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Experimental study and numerical simulation of hydraulic fracturing tight sandstone reservoirs

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HIGHLIGHTS

- Non-Darcy flow in water-bearing cores from tight sandstone reservoir has been measured.
- Numerical simulation program considering non-Darcy flow has been developed.
- Development performance of MsFHW are compared based on different flow models.
- The proposed simulator has been validated against actual field production data.
- Water injection optimization is performed for F116 block based on developed simulator.

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ABSTRACT

Unconventional tight sandstone reservoirs have been developed during recent years and a large number of multi-stage fractured horizontal wells have been drilled to stimulate reservoir performance. However, fluid flow in low permeability porous media no longer obeys Darcy's law and instead conforms to low-velocity non-Darcy flow. Most commercial numerical simulation software for multi-stage fractured horizontal well development may cause inaccuracy in simulating performance of tight sandstone reservoirs. In this paper, the investigation of existing conditions of low velocity non-Darcy flow for oil flow in irreducible water saturation tight sandstone cores was conducted and discussed through lab-experiments. And existence of low velocity non-Darcy flow was proven. Then, based on the low velocity non-Darcy flow model, the multistage fractured horizontal well numerical simulator was developed and verified. The comprehensive comparison and analysis of the simulation results of Darcy flow and non-Darcy flow were presented including liquid production rate, oil production rate, water cut, reservoir pressure, oil saturation distribution, and dimensionless permeability coefficient. With considering the non-Darcy flow, the fluid flow in reservoir consumes more driving energy and the water flooding efficiency was reduced. Finally, a multistage fractured horizontal well water injection pilot test in Fan-116 block was analyzed to perform the non-Darcy flow numerical study on an actual tight sandstone reservoir. The results show that for the tight sandstone reservoir, the optimal water injection time is when the average reservoir pressure declined to 26.92 MPa based on maximizing the total field oil production in 15 years. This pressure level is close to the hydrostatic pressure and the optimized recovery is 20.51% in the final simulation time. This approach is an initial exploration for the "multi-stage fractured horizontal well development for tight sandstone reservoirs considering non-Darcy flow" and could be applied to other tight oil/gas reservoirs.

1. Introduction

The development of unconventional oil and gas has become a hot issue due to increasingly difficulty in developing conventional resources [1–3]. Tight reservoirs have played an important role in the unconventional oil and gas production which is defined as the oil in sandstone reservoirs with air permeability below $2 \times 10^{-3}\ \mu m^2$ [4,5]. The low permeability tight sandstone reservoir is defined as the permeability of the matrix is 0.1×10^{-3}–$10 \times 10^{-3}\ \mu m^2$ [6].

For the low-permeability tight sandstone reservoirs, fluid flow in porous media no longer obeys Darcy's law and instead conforms

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Nomenclature

∇p	pressure gradient, Pa/m	P_f	well grid pressure, Pa
K	permeability, m^2	Γ	boundary domain
K_r	relative permeability	ξ	low velocity non-Darcy coefficient, Pa/m
v	velocity, m/s	χ	dimensionless permeability correction coefficient
μ	fluid viscosity, Pa∗s	o,w,g	oil, water, gas
r_w	wellbore radius, m	Γ	boundary domain
r_e	reservoir out boundary radius, m	t	time, s
h	reservoir thickness, m	x,y,z	cartesian coordinate
S	saturation, fraction	ρ	density, kg/m^3
B	volume coefficient, m^3/m^3		
P_c	capillary pressure, Pa		
q	mass production rate, kg/s		
q_v	volume production rate, m^3/s		
ϕ	porosity, %		
c_t	total compressibility, Pa^{-1}		
P	pressure, Pa		
P_b	bottom hole pressure, Pa		

Unit conversion
Length 1[m] = 1[ft] × 3.2808
Volume 1[m^3] = 1[ft^3] × 35.3147
Viscosity 1[Pa∗s] = 1[cp] × 1000
Pressure 1[kPa] = 1[psi] × 0.1450
Permeability 1[m^2] = 1[md] × 10^{15}

to the one of low-velocity non-Darcy flow or nonlinear flow. The flow curve is a combination of a straight line and a concave curve, and the nonlinear flow exists in low permeability porous media. Pseudo threshold pressure gradient (Pseudo TPG) and minimum threshold pressure gradient (Min TPG) exist. Darcy flow model ignores the concave curve segment and the seepage curve is a straight line which goes through the origin. Quasi-linear is also a straight line which goes through pseudo threshold pressure gradient spot in X-axis. Non-nonlinear model reflects the real seepage characteristic in low permeability tight sandstone cores [7–9]. For the tight gas reservoirs, the nonlinear flow was also observed in water-bearing reservoirs [10,11]. Many scholars tried to explain the reasons which can be summarized as follows: (1) Solid liquid interaction. The interaction force between fluid and solid-molecules on the surface of porous media cannot be ignored because of the throat is in micro-scale or nano-scale. The molecules in fluid would interact with the solid surface and form a special structure which reduces the pore radius [8]. This structure is called "absorption boundary layer" by Wang et al., [9]. Water is a polar molecule which tends to orientate itself in an electrostatic field. This phenomenon can be found at a surface, especially those with clays which are widely existed in petroleum reservoir. Static water molecules can become oriented around surfaces, forming a quasi-crystalline structure which will significantly narrow the pores or completely occludes them. Only higher displacing pressure gradient can overcome the force gradually [12]. (2) Non-Newtonian characteristics. Huang [13] assumed that fluid attached to the pore wall (boundary layer fluid) shows stronger non-Newtonian properties under lower shear rate. And as the shear rate increases, more boundary layer fluid will flow.

To describe the non-nonlinear model with formula in low permeability tight reservoirs, various empirical formulas have been proposed including pseudo TPG model, piecewise model, and continuous model. Pseudo TPG model was presented first by former Soviet scholars and now many researchers have extended the work with considering this model [14–17]. The piecewise model and continuous model [13,18,19] are also established based on experimental data which can describe the nonlinear flow in low permeability tight reservoirs.

In that case, in fact, the use of conventional reservoir numerical simulation software which based on Darcy equation will lead to inaccurate production performance evaluation. At present, some non-Darcy flow numerical simulator for vertical well have been developed [20–22]. But for multistage fracturing horizontal well (MsFHW), the non-Darcy flow simulator has never been proposed so far. In recent years, development of tight oil/gas reservoirs has become a hot issue due to shortage of conventional resources. MsFHW is widely used to develop tight formations [23–26]. Compared with the vertical well, the MsFHW is more complex to simulate. The horizontal well will be perforated in different positions along the well and thus different stages were created [27–29]. In the numerical simulation, different fracture stages as inner boundary conditions will be dealt with in simulation and the Local Grid Refinement (LGR) technique should be used to improve simulation speed in simulation runs [30–34].

As an important technique to develop tight sandstone reservoirs, MsFHW has been widely used. However, fluid flow does not conform to Darcy flow in tight sandstone reservoirs, the application of traditional commercial software design of tight sandstone reservoirs in the reservoir simulation will result in great error. Therefore, the development of new software which is suitable for tight sandstone reservoir with multistage fracturing horizontal well is necessary. On the other hand, although water flooding is a mature secondary recovery method for conventional reservoirs, it has not been applied in tight sandstone reservoirs in a large commercial scale [35]. Therefore, it is necessary to establish multi-stage fracturing horizontal well numerical simulation technology to guide the tight sandstone reservoirs' development.

This paper was organized as follows: Firstly, the experimental investigation of existing conditions of the non-Darcy flow in irreducible water saturation cores was conducted and discussed using the tight sandstone cores from Shengli oilfield and the non-Darcy coefficients were obtained; Then, the three-dimensional three-phase multi-stage fractured horizontal well numerical simulator was developed with considering the non-Darcy flow. The development characteristics of MSFHW was presented by comparing the Darcy model, non-Darcy model, and strong non-Darcy model; Finally, the multi-stage fracturing horizontal well water flooding development laws is studied with the F116 block as an example, the water injection time based on the properly history matched geology model was optimized.

2. Low velocity non-Darcy experiments

2.1. Experiment

Four natural cores are taken from the tight sandstone reservoir in the F116 block in Shengli oilfield, with the diameter of about