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Analysis of superheated steam performance in offshore concentric dual-tubing wells

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ABSTRACT

Superheated steam (SHS) injection in concentric dual-tubing wells (CDTW) is a new technology for offshore heavy oil recovery.

Firstly, compared with conventional saturated steam injection in single-tubing wells, the key advantages of SHS injection in CDTW for heavy oil recovery are introduced. Secondly, a novel mathematical model is proposed to analysis the heat transfer characteristics of SHS flow in offshore CDTW. Then, based upon the validated model, type curves of SHS flow in offshore CDTW are analyzed in detail. The results show that: (1). The heat exchange between the integral joint tubing (IJT) and annuli has a significant influence on SHS temperature and superheat degree in each tubing. (2). More heat get lost when the seawater starts to flow, and the heat loss rate in the sea section of the wellbores is larger than that in the formation section of the wellbores.

Moreover, in order to flexibly use the model in practice, the key intrinsic flow characteristics of SHS in offshore CDTW are unraveled. It is found that: (1). The SHS temperature increases at first but turns to decrease with the continuous increase of injection rate due to the fact that the drop of SHS pressure gradually replaces heat losses as the dominant factor on temperature change. (2). The superheat degree at well bottom always increases with the increase of injection rate.

This paper presents a basic reference for engineers in heat loss evaluations as well as performance estimations of SHS flow in offshore CDTW.

1. Introduction

Thermal injection is one of the important methods for heavy oil recovery, and those thermal methods have been proved effective in practice (Willman and Valleroy, 1961; Vander et al., 2007; Al Bahlani et al., 2009; Sandler et al., 2014; Sun et al., 2018a,b,c,d,e,f,g,h). For instance, steam-assisted gravity drainage (Miura and Wang, 2012; Yang et al., 2016) and steam huff and puff (Marx and Langenheim, 1959; Boberg and Lanz, 1966; Hou and Chen, 1997) are widely used techniques for heavy oil recovery. When these method are used, one of the foremost tasks for engineers is to obtain the typical flow curves in the wellbores. However, it is not easy to do so due to the complexity of thermal fluid flow in the wellbores.

The study on wellbore modeling originates from the early 1960s (Ramey, 1962; Holst and Flock, 1966; Willhite, 1967; Orkiszewski, 1967; Beggs et al., 1973). In recent years, with the increasing demand for heavy oil and the emergence of new technologies, wellbore modeling gets its attention in the thermal recovery engineering (Cheng et al., 2011, 2012; 2013, 2014; Dong et al., 2014a; 2014b; Gu et al., 2014, 2015a; 2015b; Wei et al., 2015; Fan et al., 2016).

Satter (1965) proposed an early model for predicting steam quality in the wellbores. While Satter ignored the kinetic energy change during the downward flow process, his work still laid a basic reference for later studies (Pacheco and Farouq, 1972; Farouq Al-Bahlani and Babadagli, 2009; Durrant and Thambynayagam, 1986). Ejiogu and Fiori (1987) and Tortike (1989) brought great convenience to the programming solution by introducing regression formulas to calculate thermal parameters of saturated steam. Sagar et al. (1991) proposed an improved

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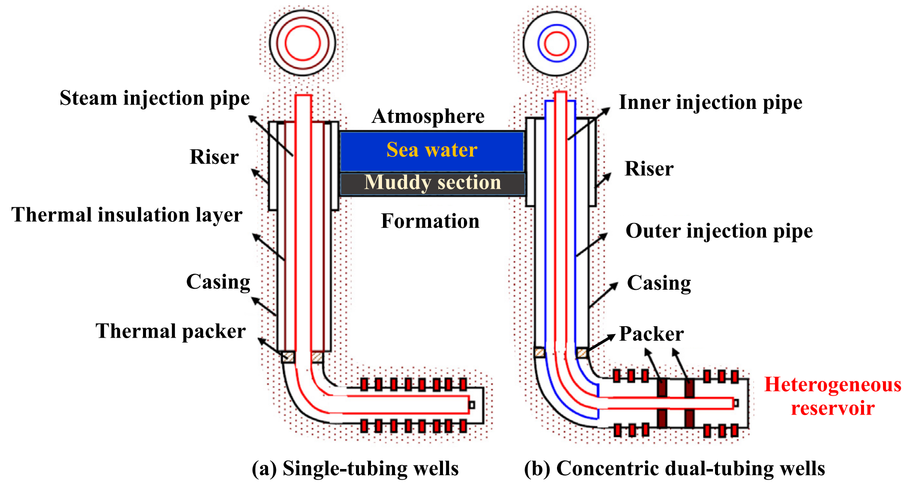

Fig. 1. Comparison between single-point and multi-point steam injection for offshore heterogeneous reservoirs with a long horizontal section (Dong, 2014).

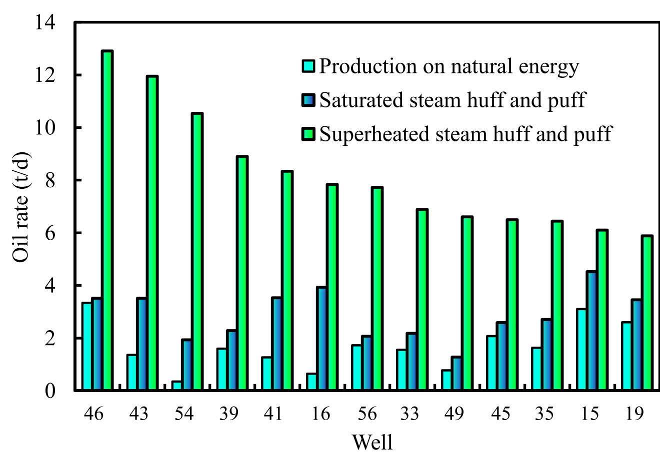

Fig. 2. Oil rate of single well under three different recovery methods (Xu et al., 2013a).

algorithm to predict saturated steam temperature along the wellbore, which gave a reference for follow-up studies (Alves et al., 1992; Bahonar et al., 2010, 2011). Hasan and Kabir (1991) proposed a mathematical model for predicting wellbore heat loss rate and a new expression for calculating transient temperature in the formation. Then, great works were done by Hasan and Kabir (1994, 1995; 2007a; 2009; 2010; 2012) on heat transfer rate in the formation. All of these early researches presented basic references for later studies (Chiu and Thakur, 1991; Cheng et al., 2011, 2012; 2013, 2014). All of these efforts laid a solid foundation for further study of CDTW.

It is proved by field practices that single-tubing steam injection wells (STSJW) may lead to serious fingering phenomenon (Hight et al., 1992; Griston and Willhite, 1987; Liu, 2009; Gu et al., 2014), especially for wells with a long horizontal section and reservoirs with serious heterogeneity. Therefore, CDTW was proposed to deal with the problems and it has been proved effective (Brill, 1987; 1999; Hasan and Kabir, 1992; Barua, 1991; Hight et al., 1992; Dong, 2014; Gu et al., 2014). The structure comparison between STSJW and CDTW is shown in Fig. 1 (Dong, 2014). As can be seen clearly, with the help of dual-tubing structure, synchronous steam injection at heel and toe points can be achieved. Moreover, periodic alternating injection at heel and toe points is another advantage brought by CDTW, which significantly relieves the uneven steam suction phenomenon along the horizontal wellbores (Dong, 2014).

While CDTW brought obvious improvement of oil recovery rate, it also brought great challenges for researchers due to the complexity of heat exchange characteristics during the downward flow process of thermal fluid in the IJT and annuli. Caetano (1985) developed a mechanical model for predicting pressure drop in annuli. In this study, the flow pattern conversion standard and the flow mechanism were studied separately. Their study presented a basic reference for later researches (Antonio and Rune, 2000; 2002; Yu et al., 2010). Griston and Willhite (1987) and Wu et al. (2011) presented different models for predicting pressure drop of saturated steam in annuli based on a new concept of equivalent radius, which has been proved effective in practice (Kaya et al., 2001). By improving the calculation method of equivalent radius, Gu et al. (2014) presented a new model to calculate pressure drop of saturated steam in annuli. Overall, the study on CDTW is still at its early stage, there are many unknowns to be explored.

Moreover, all of these previous studies were focused on saturated steam. SHS, however, is becoming another good choice with the progress of technology (Wu et al., 2010; Zhou, 2010; Xu et al., 2013a, 2013b; Sun et al., 2017a). SHS is obtained by continued heating of saturated steam under the given pressure, and the superheat degree is defined as the temperature difference between SHS and saturated steam under the same pressure (Rohsenow et al., 1992; Chang et al., 1997; Shen et al., 2000). Xu et al. (2013a) analyzed the production data of some wells in Kenkiyak oil field, Kazakhstan, as shown in Fig. 2. As can be seen clearly, compared with conventional methods, SHS injection has a significant promoting effect on oil production rate.

Xu et al. (2013a), Zhou (2010) and Sun et al. (2017a) have done a series of researches on the promoting mechanism of SHS for heavy oil reservoirs. They found that there were mainly four factors contributing to the increase of oil recovery ratio by SHS injection. (a). Compared with saturated steam, cyclic SHS stimulation is able to heat the reservoir to a higher temperature and to create a larger heated radius, as shown in Fig. 3(a) (Xu et al., 2013a; Sun et al., 2017a). (b). The hydrothermal cracking reaction of heavy oil is more easier to occur under a higher temperature (Fig. 3(b)) and the capacity of SHS to dissolve light component from crude oil is very strong (Zhou, 2010; Xu et al., 2013a). (c). SHS is able to reform the pore structure and to destroy the micro-pore throat. As a result, the permeability has an increase of 300%–400% after SHS flooding, as shown in Fig. 3(c) (Xu et al., 2013a). (d). The high temperature SHS reduces the oil-water interfacial tension to a satisfactory level and turns the wettability of rock from oleophilic to hydrophilic (Martin, 1967; Xu et al., 2013a).

While these attractive advantages are still being studied in depth (Sun et al., 2017a), it has already attracted the attention of scholars to study how to get the maximum superheat degree at well-bottom in order to make full use of the advantages of SHS. Zhou et al. (2010), Xu et al. (2013a, 2013b), Fan et al. (2016), Pang and Wang (2016) and Sun et al. (2017b, 2017c, 2017d, 2017e) developed numerical models to