r_{De}) = \frac{ce^{-s} \sqrt{g} I_1 \left( e^{-s} \sqrt{g} r_{De} \right)}{I_1 \left( e^{-s} \sqrt{g} R_{De} \right)}
\]

\[
c = \frac{\lambda_{vbd} e^{-s}}{g} K_{1_{R_{De},e^{-s} \sqrt{g}}} h^{R_{De},} I_0 (\tau e^{-s} \sqrt{g}) d\tau
\]

\[
e = \frac{\lambda_{vbd} e^{-s}}{g} e^{-s} \sqrt{g} I_1 (e^{-s} \sqrt{g}) h^{R_{De}} K_0 (\tau e^{-s} \sqrt{g}) d\tau
\]

\[
b = \frac{1/g - H(r_{De} = 1) - d}{E(r_{De} = 1)}
\]

\[
E(r_{De}) = I_0 \left( e^{-s} \sqrt{g} r_{De} \right) K_1 \left( e^{-s} \sqrt{g} R_{De} \right) + K_0 \left( e^{-s} \sqrt{g} r_{De} \right) I_1 \left( e^{-s} \sqrt{g} R_{De} \right)
\]

\[
H(r_{De}) = \frac{cl_0 (e^{-s} \sqrt{g} r_{De})}{I_1 \left( e^{-s} \sqrt{g} R_{De} \right)}
\]

\[
d = \frac{\lambda_{vbd} e^{-s}}{g} I_0 (e^{-s} \sqrt{g}) h^{R_{De}} K_0 (\tau e^{-s} \sqrt{g}) d\tau
\]

4. Production decline characteristic

By using the Stehfest numerical inversion program, the solution of the model in Laplace space can be obtained by changing the relationship between dimensionless yield, dimensionless cumulative yield, and dimensionless time in real space[6]. For the solution of the flow boundary model, the iterative method is still adopted to first calculate the boundary radius of the flow leading edge, and then calculate the relationship between the change of dimensionless flow, dimensionless cumulative flow, and dimensionless time[7].

Figure 1 is the influence of the non-Darcy effect and flow boundary characteristics on bottom hole flow dynamics. From the figure, the flow boundary characteristics and start-up pressure gradient to the bottom hole flow dynamics in the early production almost has no effect, but with the extension of production time, non-darcy effect, and the influence of flow boundary characteristics gradually, the instantaneous pressure wave propagation model of non-darcy seepage flow is much faster than darcy seepage flow decreasing. It is similar to the closed boundary case of Darcy seepage, and the non-Darcy seepage model with flow boundary is slower than the instantaneous pressure wave propagation model, but also much faster than the Darcy seepage model. The flow behavior of non - Darcy seepage also shows that the control range for low permeability Wells is limited.
Figure 1. Influence of flow boundary characteristics on flow dynamics

Figure 2 is a double logarithmic diagram of the effect of dimensionless start-up pseudo-pressure gradient on bottom hole flow dynamics. The larger the non-dimensional pseudo pressure gradient GVB is, the earlier the non-Darcy flow rate deviates from the Darcy flow rate, and the faster the decrease rate is, and so on tends to zero.

Figure 2. Effect of S on bottom hole flow dynamics

Figure 3 is a double logarithmic diagram of the influence of skin factors $S$ on bottom hole flow dynamics. The size of $S$ almost has an impact on the whole production process (except the last three points). When the skin coefficient $S > 0$ (the formation near the bottom of the well is damaged), the total flow rate is lower than that when the skin coefficient $S = 0$ (the formation near the bottom of the well is neither improved nor pollution-free). The larger the skin coefficient $S$ is, the greater the decrease range of the flow rate is. When the skin coefficient is $S < 0$ (the formation near the bottom of the well is improved), the flow rate is always higher than that when the skin coefficient is $S = 0$. 
The smaller the skin coefficient \( S \) is, the larger the amplitude of the flow rate is above zero skin coefficient.

![Figure 3. Influence of skin factor \( S \) on bottom hole flow dynamics](image)

Figure 4 is a diagram of the effect of closed boundaries on bottom hole flow dynamics. Before the pressure wave propagates to the boundary, the bottom hole flows dynamic follows the law of the infinite boundary. The larger the radius of the outer boundary is, the longer the time for the pressure wave to reach the boundary is. When the pressure wave spreads to the boundary, the flow rate decreases faster and tends to zero quickly. Even if the outer boundary is infinite, the propagation range of the pressure wave is limited.

![Figure 4. Effect of closed boundary on bottom hole flow dynamics](image)

5. Conclusion

(1) Seepage mechanics in this paper, from the point of view, the establishment of tight sandstone gas reservoir river unstable low-speed non-darcy seepage flow mathematical model, draw the non-darcy effect and characteristics of the flow boundary on bottom hole flow dynamic relationship chart, the chart shows that instant pressure wave propagation model of non-darcy seepage flow than darcy seepage flow decline faster.
(2) The analysis results of influencing factors show that the larger the pseudo-pressure gradient of non-dimensional starting is, the faster the decreasing speed is. The larger the skin coefficient is, the greater the decrease of flow rate is. The larger the radius of the outer boundary is, the longer the time for the pressure wave to reach the boundary is, and the faster the velocity of flow decline is.

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