Journal of Petroleum Exploration and Production Technology (2019) 9:1203–1210
https://doi.org/10.1007/s13202-018-0527-3

ORIGINAL PAPER - PRODUCTION ENGINEERING

Effect of physical heating on productivity of cyclic superheated steam stimulation wells

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Received: 2 March 2018 / Accepted: 27 July 2018 / Published online: 2 August 2018

Abstract

Previous works have focused on the single factor analysis of the effects of chemical reactions of superheated steam with oil and rock minerals on the oil well productivity. However, the relationship between the factors and the contributions to productivity is still unknown. In this paper, the contribution of physical heating of superheated steam to well productivity is studied with the numerical method. Results show that: (a) the heat in the area has a very limited increase when the temperature of superheated steam continues to increase. (b) At the starting stage, the oil is heated to a higher temperature and the mobility is increased. The elastic energy becomes the dominant factor controlling the productivity of the oil well in the following stage. (c) The chemical reactions of superheated steam with oil and rock minerals are the dominant factors contributing to the productivity.

Keywords Cyclic steam stimulation · Numerical model · Contribution to productivity · Physical heating · Chemical reactions

Introduction

Thermal method has been widely adopted in practical engineering application (Sheikholeslami et al. 2017a, b, c, d, e, f, g, h, 2018a, b, c, d, e, f, g, h). At present, the development of unconventional resources has become a hotspot (Yin et al. 2017, 2018; Zhang et al. 2017a, b, 2018a, b; Feng et al. 2018a, b, c; Hu et al. 2018a, b, c; Shi et al. 2014, 2015a, b, 2018). For the heavy oil industry, thermal fluid injection has been widely adopted (Sun et al. 2017a, b, c; Gao 2018; Huang et al. 2018a, b; Calder et al. 2018). Water heated to the saturated or superheated state is always selected as the thermal carrier due to both economic and enthalpy factors (Sun et al. 2017d, e, f, g). Saturated steam is the mixture of steam and water under a certain pressure condition (Arab et al. 2018; Struchkov and Rogachev 2018), while superheated steam is completely gas phase (Sun et al. 2017h, i, j). Superheated steam is obtained by continuous heating of saturated steam (Sun et al. 2018a, b, c, d, e, f, g).

It has been reported that, compared with saturated steam, superheated steam has mainly three advantages: (a) heating the reservoir to a higher temperature, (Zhou 2010; Sun et al. 2018h, i, j, k) (b) higher water thermal cracking efficiency, and (c) chemical reaction with rock minerals (Sun et al. 2018l, m, n, o, p, q, r, s, t). The first advantage is a physical factor, while the other two are chemical factors. However, at present it is still unknown how these three factors contribute to the recovery of heavy oil.

When it comes to a method of solving a problem, one may adopt the theoretical, experimental or numerical method (Livescu and Craig 2018; Dabirian et al. 2018; Giovani et al. 2018; Babadagli and Cao 2018; Wang et al. 2018; Fu et al. 2018; Fu and Liu 2017a, b; Duan et al. 2018; Wen et al. 2018a, b; Xiong and Wu 2018; Zhang et al. 2018c). At present, the theoretical study on cyclic steam stimulation has encountered the bottleneck. Researchers find it hard to couple the effects of both physical heating and chemical

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reactions into one mathematical model, and then there exists a large calculation error (Yang et al. 2018). The experimental method is able to discover the component change of heavy oil, or the mineral composition change, after steam flooding (Zhou 2010). However, it is hard to make a conclusion of its contribution to heavy oil recovery at field condition. Numerical simulation, on the other hand, is able to make up for this defect, while it cannot couple the chemical reactions into calculation. But, the failure in considering chemical reactions is its advantage. The contribution of physical heating can be studied separately.

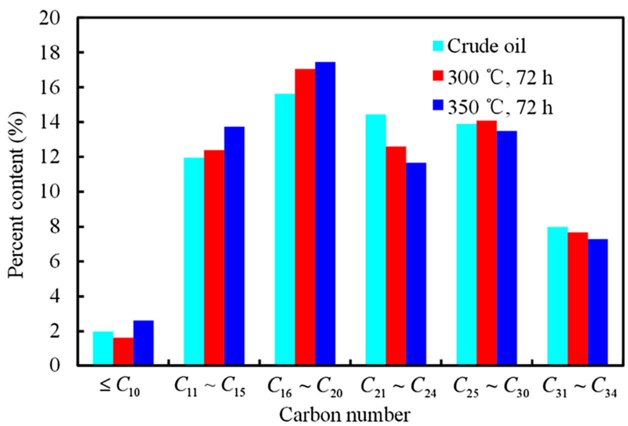


Fig. 1 Transformation of heavy component of heavy oil into light component under superheated steam injection (Zhou et al. 2009)

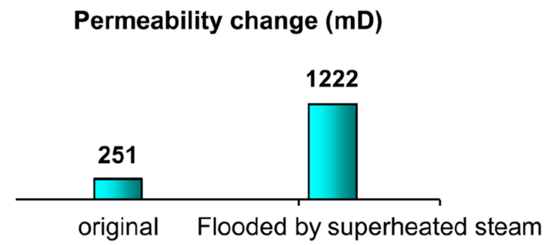


Fig. 3 Increase of the permeability of reservoir (Xu et al. 2013)

In this paper, a numerical model is established to study the contribution of physical heating in the recovery of heavy oil. Then, based on the field data collected from literatures, the contribution of chemical reactions (water thermal cracking of heavy oil and chemical reaction with rock minerals) can be obtained.

Background

Zhou et al. (2009) conducted a series of experiments on thermal cracking efficiency of heavy oil with superheated steam injection. It is found that, compared with saturated steam injection, the heavy components of heavy oil have high conversion efficiency to light components under superheated steam injection condition, as shown in Fig. 1.

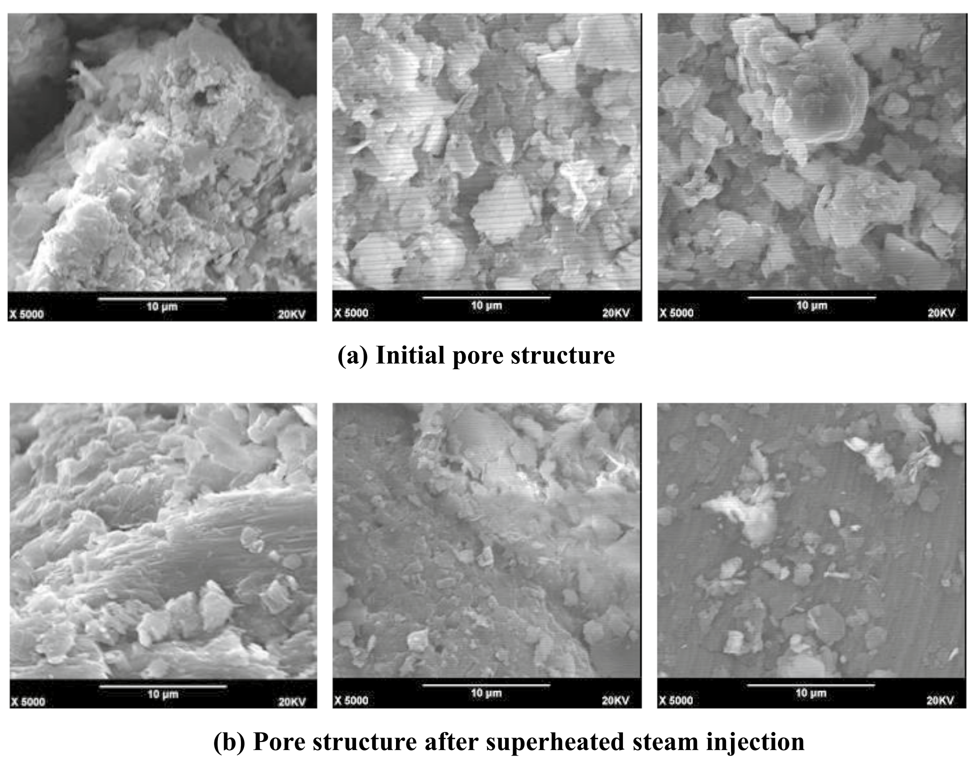


Fig. 2 Comparison of pore structure before and after superheated steam injection using scanning electron microscope (Zhou 2010)

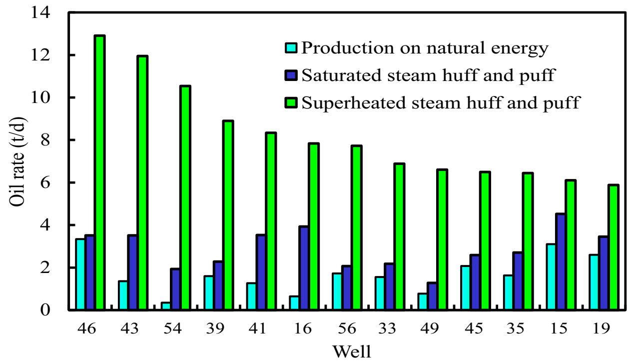


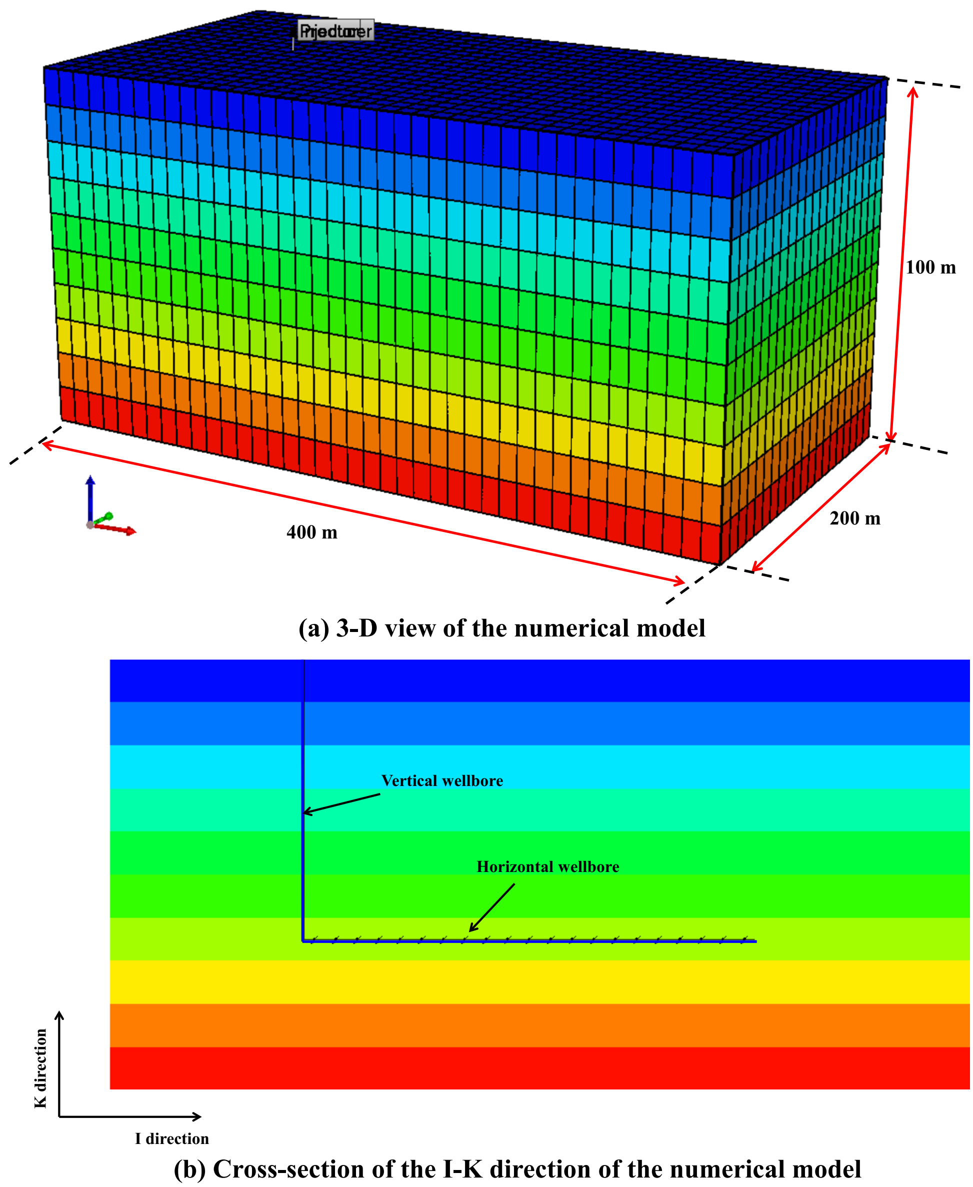
Fig. 4 Numerical model of a cyclic superheated steam stimulation horizontal well

Besides, they also conducted the experiments on the change of rock and mineral composition under superheated steam. The comparison of the pore structure before and after superheated steam injection is shown in Fig. 2 (Zhou 2010). It is found that the clay mineral microcrystallines are richly distributed on the surface of the oil sand particles (Fig. 2a), while the shape and morphology of the clay minerals have been destroyed after superheated steam injection (Fig. 2b).

A further study revealed that the permeability of the rock is increased after superheated steam (as shown in Fig. 3), which also contributes to the increase of productivity.

The above two factors are from the view of chemical reactions. The other main factor influencing the productivity of the cyclic superheated steam wells is the physical heating, which is studied in this paper. One problem that needs to be explained is

Fig. 5 Basic relationships used in the numerical model



the contribution degree of these three factors to the productivity of cyclic superheated steam stimulation wells.

Statistical results showed that, compared with saturated steam injection, the productivity of cyclic superheated steam stimulation wells increases significantly. However, at present, how these factors contribute to this increase is still unknown.

Numerical simulator is an effective tool to study the physical heating effect on productivity because the chemical reactions are neglected.

Numerical model

A 400 m×200 m×100 m model is built with a horizontal well, as shown in Fig. 4. The initial formation pressure is 2.36 MPa. The initial oil saturation is 0.815. The initial formation temperature is 291 K. The buried depth is 280 m.

The relationship between oil viscosity and temperature, and the relative permeability are shown in Fig. 5.

Discussion

To capture the key physic of the heating effect on the productivity of cyclic superheated steam stimulation wells, only the first cycle is studied. This is because oil saturation, waste heat, formation pressure and heated radius after several cycles vary from each other. As a result, the productivity of the following cycles are influenced by many factors, and the effect of physical heating is hard to be studied separately. The study of the first cycle has an advantage because of the uniform initial parameters (pressure, temperature and oil saturation, etc.).

The enthalpy of the steam is set as 0.2, 0.5, 0.8, 1.0 (saturated steam) and 20 K (superheated steam) with the same value of total mass injection. The temperature distributions in the I–J direction are shown in Fig. 6. It is observed that when the steam is at the saturated state, the heated area increases obviously with increasing steam quality. This is because the enthalpy of steam increases rapidly when the steam quality increases. However, when the steam is at the superheated state, the enthalpy increases slowly with rapid increase of temperature (Zhou 2010; Xu et al. 2013). As a result, the heat in the area has a very limited increase when the temperature of superheated steam continues to increase.

For the process of cyclic steam stimulation, the effect of steam on productivity increase is only obvious at the starting stage of the production period, as shown in Fig. 7 below.

It is observed that at the starting stage (from 50 to 100 days), the gradient of the curve increases with increasing steam quality, while, after 100 days, the gradient of the curve is almost equal to each other. This is because the temperature difference is obvious at the starting stage under different steam state conditions, while the temperature difference

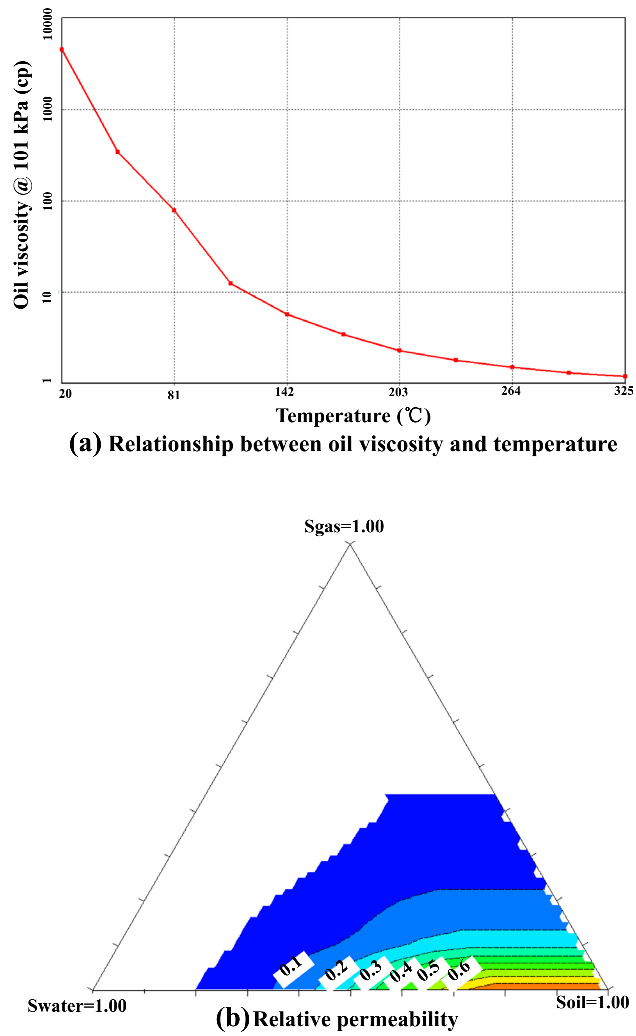


Fig. 6 Comparison of the distributions of temperature when the injection process is finished

becomes small when the heated water and oil are produced. When it is larger than 100 days, the dominant factor controlling the productivity becomes the compressibility of the rock, oil and water. The place initially occupied by heated water and oil are now occupied by cold oil flowing from the faraway places that has not been heated. Second, the pink curve and the blue dotted line coincide. This is a strong evidence that proves the small contribution of physical heating for productivity of cyclic superheated steam stimulation wells. That is to say, the chemical reactions of superheated steam with oil and rock minerals are the dominant factors contributing to the productivity.

Another aspect of the evidence can be found in the daily oil production rate, as shown in Fig. 9 below. It is observed that, from 50 to 100 days, the oil production rate increases rapidly with increasing steam quality. This is because, at the starting stage, the oil is heated to a higher temperature

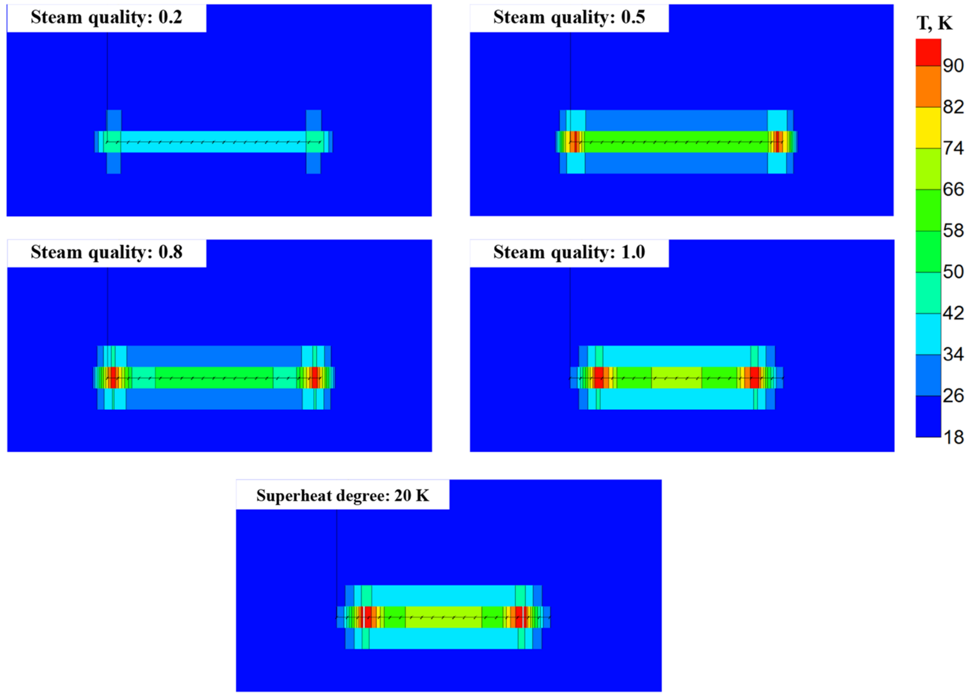


Fig. 7 Cumulative oil production under different steam state conditions

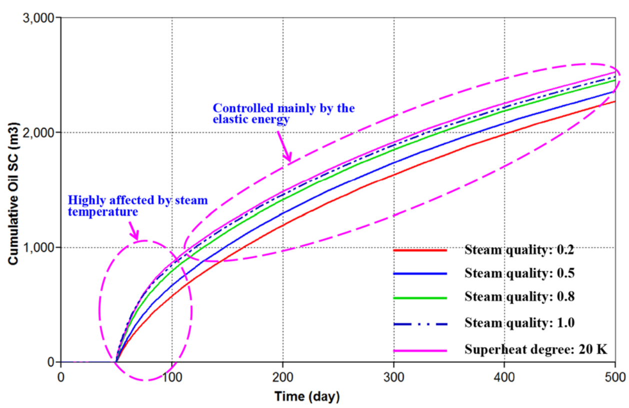


Fig. 8 Comparison of the oil production rate under saturated or superheated steam injection (Xu et al. 2013)

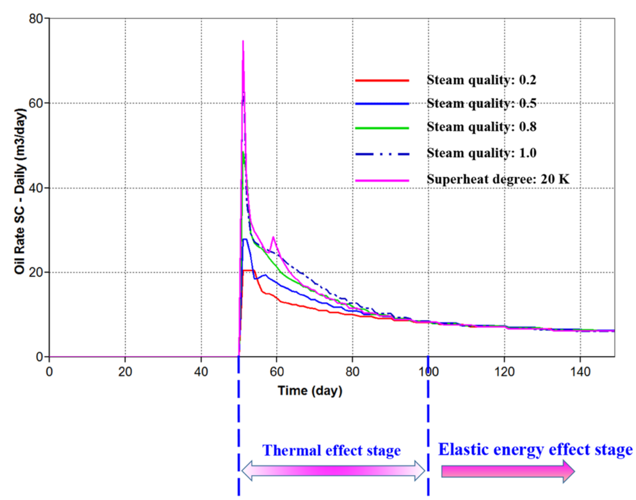


Fig. 9 Daily oil production rate under different steam state conditions

and the mobility is increased. However, after 100 days, the curves coincide with each other, and, at this stage, the elastic energy becomes the dominant factor controlling the productivity of the oil well. Second, the pink curve, representing superheated steam injection, coincide with the blue dotted curve at even the beginning stage with only small increase in oil production rate at the first 10 days. These figures proves that, compared with chemical reactions, the physical heating effect of superheated steam on well productivity is weak. Now, it is clear that the main factors contributed to the increase shown in Fig. 8 are the chemical reactions of superheated steam with heavy oil and rock minerals.

Conclusions

In this paper, the contribution of physical heating of superheated steam on well productivity is studied with numerical method. Some meaningful conclusions are listed below:

(a) The heat in the area has a very limited increase when the temperature of superheated steam continues to increase.
(b) At the starting stage, the oil is heated to a higher temperature and the mobility is increased. The elastic

energy becomes the dominant factor controlling the productivity of the oil well in the following stage.

(c) The chemical reactions of superheated steam with oil and rock minerals are the dominant factors contributing to the productivity.

Acknowledgements The research was supported by National Science and Technology Major Projects of China (nos. 2016ZX05042, 2017ZX05039 and 2016ZX05039) and the National Natural Science Foundation Projects of China (nos. 51504269, 51490654 and 40974055). The authors also acknowledge Science Foundation of China University of Petroleum, Beijing (no. C201605), the National Basic Research Program of China (2015CB250900), the Program for New Century Excellent Talents in University (Grant no. NCET-13-1030) to support part of this work.

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