COUPLED NUMERICAL SIMULATION OF FRACTURING MULTILAYER RESERVOIR FLOW WITH LEAN-STRATIFIED WATER INJECTION

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Original Manuscript Submitted: 7/2/2015; Final Draft Received: 7/11/2018

Many multilayer sandstone reservoirs have reached extreme high water content and high recovery stage after long time waterflooding. These inner LPTOLs have been the main potential reserves. Lean-stratified water injection is one of the most important technologies to increase production and develop potential for multilayer oilfields with extreme high water content. However, traditional models cannot entirely solve the inner boundary conditions of lean-stratified water injection. Therefore, we established the injection wellbore constraint equations, which were coupled with the oil/water two-phase numerical reservoir models. Upon an embedded fracture model for simulating hydraulic fractures, a method to simulate the reservoir with horizontal fractures is shown. The influences of reservoir and fluid, horizontal fractures, and injection-production characteristics are analyzed for oil production and water-content dynamic. Considering the specific situation of lean-stratified water injection wells, the influences of different segments numbers, modes of combination in segment layers, and rhythm characteristics of remaining oil reserves and distribution are evaluated.

KEY WORDS: *Lean-stratified water injection, Well model, numerical reservoir simulation, horizontal fracture, low-permeability thin oil layers*

1. INTRODUCTION

Lean-stratified water injection (LSWI) enhances waterflooding recovery of multilayer reservoirs, which divides wellbore into 5 or more segments, of which each injects water for less than 6 layers. This technology can improve waterflood vertical sweep efficiency, and has been widely used in many multilayer sandstone reservoirs with high water content, such as the Chinese Daqing Oilfield with higher than 40% waterflood recovery (Gao et al., 2016). Furthermore, it is required to match the development dynamic history for every oil layer in the process of reservoir numerical simulation during waterflooding development, for the sake of increasing the prediction precision for remaining oil in each sand body, especially in the main sand body (Han et al., 2010).

Low permeability thin oil layers (LPTOLs) mainly contain argillaceous siltstone, mudstone, and calcium powder sandstone with oil immersion existing in the multilayer sandstone reservoir. LPTOLs' permeability and oil content are obviously worse than the high permeability thick layers crosslink with LPTOLs. When the water content of the multilayer sandstone reservoir reaches extreme high in the later development stage, LPTOLs become the primary objects for waterflooding development. Due to the ineffective circling of injection water, the remaining potential of LPTOLs becomes more prominent.

1091–028X/18/$35.00

NOMENCLATURE

B	volume factors
H	depth
L	distance between well and grid boundary
P	oil pressure
P_{wf}	inject pressure adjusted by water chokes
q	rate
R	residual for grid
s	saturation
T	transmissibility between grids

Greek Symbols

γ	gravity
ϕ	is the porosity
λ	threshold pressure gradient
ξ	pressure gradient in well segment

Subscripts and Superscripts

seg	injector well segment label
lay	oil layer label
l	phase label
n	time step
N	total segment number of one LSWI well
M	total number of layers
w	water phase label
o	oil phase label
a	center grid label
b	total number of adjacent grids
WI	well index
i	adjacent grid label

All four sets of well patterns, base well, first infilling well, secondary infilling well, and tertiary infilling well, perforate the LPTOLs from initial development. The perforating thickness ratio (PTR, the ratio of the perforation thickness to the total reservoir thickness) gradually increases, while the average PTR reaches more than 55% after tertiary infilling wells perforate the reservoir. According to the monitoring data obtained from coring wells in the Daqing Oilfield, geologic features of different types of LPTOLs are analyzed. Connective-type and expanded-type LPTOLs have been better developed by waterflooding in the past, and the waterflooding producing ratio (WPR, ratio of the number oil layers produced by waterflooding to the number of whole layers perforated) is 65.4%; and the WPR of both the stratified type and lens-type LPTOLs is only 11.8%, so there is enough potential in the lens-type LPTOLs. Because the lens-type LPTOLs' sand body size is too small, the stratified-type LPTOLs are the key of independent development.

The water injection rate entering each oil layer cannot follow the mobility allocated principle set in conventional simulation models. This defect leads to inaccuracy for matching the remaining oil distribution and injected water rate in reservoir numerical simulation. Reservoir numerical simulation methods considering LSWI contain injected water deduplication by many injection wells and coupled simulation for water chokes, injection well, and reservoir. The former is suitable for reservoir with enough injectivity test data, and the water injection rate can be calculated by real-time monitoring test data. These rates can be used as inner boundary conditions in models (Stone et al., 1989; Francis et al., 2012; Bielenis et al., 2013). Practically, injectivity test data are very few, and do not represent the complete injection process (Gao et al., 2015). The latter needs enough data of injection well devices, such as diameters of water chokes, which should be used to calculate the pressure loss coupled with well bottom pressure (BHP) and reservoir pressure (Lin et al., 2011; Zhao et al., 2012). This results in quit complex calculation. In this article, we propose a simple method of modeling LSWI considering inner wellbore constraint conditions. Because this method can be used to simulate the development effect and remaining oil distribution in reservoir with extreme high water content, a reliable evidence will be provided for reservoir history matching and project design.

Because of the low fracturing pressure gradient of low permeability shallow oil layers, horizontal fractures are easily formed after hydraulic fracturing. In addition, the reservoir's stress gradient has been changed after enhanced oil extraction. When the vertical stress is less than the horizontal stress, the hydraulic fracturing of the reservoirs will produce horizontal fractures (Wright et al., 1997), such as the Belridge Oilfield in the United States. The fractured surface of the horizontal fracture is perpendicular to the direction of the wellbore, and has a great influence on the fluid flow in the low permeability oil reservoir. The methods of dealing with horizontal fractures in numerical simulation of reservoirs mainly include local grid refinement (LGR), multi-segment well model and fracture permeability equivalent model (Karimi-Fard et al., 2011), among which the LGR method is the addition of high-permeability fractures between the matrix layers to replace the horizontal fractures. The simulation accuracy of this method is high, but it does not apply to a large quantity of fractures and complex layer direction. The multi-segment well model is used to approximate the influence of horizontal fractures in the matrix into multi-segment wells. However, there are some differences between the tube flow in the wellbore and the high velocity flow within the fracture (Edwards et al., 2013), and the simulation error of multi-segment well model is obvious. The equivalent method of fracture permeability is simulated by increasing the permeability of the matrix grid near the fractures, which cannot reflect the flow in the longitudinal direction between the fracture and the matrix. In order to overcome these shortcomings, we suggest a new horizontal fracture model coupled with LSWI based on the embedded fracture model (Lee et al., 2001; Hajibeigi et al., 2011). It can be applied for LSWI of multilayer reservoir with high water content.

2. COUPLED NUMERICAL MODEL OF LSWI AND HORIZONTAL FRACTURES

A new well model considering LSWI as the inner boundary condition is given by Gao and Ye (2016), and the well model [Eq. (1)] considering LSWI is deduced from Taylor expansion upon these assumptions: **a.** injection well is divided into N segments vertically, and every segment contains M oil layers; **b.** the total injected water rate is known, and remains constant; **c.** every segment is separated by packers in tubing-casing annulus, so there is no fluid flowing through between them; **d.** only oil and water phases are considered in the model, and the capillary is neglected.

$$P^{n+1}_{wf_{(seg)}} = P^{n}_{wf_{(seg)}} - \sum_{lay=1}^{M}\left[\left(\frac{\partial q_{w_{(seg)(lay)}}}{\partial S_{w_{(lay)}}}\right)^{n}\left(S^{n+1}_{w_{(lay)}} - S^{n}_{w_{(lay)}}\right) + \left(\frac{\partial q_{w_{(seg)(lay)}}}{\partial P_{o_{(lay)}}}\right)^{n}\left(P^{n+1}_{o_{(lay)}} - P^{n}_{o_{(lay)}}\right)\right] \Big/ \sum_{lay=1}^{M}\left(\frac{\partial q_{w_{(seg)(lay)}}}{\partial P_{wf_{(seg)}}}\right)^{n} \tag{1}$$

Assuming that the pressure gradient in the tubing-casing annulus is constant at different time steps, the injected pressure after water chokes is shown as follows.

Wellbore pressure model:

$$P^{n+1}_{wf_a} = P^{n+1}_{wf_{(seg)}} + \xi_w\left(H_a - H_{(seg)}\right) \tag{2}$$

Flow model of reservoir grid without any fracture:

$$q^{n+1}_{w_a} = q^{n+1}_{w_{(seg)(lay)}} = WI_{w_a}\left(P^{n+1}_{wf_a} - P^{n+1}_{o_a} - \lambda\frac{L_a}{2}\right) \tag{3}$$

Oil phase residual equations of reservoir grid, without producer and injector, are conventional as the black oil model, and injected pressure needs to be considered only for these grids with injector. These terms are functions of water saturation and oil pressure, so the unknown parameters are water saturation and oil pressure when solving the nonlinear equation set consists of these residual equations of every grid. Coupled with LSWI well model and reservoir grid flow model, the water phase residual equation for reservoir grids with injector is expressed as:

$$\begin{aligned} R_{w_a} = {} & \frac{V_a}{\Delta t}\left[\left(\frac{\phi S_w}{B_w}\right)^{n+1}_a - \left(\frac{\phi S_w}{B_w}\right)^{n}_a\right] - \sum_{i=1}^{b}\left[T_{w_{ai}}(\Delta P - \gamma_w \Delta Z)\right]^{n+1} \\ & - WI_{w_a}\left\{P^{n}_{wf_{(seg)}} + \xi_w\left(H_a - H_{(seg)}\right) - P^{n+1}_{o_a} - \lambda\frac{L_a}{2}\right. \\ & \left. - \sum_{lay=1}^{M}\left[\left(\frac{\partial q_{w_a}}{\partial S_{w_a}}\right)^{n}\left(S^{n+1}_{w_a} - S^{n}_{w_a}\right) + \left(\frac{\partial q_{w_a}}{\partial P_{o_a}}\right)^{n}\left(P^{n+1}_{o_a} - P^{n}_{o_a}\right)\right] \Big/ \sum_{lay=1}^{M}\left(\frac{\partial q_{w_a}}{\partial P_{wf_{(seg)}}}\right)^{n}\right\} \end{aligned} \tag{4}$$

Horizontal fractures and matrix flow models include cumulative items, flow items, and source sink items, respectively. The matrix flow equation characterizes the flow of fluid between adjacent matrix units and the channeling between the matrix and the adjacent fractures. The fracture flow equation characterizes the fluid flow between the adjacent fracture units, the well production through the fracture, and the channeling between the fracture and the matrix. The residual equations for each grid in the matrix and the fracture are all implicitly discrete as shown in Eqs. (5) and (6).

$$R_{m,l} = \frac{\phi_{m,c} V_c}{\Delta t}\left[(b_{m,l,c} S_{m,l,c})^{n+1} - (b_{m,l,c} S_{m,l,c})^{n}\right] - \sum_{i=1}^{b}\left[T_{m,l,i,c}\left(\Delta P_{m,l,i,c} - \gamma_l \Delta z_{m,i,c}\right)\right]^{n+1} - q_{m,l,w}^{n+1} + q_{m,l,c,NNC}^{n+1} \quad (5)$$

$$R_{f,l} = \frac{\phi_{f,c} V_c}{\Delta t}\left[(b_{f,l,c} S_{l,f,c})^{n+1} - (b_{f,l,c} S_{f,l,c})^{n}\right] - \sum_{i=1}^{b}\left[T_{f,l,i,c}\left(\Delta P_{f,l,i,c} - \gamma_l \Delta z_{f,i,c}\right)\right]^{n+1} - q_{f,l,w}^{n+1} + q_{f,l,c,NNC}^{n+1} \quad (6)$$

3. HORIZONTAL FRACTURE MODEL VALIDATION

According to the basic physical parameters of the LPTOLs in the Daqing Oilfield, a mechanism case is established to verify the reliability of the model. Assuming that the porosity of the reservoir is 0.25, the permeability of the matrix and the fracture are 10 mD and 10000 mD, the thickness of the one LPTOL is 0.5 m, the long axis and minor axis of the horizontal fracture are 180 m and 90 m, respectively; the dimensionless conductivity of the fracture is 0.3. The results of the horizontal fracture model are compared with the LGR model. Figures 1 and 2 show the simulation results of our model and the reference model. It can be seen that the model is close to the reference model.

4. CASE STUDY

Remaining oil caused by an incomplete waterflood well pattern cannot be swept effectively. Taking Overflow 2 oil layer as an example (Fig. 3), only one injector locates in the center of the interactive oil layer, whose low-permeability part is connected with high-permeability parts at both sides, so there is no producer corresponded with the injector in low-permeability parts. Because of this, much remaining oil concentrates in I and II parts. Although there is no

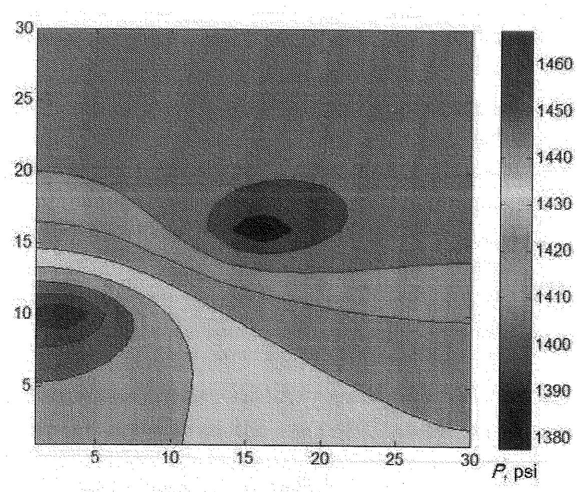

FIG. 1: Pressure map calculated by the model in this paper

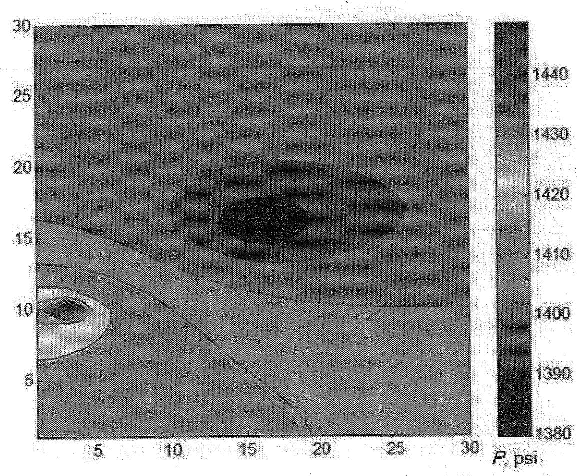

FIG. 2: Pressure map calculated by the reference model

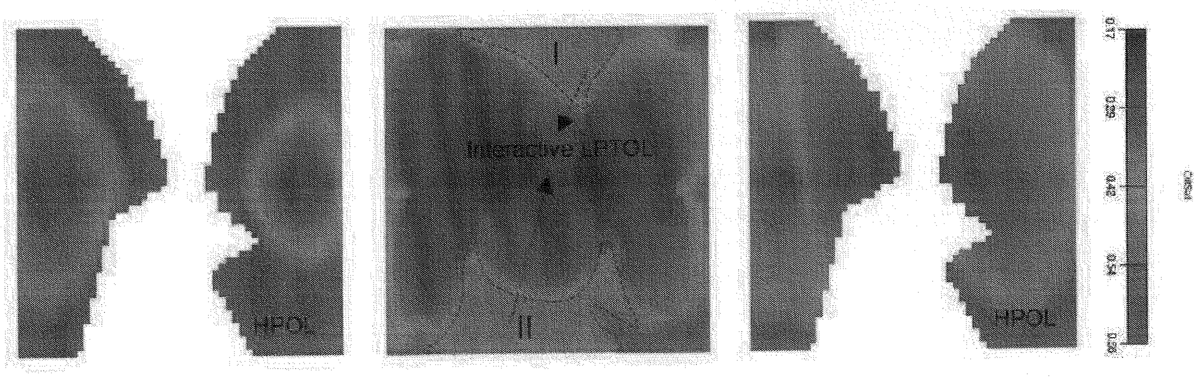

FIG. 3: Oil saturation distribution of 2 LPTOLs (Overflow 1, 2) and high permeability oil layers (HPOLs) after developing 20 years with 5 segments LSWI

injector corresponding with producer in high-permeability parts, water injected for low-permeability parts will flow to sides because of their high permeability, and effective waterflood will be formed, with remaining oil only left in top and bottom corners of high-permeability parts.

Vertical heterogeneity causes the injected water to flow mainly into the thick high-permeability oil layers rapidly. Even these layers have reached extreme high water content, so the adjacent LPTOLs have not been swept. Overflow 1 and 2, upper and lower oil layers of thick high-permeability oil layer (Fig. 4), have not been swept when five segments are divided for LSWI. That is because bottom wellbore pressure of injector is less than threshold pressure, so water cannot be injected in these LPTOLs.

Independent LPTOLs have poor physical properties, so they are difficult to sweep, and the effect of waterflooding is bad even in LSWI. Sheet 3 is an independent LPTOL, which cannot be swept when the injector is divided into five segments by LSWI (Fig. 5). It can be swept after subdividing into 10 segments, however, effective waterflooding system has not been formed. More stimulating measures are necessary, such as hydraulic fracturing and gas injection.

Horizontal heterogeneity leads waterflooding slowly in interactive LPTOLs. Continuous 3, Partial 3 and 5 are all interactive LPTOLs. These connected high-permeability parts have reached high water content, but low-permeability parts have much remaining oil in I, II, and III, because of low relative permeability and initial oil saturation. This kind of remaining oil is widespread and has great reserve. Therefore, unconventional independent development technologies may be needed to enhance recovery.

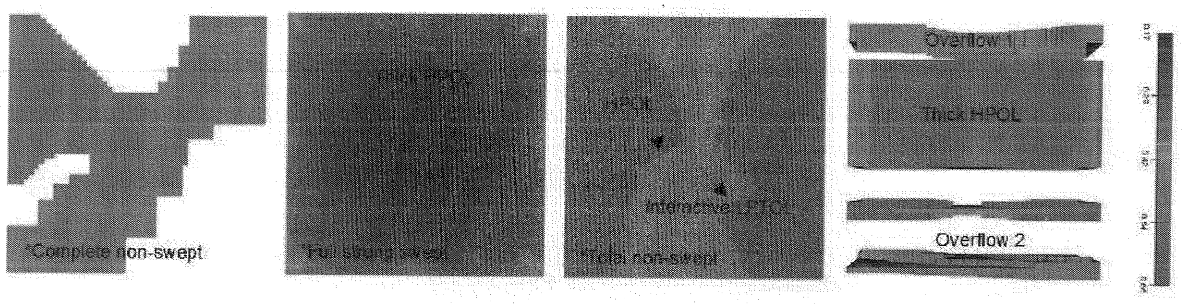

FIG. 4: Oil saturation distribution of one LPTOL after developing 20 years with 5 and 10 segments

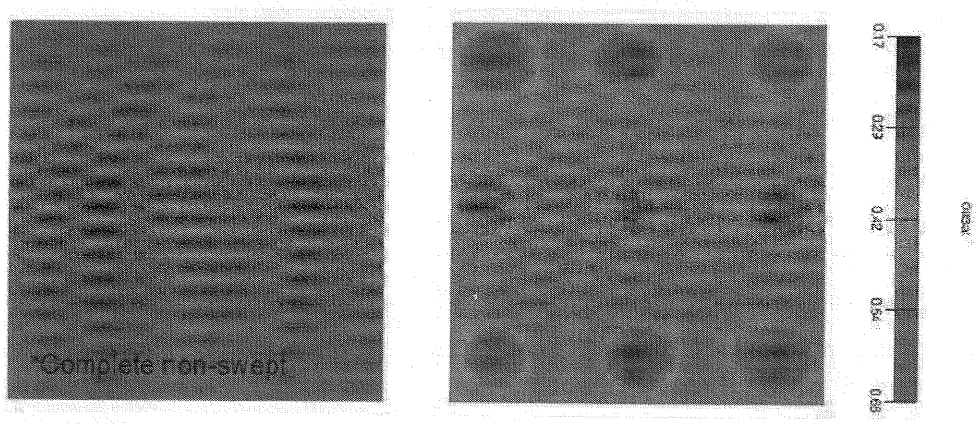

FIG. 5: Oil saturation distribution of 3 LPTOLs after developing 20 years with 10 segments

5. CONCLUSIONS

The key of enhancing waterflooding recovery is to increase vertical sweep efficiency, the remaining oil caused by vertical heterogeneity and poor physical properties can be waterflooded by adjusting the structure of segmentation. However, other stimulating technologies are necessary to develop the remaining oil caused by poor correspondence between injector and producer, horizontal heterogeneity. LPTOLs are primary potential for multilayer reservoirs with extreme high water content; LSWI will help in getting greater recovery. More segments are not the goal of LSWI, and the structure of wellbore segments must correspond with the distribution of remaining oil, with weaker vertical heterogeneity. Influencing factors of remaining oil are summarized: poor correspondence between injector and producer, vertical heterogeneity, horizontal physical characteristics, horizontal permeability and porosity.

It is possible to create horizontal fractures in the shallow reservoirs with high fractured pressure or vertical stress decreasing after enhancing oil recovery (EOR). An efficient method of numerical simulation for reservoirs with horizontal hydraulic fractures is presented here, with an embedded fracture model for simulating vertical fractures; our method simulates the development of reservoirs with horizontal fractures accurately. Multiphase flow equations, coupled reservoir matrixes, and fractures are dispersed, and the numerical model with seven-diagonal sparse coefficient matrix with attached columns and rows is constructed for 3D reservoir matrix and fracture system. We apply the model to simulate low-permeability reservoir with horizontal fractures developed by one injection well and one production well. Our results with and close to the local grid refinement model. Finally, the case of low-permeability reservoir developed by two injection wells and one production well under high injection-production pressure difference is given, in addition to the influence for the production dynamic under different fracture length/well space ratios and dimensionless conductivities.

ACKNOWLEDGMENT

The authors would like to acknowledge the funding by the project (Grant No. 51404232) sponsored by the Natural Science Foundation of China (NSFC), the National Science and Technology Major Projects (Grant No. 2011ZX05010-002; Grant No. 2011ZX05046-003).

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