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**Article**

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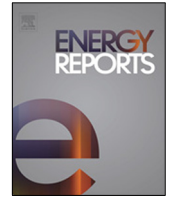
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## Research paper

# Experimental investigation on the steam injection profile along horizontal wellbore

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## ABSTRACT

Horizontal well based thermal recovery processes have been widely applied to recover the heavy oil resources all over the world. But, the flow behavior of hot fluids along a horizontal wellbore is still unclear. In this paper, a scaled cylindrical wellbore model is designed to experimentally simulate the steam injection process using horizontal well. Based on this model, a set of experiments are firstly performed to analyze the steam injection profile along horizontal wellbore. And the effects of different sensitive parameters on steam conformance are discussed. Results indicate that different steam injection operation can yield a different heating performance. During steam injection process, the wellbore segments closed to the steam outflow point can have a better heating performance. In comparison, a high steam injection rate is more beneficial on the uniform steam conformance along horizontal wellbore. The two-ends steam injection strategy can produce a more uniform steam injection profile than the single heel/toe end injection method. The addition of non-condensable gas (NCG) can also improve the steam conformance along horizontal wellbore. Moreover, from the experimental observation, it is also observed that the permeability heterogeneity along the horizontal wellbore is a significantly important parameter on the steam injection profile. The well completion method tremendously impacts the steam conformance along horizontal wellbore. For field operation, in order to obtain a more uniform steam conformance, it should be avoided to place the horizontal well in a high heterogeneous area, and slotted liner will be the preferred method for a horizontal well based thermal recovery process.

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## 1. Introduction

Heavy oil and bitumen is an important type of petroleum resources in the world. Its effective development plays an important role on the world energy supply (EIA, 2017). Different with the conventional light crude oil, heavy oil is usually characterized by high viscosity and high density in the original formation temperature condition (Speight James, 2013; Liu, 2013; Dong et al., 2019). Therefore, for heavy oil and bitumen resources, using a thermal recovery technology to reduce the oil viscosity is always the main exploitation method. There include three types of thermal recovery technologies, cyclic steam stimulation (CSS), steam flooding and steam assisted gravity drainage (SAGD) (Butler, 1991; Farouq Ali, 2007). Currently, many novel steam hybrid techniques in the post steam injection era have been also proposed and tested in field (Sun et al., 2014; Huang et al.,

2018; Dong et al., 2019). In decades, because of the reduction of directional drilling cost and the improvement of sweep efficiency, horizontal well technology has gained much attention. And the horizontal well based thermal recovery process becomes an effective development method for heavy oil resources (Liu, 2013; Dong et al., 2019; Zhang et al., 2020). Compared with vertical well, the application of horizontal well can significantly improve the thermal efficiency of steam injection process and improve the recovery performance, especially for the heavy oil reservoirs with a small thickness, a bottom aquifer or a higher oil viscosity etc. Currently, horizontal well based thermal recovery processes have been widely applied to unlock the different types of heavy oil resources all over the world (Alvarez and Han, 2013; Chang, 2013).

Due to the large contact area between formation and horizontal wellbore, the application of horizontal well can significantly increase the producible oil reserves, improve the heat distribution in formation, increase the sweep efficiency and enhance the transportation of reservoir fluids (Doan et al., 1997; Dong et al., 2013, 2019). Moreover, for the extra heavy oil reservoirs, it

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can also increase the steam injectivity (Alvarez and Han, 2013). Firstly, for steam-based recovery processes in thin and heterogeneous heavy oil reservoirs, using horizontal well can further increase the thermal efficiency of steam and strengthen the advantage of gravity drainage (Dong et al., 2013; Huang et al., 2015). El-Abbas and Shedi (2001) experimentally discussed the performance of steam flooding, caustic-steam flooding, surfactant-steam and caustic-surfactant steam flooding by horizontal well in the waterflooded reservoirs. It is found that the application of horizontal well can enhance the improvement effects of different additives on the performance of steam flooding process. Fatemi and Jamaloei (2011) conducted a series of 3D experiments to simulate the feasibility of toe-to-heel steam flooding (THSF) process in a heavy oil reservoir in Iran. It is found that THSF outperforms the conventional vertical-well based steam-flooding. Tian et al. (2017) developed a high temperature and high pressure (HTHP) 3D experimental apparatus to experimentally investigate the performance of horizontal-well based CSS process and follow-up steam flooding process in heavy oil reservoirs. Then, as another important horizontal-well based process, SAGD technique has also gained much attention since its proposal. In SAGD, a horizontal well pair will be parallelly designed in the bottom section of a reservoir (Butler, 1985, 1987, 1991). The upper horizontal well performs as a steam injector, and the bottom one is a producer. This well-deployment strategy can fully play the advantages of gravity drainage in horizontal well, and it will lead to a higher thermal efficiency and a higher production rate, especially in thick heavy oil reservoirs (Dong et al., 2014, 2015, 2017). Furthermore, for the heavy oil reservoir with a bottom aquifer, because of the low pressure drop between horizontal wellbore and reservoir, using horizontal well can also slow down the occurrence of water coning and improve the production performance.

Horizontal well has been widely applied in the different thermal recovery processes for heavy oil reservoirs. In order to accurately predict the recovery performance of horizontal well in heavy oil reservoirs, the behavior of heat and mass transfer of fluids along the horizontal wellbore is crucial. This behavior is affected not only by the well completion condition, but also by the heat transmission characteristics between formation and horizontal well (Cheng et al., 2011; Wei et al., 2015). For a steam injection process, the transient flow behavior of steam along horizontal wellbore is a gas-liquid two-phase flow, and the heat transfer behavior between wellbore and reservoir should be also taken into account (Gao and Jalali, 2008; Gui et al., 2006). In some conditions, the phase-state changes of saturated steam in horizontal wellbore caused by heat loss also significantly impacts the performance of steam injection operation (Gu et al., 2015). Doan et al. (1992) developed a series of formulas for the fluid flow behavior in the vicinity of horizontal well and flow behavior inside the wellbore. And the scaling criteria for the horizontal well based experiments are also derived. They found that compared with constant diameter horizontal well, a variable diameter horizontal well has a superior performance, which further reduces the well pressure loss by reducing flow resistance inside the wellbore. Bjomdalen and Islam (1999) proposed a group of correlations to estimate the pressure drop along the horizontal well. It is found that the effects of void fraction, viscosity and water saturation, even the presence of asphaltenes in crude oil on the pressure drop of fluids in horizontal wells cannot be neglected. Wu et al. (2004) introduced the concepts of staggered grid and equivalent permeability to assume that the steam flow along horizontal wellbore is a flow process within the porous media. Thus, based on this assumption, they proposed an equivalent flow model of horizontal wellbore and discussed the performance of horizontal wellbore in thermal recovery process. Chen et al. (2007) developed a steam outflow model from perforated horizontal well in heavy oil reservoirs. Considering the effect of gravity drainage, Wu et al. (2011)

**Table 1**

Scaling criteria for fluid flow along horizontal wellbore.

No.	Dimensionless similarity	Physical meaning
1	$\frac{k\Delta\rho g}{\mu V}$	Ratio of gravity and viscous force
2	$\frac{\rho DW}{\mu}$	Ratio of inertia force and viscous force
3	$\frac{r_w^2 p}{\mu LV}$	Ratio of displacing force and viscous force
4	$\frac{nr_p^4 L}{r_w q_{in}}$	Dimensionless injection volume

studied the characteristics of the performance of horizontal well in heavy oil reservoirs. Thus, the flowing behavior, production characteristics and inflow performance of thermal horizontal well are all investigated. Wu et al. (2012) also established a mathematical model for steam flow along the horizontal wellbore with a parallel string configuration. Thus the effect of steam injection method was discussed. Zhong et al. (2012) proposed a steam injection strategy with a separated-zones horizontal well. This technology can offset the effect of formation heterogeneity and steam fingering on the steam conformance along horizontal well. It can further increase the steamed-zone along horizontal well by approximately 70%. Hou et al. (2016) considered the heat diffusion characteristics of multi-thermal fluids to develop an analytical model for the productivity of cyclic multi-thermal fluid stimulation using horizontal well. Sun et al. (2017, 2018) also discussed the heat transfer and pressure drops of hot fluids along horizontal wellbore and derived the productivity of CSS horizontal well. Although many attempts have been carried out to investigate the behavior of heat and mass transfer of hot fluids in horizontal wellbore, most of them are performed from the numerical aspects. The accuracy and reliability of results are doubtful. Using experimental model to investigate the fluid flow behavior and heat transfer behavior within horizontal wellbore is a challenging work.

In this paper, the scaling criteria for fluid flow along horizontal wellbore are discussed firstly. Then from the criteria, a cylindrical wellbore model is built to experimentally simulate the hot fluids injection process along horizontal wellbore. Therefore, based on this experimental model, the flow behavior and heat transfer characteristics of hot fluids within the vicinity and horizontal wellbore can be discussed. And in this paper, a set of experiments are performed to analyze the steam injection profile under different conditions. Thus from the experimental observation, the effects of operation parameters, pipe-shoe depth and injection fluid type are all studied.

## 2. Horizontal wellbore model

As we know, scaling criterion is a basic theory to guide the experimental runs. Based on the valid scaling criterion, a proper design for the experimental plan can be obtained, and it also guarantees the accuracy of experimental measurement. Thermal recovery processes in heavy oil reservoir are usually operated under a high pressure (HP) condition. For the experiments under HP condition, both the reservoir properties and fluid flow behavior in experimental model are closed to the actual reservoir conditions (or prototype). Therefore, in this study, in order to accurately simulate the behavior of heat and mass transfer of hot fluids in the vicinity of horizontal well and inside the wellbore, a dimensionless scaling criterion for the fluid flow in horizontal well is used (Doan et al., 1992; Farouq Ali and Redford, 1997; Wu, 2006). Based on the dimensionless scaling criterion in Table 1, the physical properties of the experimental model can be derived, as shown in Table 2.

In Table 1,  $k$  is formation permeability,  $m^2$ ;  $\Delta\rho$  is density difference of oil and water,  $kg/m^3$ ;  $g$  is gravitational acceleration,

**Table 2**  
Parameters of prototype and physical model.

No.	Property	Prototype	Model
1	Reservoir thickness (m)	30	0.15
2	Wellbore length (m)	160	0.8
3	Porosity	0.32	0.32
4	Permeability ( $\mu\text{m}^2$ )	1.6	320
5	Oil saturation	0.75	0.75
6	Well radius (mm)	44.45	3.14
7	Hole radius (mm)	2	1
8	Aperture (mm)	0.3	0.6
9	Perforation density ( $\text{m}^{-1}$ )	450	398

$9.8 \text{ m/s}^2$ ;  $\mu$  is oil viscosity,  $\text{mPa s}$ ;  $V$  is fluid velocity inside the horizontal well,  $\text{m/s}$ ;  $\rho$  is oil density,  $\text{kg/m}^3$ ;  $D$  is wellbore diameter,  $\text{m}$ ;  $r_w$  is wellbore radius,  $\text{m}$ ;  $P$  is fluid pressure across the horizontal well,  $\text{Pa}$ ;  $L$  is the length of horizontal wellbore,  $\text{m}$ ;  $n$  is the hole number per unit length of wellbore,  $1/\text{m}$ ;  $r_p$  is radius of perforation hole,  $\text{m}$ ;  $q_{in}$  is injection volume of hot fluids per unit length of wellbore,  $\text{m}^3$ .

Based on the model properties in Table 2, a scaled cylindrical wellbore model is designed, as shown in Fig. 1. Totally, 70 temperature measure-points, 10 pressure measuring-point and 36 liquid outflow points are uniformly distributed along the wellbore. The working sketch is shown in Fig. 2. During the injection process of hot fluids, the temperature distribution and pressure distribution along the horizontal wellbore can be accurately recorded. The changes of temperature, pressure and fluid properties in the vicinity of the horizontal well can be recorded. Based on this model, we can conveniently simulate the performance of steam injection operation and oil production along the horizontal wellbore. And the performance of dual-pipe well configuration can be also experimentally investigated.

### 3. Experimental setup and procedure

The schematic for the experiment setup is shown in Fig. 3. As shown, three HP gas containers ( $\text{CO}_2$ ,  $\text{N}_2$ , and air) and steam generator are connected with the wellbore model through a six-way valve. Thus, during the operation, the effect of NCG (non-condensable gas) components on the steam conformance can be experimentally discussed. A gas flow control device is also used to control the flow rate of different NCG components. It ranges from 0.1 mL/min to 10 mL/min. Through the temperature measure-points and pressure measure-points, the temperature and pressure values along the horizontal wellbore during the whole experiment can be obtained. The liquid production data can be used to analyze the changes of fluid properties. Thus, the behavior of heat and mass transfer of hot fluids in the vicinity of horizontal well and inside the wellbore can be experimentally discussed. Fig. 4 gives the wellbore model. Fig. 5 shows the perforated well and slotted well used in the experiments. The oil samples used in this study are the dead oil from Henan oilfield, SINOPEC, in China. The distilled water is used as the simulated water in this study. Sand is the quartz sand with uniform grain size and good abrasion (80-mesh, 120-mesh).

During experimental operation, the quartz sand with a suitable mesh is screened firstly. Then the process of sand filling is performed to make sure that the permeability of porous media meets the requirement. Thereafter, the experimental apparatuses are connected according to the schematic in Fig. 3.  $\text{N}_2$  is charged into the wellbore model at room temperature to a required pressure (5 MPa). After equilibrium for 0.5~1.0 h, this wellbore model, which filled with quartz sand and high-pressure  $\text{N}_2$ , is placed in an electrically heated furnace to test the gas tightness. After test, the wellbore model is heated till the reservoir

temperature. Then injecting water to test the porosity and permeability, and injecting heavy crude oil to construct a reservoir condition with the initial oil saturation. At this time, the wellbore model is ready to run. We can set the steam injection tubing to the suitable location along the wellbore. And we can also change the injection parameters to investigate the steam conformance along horizontal well. In this process, we respectively change the location of steam injection tubing, the methods of well completion technique and the types of hot fluids to simulate the behavior of heat and mass transfer of fluids in horizontal well under different conditions. The different location of steam injection tubing represents the different steam outflow points. Furthermore, changing the mesh of quartz sand can be used to simulate the effect of formation permeability and permeability heterogeneity on steam conformance.

### 4. Results & discussion

Steam conformance along the horizontal interval is a very important controlling factor for the production performance of horizontal well in heavy oil reservoirs. In this section, based on the experimental setup above, the steam injection profile along the horizontal wellbore under different conditions is all experimentally discussed.

#### 4.1. General behavior of hot fluids in wellbore

The general behavior of mass and heat transfer of hot fluids in the vicinity of horizontal well and inside the wellbore is experimentally studied firstly. In this case, the pure saturated steam is injected and the injection rate is 60 mL/min. The fluid injection tubing is placed around the heel-end section. The well completion method used in this experiment is perforation. Formation is under a homogeneous condition with a 80-mesh quartz sand. After test, the reservoir permeability is about  $2.84 \times 10^{-3} \mu\text{m}^2$ . Fig. 6 shows the obtained temperature and pressure distribution inside the wellbore. Because of the effect of pressure drop, as the hot fluids flow along the wellbore, both the temperature and pressure inside the wellbore are reduced. The mass and heat transfer behavior between formation and horizontal wellbore is another reason for the decrease of fluid temperature. Fig. 7 gives the formation temperature distribution in the axial and radial directions. As shown, for the wellbore segment closed to the heel-end, both the formation temperature and heating radius are much higher. That is caused by the fluid outflow location used in this case is heel-end injection mode, as shown in Fig. 8. For heel-end injection mode, the heating effect around the heel-end is significantly better than that of the toe-end. In some situations, most of the fluids in wellbore will enter into formation before they reach to the toe-end section. And a seriously non-uniform steam injection profile will be created. The reservoir section closed to the toe-end even does not contribute the total oil production.

#### 4.2. Effect of steam injection rate

Steam injection rate is an important factor to improve the heating effect of steam injection operation. Under the conditions of other parameters unchanged, the steam injection rate is respectively set at 40 mL/min, 60 mL/min and 80 mL/min to explore its effect on steam conformance. Generally, the higher the steam injection rate, the higher the steam quality and the higher the total heat energy injected. In this section, based on the experimental procedure, the effect of steam injection rate on the steam conformance along horizontal well is investigated. The experimental results are shown in Fig. 9. Similarly, with the distance increases, both the temperature and pressure are

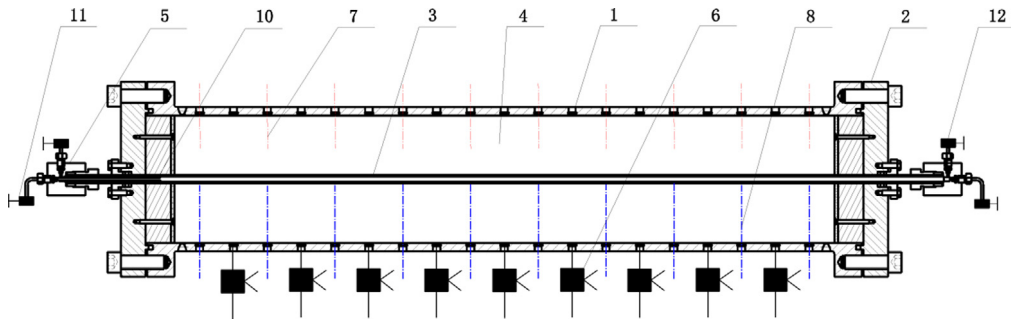


Fig. 1. Cutaway view of the scaled cylindrical wellbore model. 1- outer wall of the model; 2-flange; 3-simulated wellbore; 4-sand; 5-conversion unit; 6-connected to BPR; 7-temperature transducer; 8-pressure transducer; 10-steam injection pipe; 11, 12-valve.

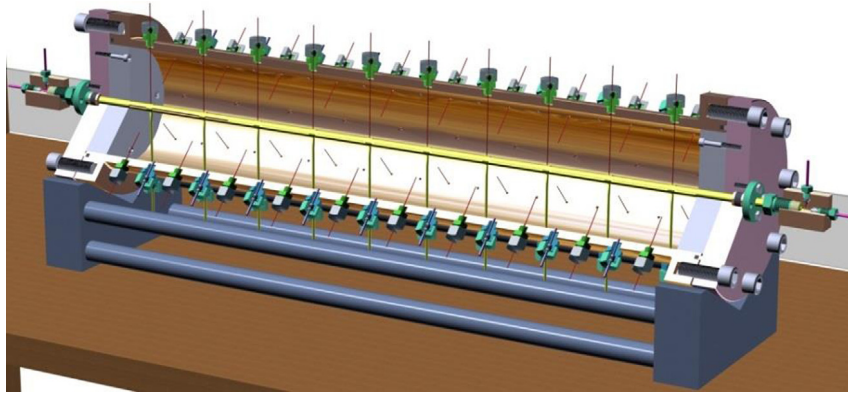


Fig. 2. Working sketch of the scaled cylindrical wellbore model.

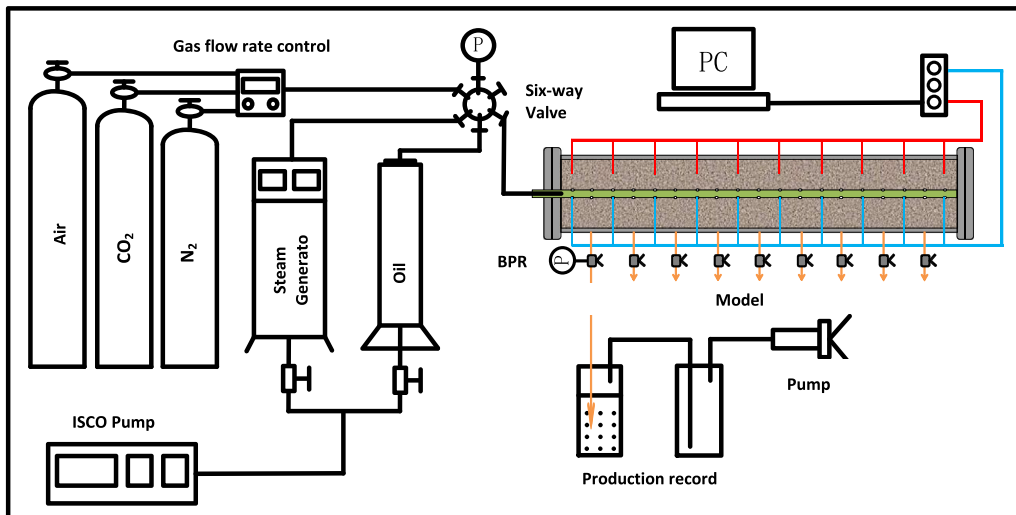


Fig. 3. Schematic for the experiment of steam injection profile along the horizontal wellbore.

reduced. The higher the steam injection rate, the higher the fluid pressure and fluid temperature. As shown, the temperature-drop along the wellbore at 40 mL/min is higher than that at 80 mL/min. Because of the limited steam adsorption capacity, the non-uniform steam injection profile can be highly improved at a higher steam injection rate.

#### 4.3. Effect of hot fluid type

Changing the types of hot fluid is another important method to overcome the non-uniform steam conformance along horizontal well. And currently the multicomponent hot fluids (MCHFs) have

been widely applied in many heavy oil field tests. The application of MCHFs not only uniformizes the steam injection profile along the wellbore but also significantly improves the performance of thermal recovery processes. In this section, the effect of hot fluid type on the steam conformance along horizontal well is experimentally discussed. During experiments, both the flow rates of pure steam and MCHFs (steam + NCG (15%CO<sub>2</sub>+85%N<sub>2</sub>)) are set as 60 mL/min. The results are shown in Fig. 10. As shown, because of the improvement of NCG on the fluid physical properties, the heat loss rate and pressure drop of MCHFs along the horizontal wellbore are much lower. That is because the co-injection of NCG and steam further reduces the density of hot fluids, and thus the



Fig. 4. The cylindrical horizontal wellbore model used in this study.



Fig. 5. Model of perforation well and slotted liner.

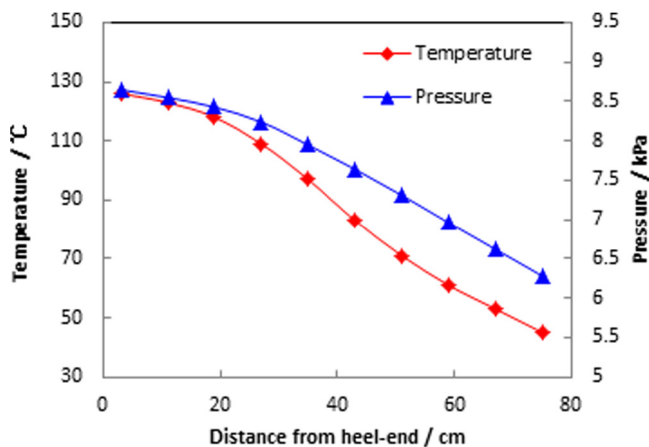


Fig. 6. General temperature and pressure distribution along the horizontal wellbore.

friction loss is reduced. Therefore, the pressure drop of MCHFs is lower. And, the steam conformance is significantly improved. Under the same condition, both the temperature and pressure of MCHFs along the wellbore are higher. Compared with pure saturated steam, the density and viscosity of MCHFs are much lower.

#### 4.4. Effect of steam outflow location

Different steam outflow location usually yields a different heating effect. A suitable steam outflow location significantly benefits the thermal recovery performance of heavy oil reservoir using horizontal well. In this section, four experiments are carried out to investigate the effect of steam outflow location on the steam conformance along horizontal well, including heel-end injection, toe-end injection, middle injection and two-ends injection. For two-ends injection, steam will be injected through the

locations of heel-end and toe-end simultaneously by a concentric pipe configuration method. In this process, the total steam injection volume for all of the experiments are the same, 60 mL/min. The experimental results are shown in Fig. 11. For all the experiments, the wellbore segment closed to the steam outflow location always have a higher fluid pressure and temperature. Because of the effect of pressure drop, heat loss and steam outflow, both the pressure and temperature of fluids are reduced away from the steam outflow location. The effective heating interval along wellbore is also directly related to the steam outflow location. In field operation, for a CSS process, the steam outflow location can be cyclically changed to improve the steam injection profile along the horizontal wellbore. Compared with the other two operation cases, the two-ends injection strategy can yield a uniform steam injection profile and improve the heating effect along horizontal wellbore. Therefore, a dual-pipe well configuration and a wellbore throttling device (FCD, flow control device) are very recommended to perform the two-ends injection process, and even a multi-points steam injection process can be also applied to improve the steam conformance along horizontal wellbore.

#### 4.5. Effect of permeability heterogeneity

Considering the large length of horizontal wellbore, the permeability distribution along wellbore is usually non-uniform. And permeability distribution is always the dominant factor to control the steam conformance along horizontal wellbore. A higher permeability represents a higher flowability of reservoir fluids in formation. Therefore, during steam injection operation, it also indicates a higher heating radius and a higher productivity. In this section, three experiments are carried out to investigate the effect of permeability heterogeneity on the steam conformance along horizontal wellbore. The permeability distributions along wellbore for the three experiments are shown in Fig. 12. The experimental results of temperature distribution and pressure distribution are shown in Fig. 13. For the steam injection process using horizontal well, the heating effect along horizontal well is directly related with the permeability distribution. High reservoir

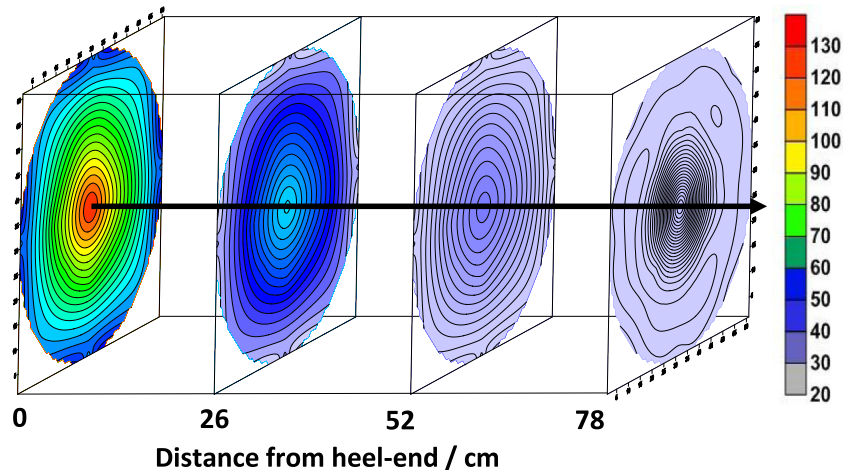


Fig. 7. Steam heating area along the horizontal wellbore.

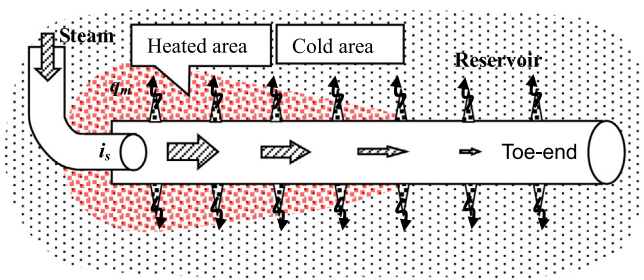


Fig. 8. Schematic of steam injection process for the heel-end mode.

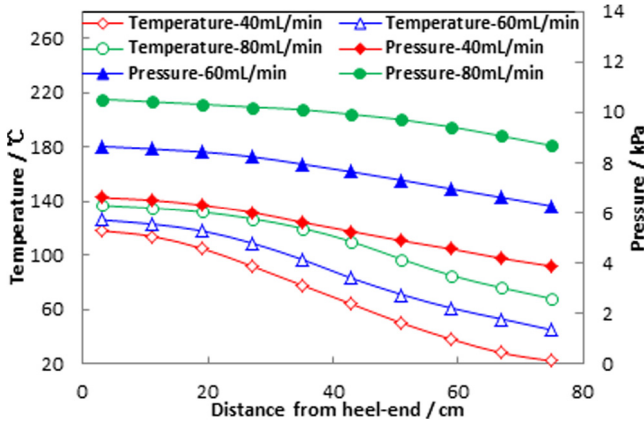


Fig. 9. The effect of steam injection rate.

permeability can yield a better steam injection profile, and thus a better heating effect. As shown in Fig. 12, case 1 is a homogeneous case. For case 2, the heel-end section has a higher permeability, and for case 3, the toe-end section has a higher permeability. The changing tendency of pressure and temperature in reservoir is directly related with the permeability distribution along horizontal wellbore. Therefore, based on the heterogeneous permeability distribution, for the temperature observation results of case 2 and case 3, an obvious piecewise phenomenon can be observed in Fig. 13. For case 2, the temperature closed to the heel-end section is reduced slowly, but the temperature for case 3 is reduced more significantly. It is because of the large permeability difference in heel-end section for case 2 and case 3. And, the result of the homogeneous case is between case 2 and case 3.

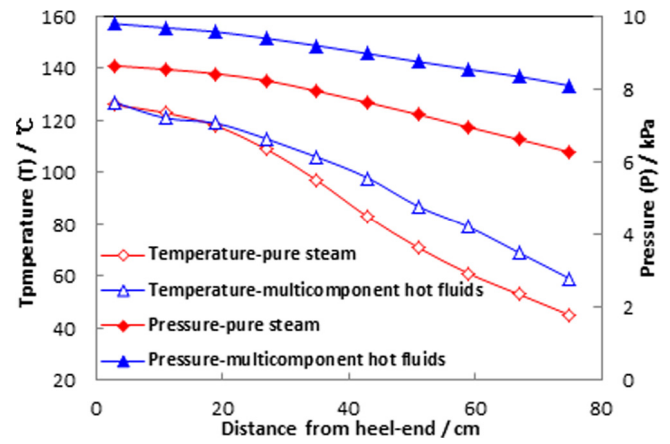


Fig. 10. The effect of hot fluid type.

#### 4.6. Effect of well completion method

In field operation, perforation and slotted liner are the two commonly-used well completion methods for horizontal well. The flow behavior of hot fluids through these two types of well completion devices is significantly different. In this section, using the experimental setup, the two different well completion methods for horizontal well, as shown in Fig. 5, are applied to investigate the effect of well completion on the steam conformance. In order to guarantee the accuracy of the experimental results, the total cross-sectional area of perforation and slotted fracture in the two devices are the same. The experimental results are shown in Fig. 14. As shown, compared with perforation method, the application of slotted liner can reduce the pressure-drop and temperature-drop along horizontal wellbore in some extent. That is mainly caused by the smaller friction loss in slotted liner. On the other hand, during experimental operation, the occurrence of well sand up can be found in the perforated wellbore. It further aggravates the non-uniform steam conformance along horizontal wellbore. It indicates that a slotted liner will be the preferred method for a horizontal well based thermal recovery process. In an actual field application, the physical properties of slotted liner should be also optimized to improve the heat and mass transfer behavior of fluids along wellbore.

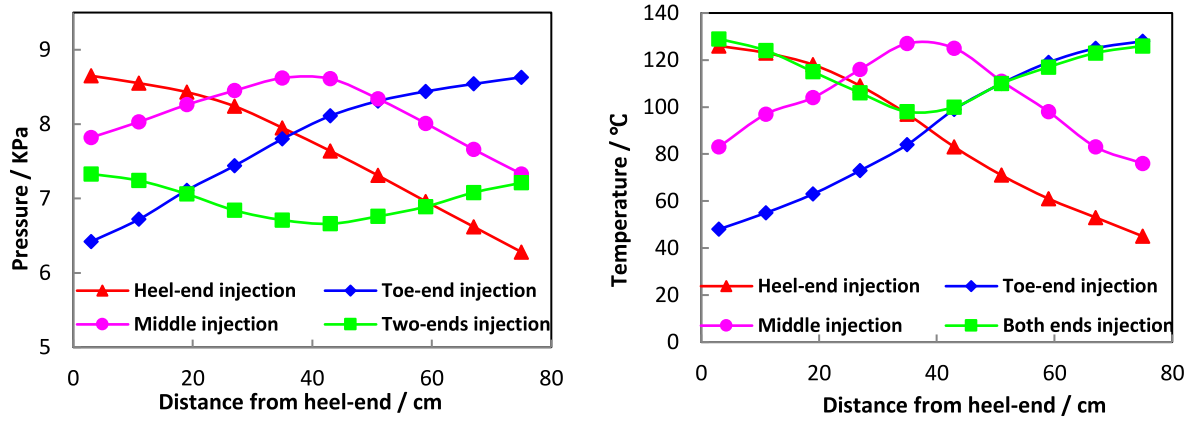


Fig. 11. The effect of fluid outflow location.

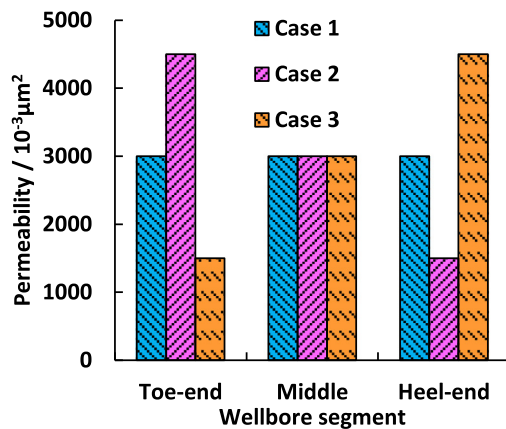


Fig. 12. The permeability distribution along the wellbore.

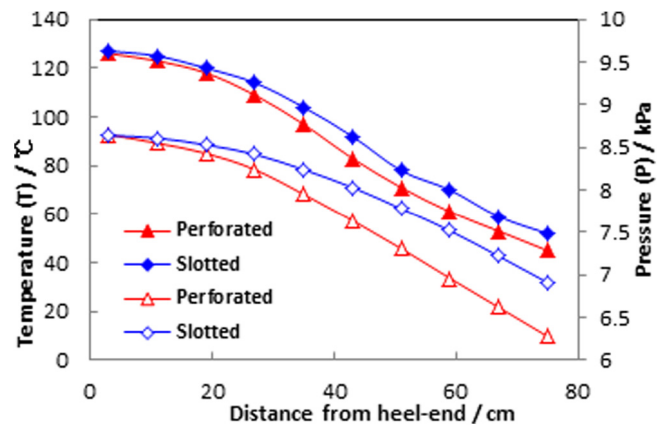


Fig. 14. The effect of well completion method.

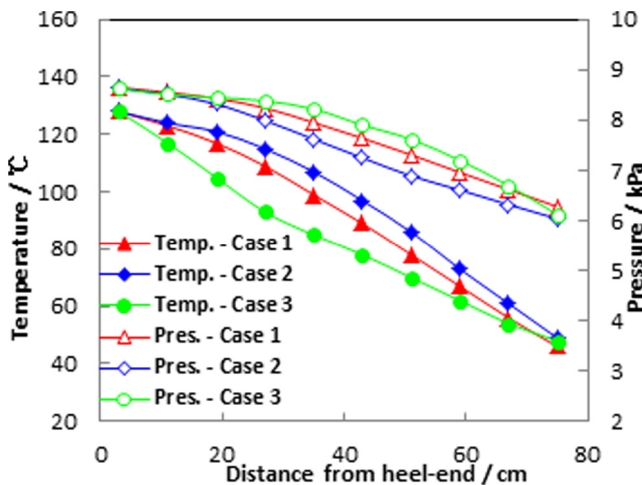


Fig. 13. The effect of permeability heterogeneity.

## 5. Conclusions

This paper experimentally investigates the heat and mass transfer behavior of hot fluids along horizontal wellbore. A scaled cylindrical wellbore model is designed, and a set of experiments are performed to analyze the steam injection profile under different conditions. The effect of steam injection rate, hot fluid type, steam outflow location, permeability heterogeneity and well completion method are discussed. Experimental results indicate

that different injection operation can yield a different heating effect. During steam injection process, the wellbore segment closed to the steam outflow point has a better heating performance. A two-ends steam injection strategy can yield a uniform steam injection profile than the previous heel/toe single-end injection method. And a higher steam injection rate can improve the steam injection profile along horizontal wellbore. Compared with pure saturated steam, the steam conformance of MCHFs is significantly improved. It is found that the permeability heterogeneity has a tremendous effect on the steam conformance. In field test, the direction of horizontal well should be optimized to avoid a high heterogeneity. Furthermore, compared with perforation well completion method, the application of slotted liner can reduce the pressure-drop and temperature-drop along horizontal well, and it is the preferred method for a horizontal well based thermal recovery process.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**Xiaohu Dong:** Conceptualization, Methodology, Writing - original draft. **Huiqing Liu:** Supervision, Investigation. **Yong Zhai:** Data curation. **Changjiu Wang:** Validation. **Zhangxin Chen:** Writing - review & editing. **Dongqing Liu:** Resources.



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## References

- Alvarez, J., Han, S., 2013. Current overview of cyclic steam injection process. *J. Pet. Sci. Res.* 2 (3), 116–127.
- Bjomdalen, N., Islam, M.R., 1999. A simple correlation for estimating pressure drop in a horizontal well. In: Paper Presented At the 8th Petroleum Conference of the South Saskatchewan Section, Regina, Canada, October 18–21.
- Butler, R.M., 1985. A new approach to the modeling of steam-assisted gravity drainage. *J. Can. Pet. Technol.* 24 (3), 42–51.
- Butler, R.M., 1987. Rise of interfering steam chambers. *J. Can. Pet. Technol.* 26 (3), 70–75.
- Butler, R.M., 1991. *Thermal Recovery of Oil and Bitumen*. Prentice Hall, Englewood Cliffs, New Jersey.
- Chang, J., 2013. Understanding HW-CSS for thin heavy oil reservoir. In: SPE 165386 Presented At the SPE Heavy Oil Conference Canada, Calgary, Alberta, Canada, June 11–13.
- Chen, D.M., Zhou, J.Y., Li, Z.P., Gu, B.L., Dong, Z.G., 2007. A steam injection model for horizontal well in heavy oil reservoir with thermal recovery. *J. Southwest Pet. Univ.* 29, 102–106.
- Cheng, W.L., Huang, Y.H., Lu, D.T., Yin, H.R., 2011. A novel analytical transient heat-conduction time function for heat transfer in steam injection wells considering the wellbore heat capacity. *Energy* 36 (7), 4080–4088.
- Doan, L.T., Doan, Q.T., Farouq Ali, S.M., George, A.E., 1997. Strategies for steam-flooding marginal heavy oil reservoirs using horizontal wells—a laboratory study. In: The 48th Annual Technical Meeting of the Petroleum Society, Calgary, Canada, June 8–11.
- Doan, Q., Farouq Ali, S.M., George, A.E., 1992. Scaling criteria and model experiments for horizontal wells. *J. Can. Pet. Technol.* 31 (9), 57–65.
- Dong, X., Liu, H., Chen, Z., Wu, K., Lu, N., Zhang, Q., 2019. Enhanced oil recovery techniques for heavy oil and oilsands reservoirs. *Appl. Energy* 239, 1190–1211.
- Dong, X., Liu, H., Hou, J., Zhang, Z., Chen, Z., 2015. Multi-thermal fluid assisted gravity drainage process: A new improved-oil-recovery technique for thick heavy oil reservoir. *J. Pet. Sci. Eng.* 133, 1–11.
- Dong, X., Liu, H., Wang, Q., Pang, Z., Wang, C., 2013. Non-Newtonian flow characterization of heavy crude oil in porous media. *J. Pet. Explor. Pet. Technol.* 3 (1), 43–53.
- Dong, X., Liu, H., Zhang, Z., Wang, C., 2014. The flow and heat transfer characteristics of multi-thermal fluid in horizontal wellbore coupled with flow in heavy oil reservoirs. *J. Pet. Sci. Eng.* 122, 56–68.
- Dong, X., Liu, H., Zhang, Z., Wang, L., Chen, Z., 2017. Performance of multiple thermal fluids assisted gravity drainage process in post SAGD reservoirs. *J. Pet. Sci. Eng.* 154, 528–536.
- EIA, 2017. *International Energy Outlook 2017*. US Energy Information Administration.
- El-Abbas, A.A., Shedid, S.A., 2001. Experimental investigation of the feasibility of steam/chemical steam flooding processes through horizontal wells. In: SPE 68767 Presented At the SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, 17–19 April.
- Farouq Ali, S.M., 2007. *Practical Heavy Oil Recovery*. Lecture Notes. University of Calgary, Calgary, Alberta, Canada.
- Farouq Ali, S.M., Redford, D.A., 1997. Physical modeling of in situ recovery methods for oil sands. *CIM Spec.* 17, 319–326.
- Fatemi, S.M., Jamaloei, B.Y., 2011. Injection well – producer well combinations in application of toe-to-heel steam flooding (THSF). In: SPE 140703 Presented At the SPE EUROPEC/EAGE Annual Conference and Exhibition, Vienna, Austria, May 23–26.
- Gao, G., Jalali, Y., 2008. Prediction of temperature propagation along a horizontal well during injection period. *SPE Reserv. Eval. Eng.* 11, 131–140.
- Gu, H., Cheng, L., Huang, S., Li, B., Shen, F., Fang, W., Hu, C., 2015. Steam injection for heavy oil recovery: Modelling of wellbore heat efficiency and analysis of steam injection performance. *Energy Convers. Manage.* 97, 166–177.
- Gui, P., Cunha, J.C., Cunha, L.B., 2006. A coupled model to simulate the fluid flow in the reservoir and horizontal wellbore. In: Paper 2006-124 Presented At the Petroleum Society's 7th Canadian International Petroleum Conference, Calgary, Alberta, Canada, June 13–15.
- Hou, J., Wei, B., Qu, Q., Wang, J., Wang, Q., Zhang, G., 2016. Production prediction of cyclic multi-thermal fluid stimulation in a horizontal well. *J. Pet. Sci. Eng.* 146, 949–958.
- Huang, S., Cao, M., Cheng, L., 2018. Experimental study on the mechanism of enhanced oil recovery by multi-thermal fluid in offshore heavy oil. *Int. J. Heat Mass Transfer* 122, 1074–1084.
- Huang, S., Huang, C., Cheng, L., Liu, T., Chen, Z., Mao, W., 2015. Experiment investigation of steam flooding of horizontal wells for thin and heterogeneous heavy oil reservoir. In: SPE 177030 Presented At the SPE Latin American and Caribbean Petroleum Engineering Conference, Quito, Ecuador, November 18–20.
- Liu, H., 2013. *Principle and design of thermal oil recovery processes*. Petroleum Industry Press, (In Chinese).
- Speight James, G., 2013. *Heavy Oil Production Processes*. Gulf Publishing Company.
- Sun, F., Li, C., Cheng, L., Huang, S., Zou, M., Sun, Q., Wu, X., 2017. Production performance analysis of heavy oil recovery by cyclic superheated steam stimulation. *Energy* 121, 356–371.
- Sun, H., Li, H., Yang, D., 2014. Coupling heat and mass transfer for a gas mixture–heavy oil system at high pressures and elevated temperatures. *Int. J. Heat Mass Transfer* 173–184.
- Sun, F., Yao, Y., Li, X., 2018. 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.
- Tian, J., Liu, H., Pang, Z., 2017. A study of scaling 3D experiment and analysis on feasibility of SAGD process in high pressure environment. *J. Pet. Sci. Eng.* 150, 238–249.
- Wei, S., Cheng, L., Huang, W., Yang, Y., 2015. Flow behavior and heat transmission for steam injection wells considering the tubing buckling effect. *Energy Technol.* 3 (9), 935–945.
- Wu, J., 2006. *The Investigation of Transforming Development Regime for Wa-38 Block By Three Dimensional Physically Scaled Simulation*. (Master thesis). Northeast Petroleum University.
- Wu, Y.B., Li, X.L., Sun, X.G., Ma, D.S., Wang, H.Z., 2012. Key parameters forecast model of injector wellbores during the dual-well SAGD process. *Pet. Explor. Dev.* 39, 481–488.
- Wu, Z., Vasantharajan, S., El-Mandouh, M., 2011. Inflow performance of a cyclic-steam-stimulated horizontal well under the influence of gravity drainage. *SPE J.* 16 (3), 494–502.
- Wu, S.H., Yu, L.J., Liu, X.E.m., Guo, S.P., 2004. Thermal recovery numerical simulation coupling flow in reservoir with various-mass-rate flow in horizontal wellbore. *Pet. Explor. Dev.* 31, 88–90.
- Zhang, Q., Liu, H., Dong, X., Liu, Y., Li, G., Wang, Y., 2020. A new comprehensive model to estimate the steam chamber expansion and recovery performance of entire SAGD process. *J. Pet. Sci. Eng.* 185, 106629.
- Zhong, L., Zhang, S., Wu, F., Lang, B., Liu, H., 2012. Improved heavy-oil recovery by separated-zones horizontal-well steam stimulation. *J. Can. Pet. Technol.* 51 (2), 106–114.