Effect of horizontal heterogeneity on productivity of cyclic superheated steam stimulation horizontal wells: numerical analysis

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Abstract

In recent decades, horizontal well has been widely used for heavy oil recovery. Besides, new developed thermal carriers, such as multi-component thermal fluid and superheated steam, have been proved effective in some oil fields. However, when the length of the horizontal wellbore is quite long or when the reservoir is of serious heterogeneity, the steam fingering phenomenon can be serious. The existence of horizontal heterogeneity leads to the low recovery efficiency and serious steam fingering phenomenon. In this paper, a numerical model is built to study the effect of horizontal heterogeneity on the productivity of production well during the cyclic superheated steam stimulation process. Simulation results show that (a) the effect of permeability distribution pattern in the horizontal direction on the recovery degree can be neglected. This may be caused by the infinity of fluid fluidity in the wellbores. (b) The effect of permeability distribution pattern in the horizontal direction on the cyclic oil production can be neglected. (c) The temperature is the highest in the high permeability section, while the temperature is the lowest in the low permeability section. However, given the fact that the wellbore conductivity is assumed to be infinity, the effect of permeability distribution pattern on the performance of the production well can be neglected.

Keywords Heavy oil · Horizontal well · Cyclic superheated steam stimulation · Horizontal heterogeneity · Permeability distribution pattern · Numerical modeling

Introduction

Unconventional resources becomes more important in present petroleum industry (Tang and Wu 2018; Xiong et al. 2018, 2017b, 2019). The heat and mass transfer process that happens in an engineering case can be a study topic for engineers (Sheikholeslami 2018; Fengrui et al. 2019a,

2020a, b; Xiong et al. 2017a; Huang 2016, 2017; Feng et al. 2018; Fengrui et al. 2019c, d, 2020c, d; Sun et al. 2017a, b, c, d; Xindi and Baojun 2017; Yu et al. 2019; Sun et al. 2019, Fengrui et al. 2019b). The mass transfer can be found in nearly every aspect in the petroleum industry (Meng et al. 2018; Fengrui et al. 2019e, f, g; Sun et al. 2017e, f, g, h; Jichao et al. 2018), while the heat transfer always happens during the thermal recovery process of heavy oil (Zhanghua et al. 2015; Huang et al. 2018a, b, c; Sun et al. 2018a, b, c; Mohammad et al. 2018; Ezeuko and Gates 2018). In this paper, the thermal recovery process of cyclic superheated steam stimulation using a horizontal well is studied.

When it comes to the enhanced oil recovery, horizontal well has been proved effective in increasing contact area (Yi et al. 2018; Yang et al. 2018; Sun et al. 2018d, e, f). On the other hand, newly developed thermal fluid, such as multi-component thermal fluid and superheated steam, have been proved successful in increasing oil recovery efficiency (Sun et al. 2018g, h, i, j, k, l, m, n, o, p, q, r, s, t, u, v; Fengrui et al. 2018). However, it comes with the difficulty that the steam channeling may become more serious when there is

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a long horizontal wellbore or the horizontal heterogeneity is serious.

Given the fact the heterogeneity always happens along the horizontal well, which may have an influence on the performance of the production well. As a result, we conducted a numerical study to investigate the effect of horizontal heterogeneity on productivity of cyclic superheated steam stimulation horizontal wells using a numerical model.

Effect of different combination of permeability in the horizontal direction is studied. First, a numerical model is established using the commercial numerical simulation software. Then, different combinations of permeability in the horizontal direction are input into the model. The effect of different combinations of permeability in the horizontal direction on the productivity of the horizontal well is studied.

Numerical model

Corner grid is used to build the structure of the model. The reservoir size is $450 \times 200 \times 20$ m. The grid size is $10 \times 10 \times 2$ m. The length of the horizontal well is 250 m.

Fig. 1 The I-J and I-K profiles of the numerical model

The location of the wellbore in the reservoir is shown in Fig. 1 below.

Some basic parameters used for calculation are shown in Table 1 below. Note that the permeability in the horizontal direction is 1000 mD.

Based on the above model, the permeability along the horizontal direction is modified to study the effect of horizontal heterogeneity on the performance of the production well. The permeability distribution pattern is shown in Fig. 2 below.

Totally nine permeability distribution patterns are studied in this paper. The detailed permeability distribution patterns are shown in Fig. 3 below. The permeability level has been classified as high, medium and low. The high level is equal to 1700 mD. The medium level is equal to 1000 mD. The low level is equal to 300 mD.

Results and discussion

Based on the above model, these non-permeability distribution patterns are input into the model. The calculated results are shown below.

Figure 4 shows the effect of permeability distribution pattern in the horizontal direction on the recovery degree. It is observed that the curves of different permeability

Fig. 2 The permeability distribution pattern along the horizontal wellbore

Table 1 Basic parameters of the numerical model

Physical parameter	Value	Physical parameter	Value
Reservoir size, m	$450 \times 200 \times 20$	Superheated steam temperature, °C	321
Grid size, m	$10 \times 10 \times 2$	Soak time, day	15
Buried depth, m	320	Injection pressure, kPa	5100
Porosity, dimensionless	33.8	Length of the horizontal well, m	250
Rock compression coefficient, KPa^{-1}	3.58×10^{-5}	Reservoir temperature, °C	16

Fig. 3 The detailed permeability distribution pattern along the horizontal wellbore

Fig. 4 The effect of permeability distribution pattern on the recovery degree

distribution patterns are close to each other. The effect of permeability distribution pattern in the horizontal direction on the recovery degree can be neglected. This may be caused by the infinity of fluid fluidity in the wellbores.

Figure 5 shows the effect of permeability distribution pattern in the horizontal direction on the cyclic oil production. It is observed that the cyclic oil production is

Fig. 5 The effect of permeability distribution pattern on the cyclic oil production

close to each other under all cycles. The effect of permeability distribution pattern in the horizontal direction on the cyclic oil production can be neglected.

Figure 6 shows the temperature fields under various permeability distribution patterns. It is observed that the temperature is the highest in the high permeability section, while the temperature is the lowest in the low permeability section. However, given the fact that the wellbore conductivity is assumed to be infinity, the effect of permeability distribution pattern on the performance of the production well can be neglected.

Conclusion

The horizontal heterogeneity is always the issue that bothers the practical engineers. The existence of horizontal heterogeneity leads to the low recovery efficiency and serious steam fingering phenomenon. In this paper, a numerical model is built to study the effect of horizontal heterogeneity on the productivity of production well during the cyclic superheated steam stimulation process. Some meaningful conclusions are listed below:

- The effect of permeability distribution pattern in the horizontal direction on the recovery degree can be neglected. This may be caused by the infinity of fluid fluidity in the wellbores.
- The effect of permeability distribution pattern in the horizontal direction on the cyclic oil production can be neglected.
- The temperature is the highest in the high permeability section, while the temperature is the lowest in the

Fig. 6 The temperature fields under various permeability distribution patterns

low permeability section. However, given the fact that the wellbore conductivity is assumed to be infinity, the effect of permeability distribution pattern on the performance of the production well can be neglected.

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References

- Ezeuko CC, Gates ID (2018) Thermal oil recovery from fractured reservoirs: energy and emissions intensities. *Energy* 155:29–34
- Feng D, Li XF, Wang XZ, Li J, Zhang T, Sun Z, He MX, Liu Q, Qin JZ, Han S, Hu JC (2018) Anomalous capillary rise under nanoconfinement: a view of molecular kinetic theory. *Langmuir* 34(26):7714–7725
- Fengrui S, Yuedong Y, Guozhen L (2018) Comments on: the flow and heat transfer characteristics of compressed air in high-pressure air injection wells [Arabian Journal of Geosciences (2018) 11: 519]. *Arab J Geosci* 11(20):631
- Fengrui S, Yuedong Y, Guozhen L, Xiangfang L (2019a) Effect of critical thickness on nanoconfined water fluidity: review, communication, and inspiration. *J Pet Explor Prod Technol*. <https://doi.org/10.1007/s13202-018-0540-6>
- Fengrui S, Yuedong Y, Guozhen L (2019b) Comments on heat and mass transfer characteristics of steam in a horizontal wellbore with multi-point injection technique considering wellbore stock liquid [International Journal of Heat and Mass Transfer 127 (2018) 949–958]. *Int J Heat Mass Transf* 132:1319–1321
- Fengrui S, Yuedong Y, Guozhen L, Xiangfang L (2019c) Transport zones of oil confined in lipophilic nanopores: a technical note. *Arabian J Geosci* 12(4):136
- Fengrui S, Yuedong Y, Guozhen L, Xiangfang L (2019d) A slip-flow model for multi-component shale gas transport in organic nanopores. *Arabian J Geosci* 12(5):143
- Fengrui S, Yuedong Y, Xiangfang L, Guozhen L (2019e) An analytical equation for oil transport in nanopores of oil shale considering viscosity distribution. *J Pet Explor Prod Technol*. <https://doi.org/10.1007/s13202-018-0486-8>
- Fengrui S, Yuedong Y, Guozhen L (2019f) New analytical equations for productivity estimation of the cyclic CO₂-assisted steam stimulation process considering the non-Newtonian percolation characteristics. *J Pet Explor Prod Technol*. <https://doi.org/10.1007/s13202-018-0518-4>
- Fengrui S, Yuedong Y, Guozhen L, Xiangfang L (2019g) Effect of physical heating on productivity of cyclic superheated steam stimulation wells. *J Pet Explor Prod Technol*. <https://doi.org/10.1007/s13202-018-0527-3>
- Fengrui S, Yuedong Y, Guozhen L (2020a) Effect of bottom water on performance of cyclic superheated steam stimulation using a horizontal well. *J Pet Explor Prod Technol*. <https://doi.org/10.1007/s13202-019-0625-x>
- Fengrui S, Yuedong Y, Guozhen L (2020b) Slight insights and perspectives of future heavy oil recovery. *J Pet Explor Prod Technol*. <https://doi.org/10.1007/s13202-019-0615-z>

- Fengrui S, Yuedong Y, Guozhen L, Dong M (2020c) Transport behaviors of real gas mixture through nanopores of shale reservoir. *J Pet Sci Eng*. <https://doi.org/10.1016/j.petrol.2018.12.058>
- Fengrui S, Yuedong Y, Guozhen L, Wenyuan L (2020d) A numerical model for wet steam circulating in horizontal wellbores during starting stage of the steam-assisted-gravity-drainage process. *Heat Mass Transf*. <https://doi.org/10.1007/s00231-019-02564-7>
- Huang S, Xiong Hao, Wei S et al (2016) Physical simulation of the interlayer effect on SAGD production in MacKay river oil sands. *Fuel* 183:373–385. <https://doi.org/10.1016/j.fuel.2016.06.104>
- Huang S, Xiong H, Kuiqian MA et al (2017) A mathematical model for productivity prediction of SAGD process considering non-uniform steam distribution. *J Chin Univ Pet (Edition of Natural Science)* 41(4):107–115. <https://doi.org/10.3969/j.issn.1673-5005.2017.04.014>
- Huang SJ, Cao M, Cheng LS (2018a) Experimental study on the mechanism of enhanced oil recovery by multi-thermal fluid in offshore heavy oil. *Int J Heat Mass Transf* 122:1074–1084
- Huang SJ, Cao M, Xia Y, Chen X, Yang ML (2018b) Heat and mass transfer characteristics of steam in a horizontal wellbore with multi-point injection technique considering wellbore stock liquid. *Int J Heat Mass Transf* 127(Part B):949–958
- Huang SJ, Cao M, Cheng LS (2018c) Experimental study on aquathermolysis of different viscosity heavy oil with superheated steam. *Energy Fuels* 32(4):4850–4858
- Jichao H, Changdong Y, Jixiang H (2018) Transient pressure analysis of horizontal well with nonorthogonal transverse fractures and drainage volume characterization using fast marching method. *J Nat Gas Sci Eng* 54:110–119
- Meng Y, Li X, Jiang M et al (2018) Experimental research on three dimensional flow characteristics of multiple horizontal fractures utilizing an innovative experiment apparatus. *Arab J Geosci* 11:243. <https://doi.org/10.1007/s12517-018-3589-0>
- Mohammad IM, Murtada AE, Salim A, Hossain ME (2018) Modeling of temperature distribution and oil displacement during thermal recovery in porous media: a critical review. *Fuel* 226:423–440
- Sheikholeslami M (2018) Finite element method for PCM solidification in existence of CuO nanoparticles. *J Mol Liq* 265:347–355
- Sun F, Yao Y, Li X, Yu P, Ding G, Zou M (2017a) The flow and heat transfer characteristics of superheated steam in offshore wells and analysis of superheated steam performance. *Comput Chem Eng* 100:80–93
- Sun F, Yao Y, Chen M, Li X, Zhao L, Meng Y, Sun Z, Zhang T, Feng D (2017b) Performance analysis of superheated steam injection for heavy oil recovery and modeling of wellbore heat efficiency. *Energy* 125:795–804
- Sun F, Yao Y, Li X, Yu P, Zhao L, Zhang Y (2017c) A numerical approach for obtaining type curves of superheated multi-component thermal fluid flow in concentric dual-tubing wells. *Int J Heat Mass Transf* 111:41–53
- Sun F, Yao Y, Li X, Zhao L (2017d) Type curve analysis of superheated steam flow in offshore horizontal wells. *Int J Heat Mass Transf* 113:850–860
- Sun F, Yao Y, Li X, Zhao L, Ding G, Zhang X (2017e) The mass and heat transfer characteristics of superheated steam coupled with non-condensing gases in perforated horizontal wellbores. *J Pet Sci Eng* 156:460–467
- Sun F, Yao Y, Li X, Tian J, Zhu G, Chen Z (2017f) The flow and heat transfer characteristics of superheated steam in concentric dual-tubing wells. *Int J Heat Mass Transf* 115:1099–1108
- Sun F, Yao Y, Li X, Li H, Chen G, Sun Z (2017g) A numerical study on the non-isothermal flow characteristics of superheated steam in ground pipelines and vertical wellbores. *J Pet Sci Eng* 159:68–75
- Sun F, Yao Y, Li X (2017h) Effect of gaseous CO₂ on superheated steam flow in wells. *Eng Sci Technol Int J* 20(6):1579–1585
- Sun F, Yao Y, Li X (2018a) The heat and mass transfer characteristics of superheated steam coupled with non-condensing gases in horizontal wells with multi-point injection technique. *Energy* 143:995–1005
- Sun F, Yao Y, Li X, Li G, Chen Z, Chang Y, Cao M, Han S, Chaohui L, Feng D, Sun Z (2018b) Effect of flowing seawater on supercritical CO₂—superheated water mixture flow in an offshore oil well considering the distribution of heat generated by the work of friction. *J Pet Sci Eng* 162:460–468
- Sun F, Yao Y, Li X, Li G, Miao Y, Han S, Chen Z (2018c) Flow simulation of the mixture system of supercritical CO₂ & superheated steam in toe-point injection horizontal wellbores. *J Pet Sci Eng* 163:199–210
- Sun F, Yao Y, Li X, Li G, Sun Z (2018d) A numerical model for predicting distributions of pressure and temperature of superheated steam in multi-point injection horizontal wells. *Int J Heat Mass Transf* 121:282–289
- Sun F, Yao Y, Li X, Li G, Huang L, Liu H, Chen Z, Liu Q, Liu W, Cao M, Han S (2018e) Exploitation of heavy oil by supercritical CO₂: effect analysis of supercritical CO₂ on H₂O at superheated state in integral joint tubing and annuli. *Greenh Gases Sci Technol* 8(3):557–569
- Sun F, Yao Y, Li X, Li G, Liu Q, Han S, Zhou Y (2018f) Effect of friction work on key parameters of steam at different state in toe-point injection horizontal wellbores. *J Pet Sci Eng* 164:655–662
- Sun F, Yao Y, Li X, Li G, Han S, Liu Q, Liu W (2018g) Type curve analysis of multi-phase flow of multi-component thermal fluid in toe-point injection horizontal wells considering phase change. *J Pet Sci Eng* 165:557–566
- Sun F, Yao Y, Li G, Li X, Chen M, Chen G, Zhang T (2018h) Analysis of superheated steam performance in offshore concentric dual-tubing wells. *J Pet Sci Eng* 166: 984–999
- Sun F, Yao Y, Li G, Li X, Lu C, Chen Z (2018i) A model for predicting thermophysical properties of water at supercritical state in offshore CDTW. *Measurement* 124:241–251
- Sun F, Yao Y, Li G, Li X, Zhang T, Lu C, Liu W (2018j) An improved two-phase model for saturated steam flow in multi-point injection horizontal wells under steady-state injection condition. *J Pet Sci Eng* 167:844–856
- Sun F, Yao Y, Li G, Li X (2018k) Geothermal energy extraction in CO₂ rich basin using abandoned horizontal wells. *Energy* 158:760–773
- Sun F, Yao Y, Li G, Li X, Li Q, Yang J, Wu J (2018l) A coupled model for CO₂ & superheated steam flow in full-length concentric dual-tube horizontal wells to predict the thermophysical properties of CO₂ & superheated steam mixture considering condensation. *J Pet Sci Eng* 170:151–165
- Sun F, Yao Y, Li G, Li X (2018m) Performance of geothermal energy extraction in a horizontal well by using CO₂ as the working fluid. *Energy Convers Manag* 171:1529–1539
- Sun F, Yao Y, Li X (2018n) The heat and mass transfer characteristics of superheated steam in horizontal wells with toe-point injection technique. *J Pet Explor Prod Technol* 8(4):1295–1302
- Sun F, Yao Y, Li X, Li G (2018o) A brief communication on the effect of seawater on water flow in offshore wells at supercritical state. *J Pet Explor Prod Technol* 8(4):1587–1596
- Sun F, Yao Y, Li X (2018p) Effect analysis of non-condensable gases on superheated steam flow in vertical single-tubing steam injection pipes based on the real gas equation of state and the transient heat transfer model in formation. *J Pet Explor Prod Technol* 8(4):1325–1330
- Sun F, Yao Y, Li X (2018q) Numerical simulation of superheated steam flow in dual-tubing wells. *J Pet Explor Prod Technol* 8(3):925–937

- Sun F, Yao Y, Li G, Li X (2018r) Geothermal energy development by circulating CO₂ in a U-shaped closed loop geothermal system. *Energy Convers Manag* 174:971–982
- Sun F, Yao Y, Li G, Zhao L, Liu H, Li X (2018s) Water performance in toe-point injection wellbores at supercritical state. In: SPE Trinidad and Tobago section energy resources conference, SPE-191151-MS, 25–26 June 2018 in Port of Spain, Trinidad and Tobago. <https://doi.org/10.2118/191151-MS>
- Sun F, Yao Y, Li G, Li X (2018t) Numerical simulation of supercritical-water flow in concentric-dual-tubing wells. *SPE J* 23(6):2188–2201. <https://doi.org/10.2118/191363-PA>
- Sun F, Yao Y, Li G, Li X, Sun J (2018u) Comparison of steam front shape during steam flooding process under varying steam state condition: numerical analysis. In: Abu Dhabi international petroleum exhibition and conference, SPE-192996-MS, 12–15 November, 2018, Abu Dhabi, UAE
- Sun F, Yao Y, Li G, Qu S, Zhang S, Shi Y, Xu Z, Li X (2018v) Effect of pressure and temperature of steam in parallel vertical injection wells on productivity of a horizontal well during the SAGD process: a numerical case study. In: SPE international heavy oil conference & exhibition, SPE-193659-MS, 10–12 December 2018 in Kuwait City, Kuwait
- Sun F, Yao Y, Li G, Zhang S, Xu Z, Shi Y, Li X (2019) A slip-flow model for oil transport in organic nanopores. *J Pet Sci Eng* 172:139–148
- Tang J, Wu K (2018) A 3-D model for simulation of weak interface slippage for fracture height containment in shale reservoirs. *Int J Solids Struct* 144–145:248–264. <https://doi.org/10.1016/j.ijsolstr.2018.05.007>
- Xiong H, Huang S, Liu H, Cheng L, Ma K, Huang Q (2017a) A novel optimization of SAGD to enhance oil recovery - The effects of pressure difference. In: 19th European Symposium on Improved Oil Recovery, Norway, Stavanger, 24–27 April 2017. <https://doi.org/10.3997/2214-4609.201700250>
- Xiong H, Huang S, Liu H, Cheng L, Li J, Xiao P (2017b) A novel model to investigate the effects of injector-producer pressure difference on SAGD for bitumen recovery. *Int J Oil Gas Coal Technol* 16(3):217–235
- Xiong H, Huang S, Devegowda D et al (2018) Simulation and modeling of pressure difference on steam chamber and production performance[C]. Society of Petroleum Engineers, California, USA, 22–27 April 2018. <https://doi.org/10.2118/190107-MS>
- Xiong H, Huang S, Devegowda D, Liu H, Li H, Padgett Z (2019) Influence of pressure difference between reservoir and production well on steam chamber propagation and reservoir production performance. *SPE J*. <https://doi.org/10.2118/190107-PA>
- Xindi SUN, Baojun BAI (2017) Comprehensive review of water shutoff methods for horizontal wells. *Pet Explor Dev* 44(6):1022–1029
- Yang L, Tianshou M, Ping C, Chuan Y (2018) Method and apparatus for monitoring of downhole dynamic drag and torque of drill-string in horizontal wells. *J Pet Sci Eng* 164:320–332
- Yi D, Pingya L, Xiangjun L, Lixi L (2018) Wellbore stability model for horizontal wells in shale formations with multiple planes of weakness. *J Nat Gas Sci Eng* 52:334–347
- Yu H, Li Q, Sun F (2019) Numerical simulation of CO₂ circulating in a retrofitted geothermal well. *J Pet Sci Eng* 172:217–227
- Zhanghua L, Qiang Z, Tiejun L, Fuhui W (2015) Experimental and numerical study of drill string dynamics in gas drilling of horizontal wells. *J Nat Gas Sci Eng* 27(Part 3):1412–1420

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