Acta Technica 62 (2017), No. 5B, 707–714

Reservoir Simulation of Multi-level Flow Medium

Yanfeng Liu[2,5], Taizhong Duan[2], Bin Nie[3], Gaige Wang[4]

Abstract. In the view of fluid flow process, continental sandstone reservoir is multi-level flow medium, in which permeability in large range causes coexistence of multiple flow regimes. Understanding of these fluid flow mechanisms contributes to improving oil recovery. In present paper we studied the seepage law by numerical simulation and contributed several recommendations for water flooding development. Based on previous literatures we obtained the relationship between reservoir permeability and fluid flow mechanisms. According to permeability, a geological model was divided into regions that follow different flow regimes. Mathematic models of fluid flow simulation were established with linear Darcy flow in high-mid permeability regions, non-linear Darcy flow in low permeability regions and real pressure gradient in extra-low permeability regions. Then equations were discretized and solved. Using the in-house simulator, we demonstrate that simulation consisting of multiple percolation regimes causes lower volume efficiency and worse reservoir development compared with commercial simulator reflecting Darcy flow merely. Pressure dropping around wells results in decrease of permeability and increase of percolating resistance in the low and extra-low permeability regions. Asynchronous injection-production strategy was proposed to take advantages of reservoir stress sensitivity and imbibition between the high and low permeability regions.

Key words. multi-level flow medium, non-Darcy flow, non-linear flow, pressure sensitivity, asynchronous injection-production.

[1]Acknowledgment - I would like to thank China National Natural Science Fund Committee. The paper is sponsored by SINOPEC technology project No G5800-17-ZS-KJB008, National Natural Science Foundation Project No. 41702359, and project XDA14010204.

[2]Workshop 1 - Sinopec Petroleum Exploration and Production Research Institute, Beijing,100083, P.R.China

[3]Workshop 2 - College of Petroleum Engineering, Yangtze University, Wu Han,434100, P.R China

[4]Workshop 3 - Geophysics department, Schlumberger(China) Company, Beijing,100015, P.R China

[5]Corresponding author:Yanfeng Liu ;email:liuyf.syky@sinopec.com

1. Introduction

Conventionally, in numerical simulation, reservoir is divided into permeable and non-permeable cells by net to gross ratio. Fluid flow only in permeable cells is characterized by Darcy or nonlinear Darcy law [1,2]. However, in fact multi-level flow mediums always coexist in heterogeneous multilayer sandstone reservoir, including super high permeability section, middle-high permeability section, and low or super low permeability section. We proposed the concept of multi-level flow medium, which means all parts of a reservoir are permeable and they differ in the fluid flow mechanism. Actually, physical properties of the porous media have continuous variation in large range [3,4]. Flow regimes in low and extra low permeability regions obviously differ from that in regions with high-mid permeability [5−8]. Then study of the seepage law ignoring differences and interactions of fluid flow mechanisms between the high and the low permeability regions within one reservoir will no doubt cause non-ignorable errors. Therefore, we should divide a reservoir into intervals according to fluid flow regimes to study the fluid flow.

The paper is structured as follows. In the next section, we establish a new reservoir simulator consisting of multiple fluid flow mechanisms at different regions within a reservoir. Then, several cases is carried out to study the effect of fluid flow mechanism on water flooding efficiency. In the discussion section, we summarize the seepage law on multi-level flow medium sandstone reservoir and revealed some key points on the fine reservoir simulation. At last, the paper ends up with a short conclusion.

2. Characterization of fluid flow in multi-level flow medium sandstone reservoir

2.1. Equations of motion

Motion equation quantifies the properties of velocity in reservoir fluid flow simulation. It reflects the details of each type of flow mechanism. Different motion equations are assigned to regions with different permeability range. In the region where permeability is higher than 10 mD, fluid flow is described with linear Darcy's law; for region where permeability is ranged 1mD $\sim$ 10 mD, seepage flow conforms to nonlinear Darcy's flow; for region where permeability is at 0.01mD $\sim$ 1 mD, fluid seepage holds real threshold pressure gradient. In numerical simulation, the concept of region is represented by grid cell. This division may change depend on the special situation, even though it is obtained from many literatures. It means a grid system is divided into three types of region by the grid cell permeability.

To simulate fluid flow more accurately, the behavior of nonlinear Darcy flow and pressure sensitivity of permeability must be characterized concisely. Generally, such three types of model as pseudo pressure gradient, piecewise function and fitted continuous function could be found in public literatures . In the present study we choose one of the nonlinear continuous functions latest proposed by Ruizhong Jiang to depict the behavior of threshold pressure gradient and nonlinear fluid flow. The chosen model is deviated from capillary bundle model and boundary layer theory.

The motion equations of oil and water flow in multi-level medium are respectively characterized as follows (1) to (6), depending on permeability range.

(1) Oil phase: Water phase:

(2) Oil phase: Water phase: (3) Oil phase: Water phase:

2.2. Continuity equations

With the method of infinitesimal analysis on fluid flow process, the continuity equations (7) and (8) is derived for each phase in different regions of reservoir. Then the motion equations of (1) to (6) are substituted into the continuity equation, and we obtain these mass balance equations of (9) to (14) at each permeability region. These mass equations are what we strive for to depict fluid flow in sandstone reservoir with multi-level flow medium.

Oil phase: (7) Water phase: (8) (1) Oil phase: (9) Water phase: (10) (2) Oil phase: (11) Water phase: (12) (3) Oil phase: (13) Water phase: (14)

Based on the mathematical models above, we make a reservoir simulator. The simulator, which focus on multiple fluid regimes, could be used to investigate the complex seepage law during water flooding development. In next section, we study the seepage law by synthetic geological models processing severe permeability heterogeneity in radial, planar and vertical directions.

3. Cases study

In these synthetic models, the basic properties of reservoir and fluids are derived from one block of Liaohe oil field (Table1). In the case of 1D heterogeneous model, the model comprises three regions in radial direction (Fig 1). The permeability in region 1 is 80 mD, porosity is 0.16. The initial permeability of region 2 and region 3 respectively are 8mD and 0.8mD, and the initial porosity are 0.14 and 0.12. Both regions 2 and 3 conform to the nonlinear flow, whereas the real threshold pressure gradient exists in the region 3. The production well locates the center of the circular reservoir. We define 2D and 3D theoretic heterogeneous models in the same way. In the 2D model, permeability distribution stems from channelized reservoir. Injection and production well locate along the central of a river (Fig 2). In the 3D model, regions of permeability are an analogue of sedimentary sequence (Fig 3). Then both in-house simulator and commercial one execute the simulation. These results are illustrated to compare and discussion (Fig 4 to Fig 6):

4. Mathematical analysis

Conventionally, sandstone reservoir comprises of pay and non-pay. Fluids are assumed to flow only in pay. Petrophysical parameters dividing pay and non-pay are relatively high, such as 10% porosity and 50mD permeability, indicating large part of reservoir bulk is discarded. In this paper we suppose sandstone reservoir as

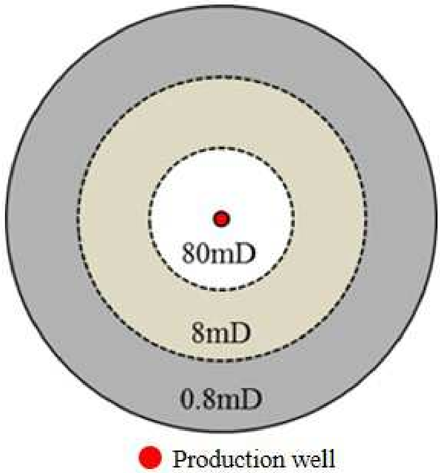

Fig. 1. 1D model of radial fluid flow

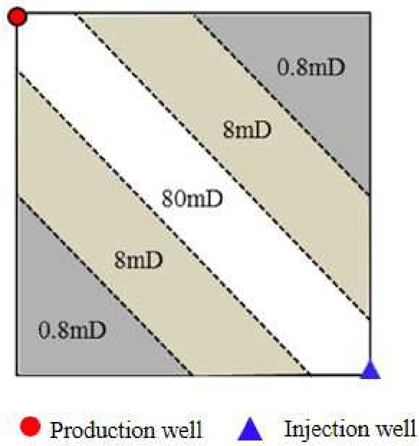

Fig. 2. 2D model of planar flow

a combination multiple regions that host different flow mechanisms. Because lowest permeability limit is 0.01mD in the new mathematic model of fluid flow simulation, almost no impermeable places exist in the reservoir. Therefore, the model holding extended flow space will provide more precise seepage laws than that by regular net pay.

By simulations of fluid flow in 1D, 2D and 3D heterogeneous sandstone reservoir with multi-level flow medium, we discover three main seepage laws. Compared with linear flow, nonlinear flow has aggravated percolation resistance involving permeability pressure sensitivity in those low and the extra low permeability regions, causing worse water flooding efficiency. Meanwhile, existence of real pressure gradient causes more residual oil locked by fluid yield stress than linear flow. Increasing

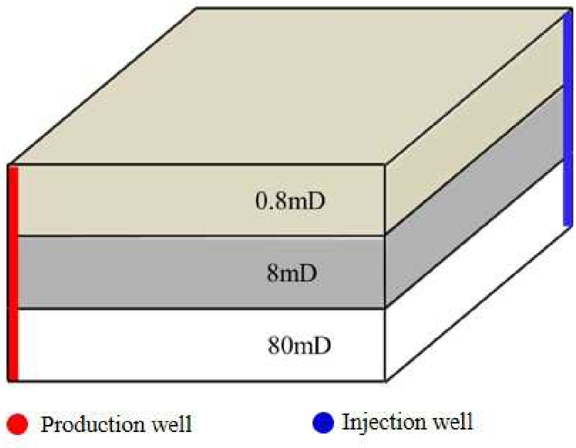

Fig. 3. 3D model of fluid flow in vertically heterogeneous media

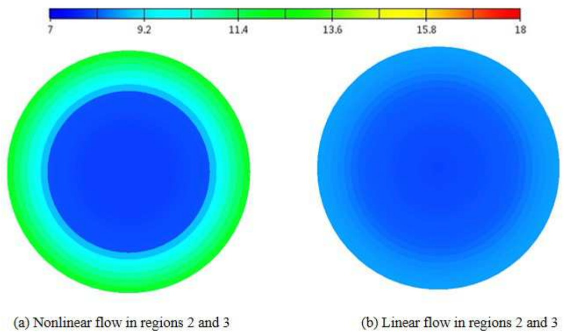

Fig. 4. Reservoir pressure distribution in single-phase fluid flow (after 360 days)

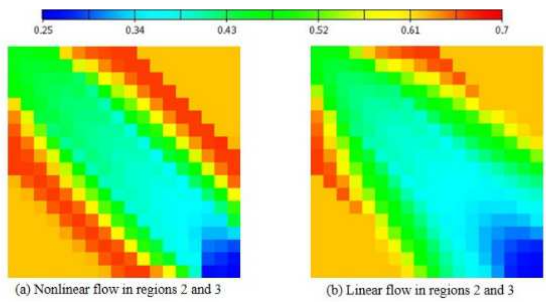

Fig. 5. oil saturation distribution (after 1800 days' production)

of percolation resistance in low and extra permeability region hastens the channeling and fingering in high permeability region, indicating earlier water breakthrough and smaller swept volume.

Based on the seepage laws above, we draw optimal water flooding strategies. Mechanism of stress sensitivity and remaining oil saturation difference between the

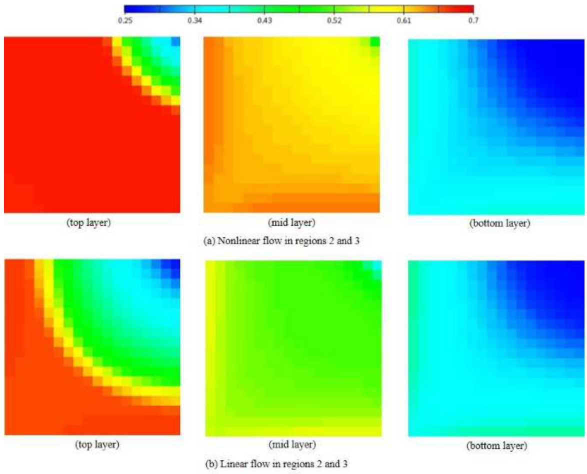

Fig. 6. Oil saturation distribution in vertically heterogeneous media model (after 1800 days' production)

high and the low permeability regions hints further strategy for improved water flooding. In the case of planar heterogeneity, we recommend maintaining formation pressure at relatively high level to reduce percolation resistances between high permeability and low permeability regions. While in the case of vertical heterogeneity, strategy of asynchronous injection-production with horizontal wells at the bottom higher permeability for injection while ones at the top low permeability layer for production at high water cut stage are proposed, during high water cut period.

Within the tolerance of time consuming, geologic grid sizes for simulation should be set as small as possible, to avoid error from permeability upscaling that determines the flow regime choice. Because small grids belonging region 1 and 3 may be averaged to region 2 where fluid bearing different flow regimes. In further, we will quantitatively study the influence of grid size on seepage law in another paper.

The new mathematic model should also take account of high rate non-Darcy flow and channeling flow in extra-high permeability region, where pore paths are always enlarged during long time water flooding development. Because particles in the pore spacing are swept out, even loose sand grain are carried out by the fluid. Permeability in the region has grown extremely high, causing fluid flow mechanism altered accordingly. Consequently, mechanism of high rate non-Darcy must be embraced in further study.

5. Conclusions

According to the permeability-range in sandstone reservoir with multi-level flow medium, we firstly established mathematical models to characterize fluid flow with coexistence of multiple seepage regimes at different permeability regions.

Second, we demonstrated that simulation focusing on Darcy seepage, non-Darcy seepage and non-linear percolation causes smaller volume sweep efficiency compared with the commercial simulator reflecting Darcy merely. Pressure dropping around wells results in decrease of permeability and increase of percolating resistance in the low and extra-low permeability regions. In addition, remaining oil is difficult to be displaced effectively since the presence of real pressure gradient.

At last, strategy of asynchronous injection-production was proposed to takes advantage of reservoir stress sensitivity and imbibition between high and low permeability regions.

References

[1] M. J. King, M. Mansfield: *Flow simulation of geologic models.* SPE reservoir evaluation *2* (1999), No. 4, 351–367.

[2] Z. W. Zeng, R. Grigg: *A criterion for non-Darcy flow in porous media.* Transport in porous media *63* (2006), No. 1, 57–69.

[3] Y. F. Liu, Y. T. Liu, L. Sun: *Multiscale fractal characterization of hierarchica heterogeneity in sandstone reservoirs.* Fractals *24* (2016), No. 3, 224–235.

[4] A. Prada, F. Civan: *Modification of Darcy's law for the threshold pressure gradient.* Journal of petroleum science and engineering *24* (1999), No. 4, 5205–5213.

[5] J. P. Davies, D. K. avies: *Stress-Dependent Permeability: Characterization and Modeling.* SPE journal *29* (2005), No. 9, 171–182.

[6] D. Swartzendruber: *Porous rock deformation and fluid flow—numerical FE-simulation of the coupled system.* Geologische rundschau *12* (2005) 606–612.

[7] S. Q. L, L. S. Cheng, X. S. Li: *Two-phase calculations and comparative flow experiments through heterogeneous orthogonal stratified systems.* Journal of Petroleum Science and Engineering *30* (2005), No. 4, 183–199.

[8] S. Q. L, L. S. Cheng, X. S. Li: *Literature review on correlations of the non-Darcy coefficient.*SPE Permian basin oil and gas recovery conference *316* (2008), Nos. 1–5, 198–210.

Received November 16, 2017