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Production performance analysis of heavy oil recovery by cyclic superheated steam stimulation

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ABSTRACT

In this paper, a novel model is proposed for heated radius calculation and production performance analysis of cyclic superheated steam stimulation (CSHSS) wells.

Firstly, the heated area after superheated steam (SHS) injection is distributed into three sub-areas whose heated radius are derived respectively. Next, a semi-analytical model for production performance analysis is proposed by using time discretization technique. After validation of the proposed model, production performance of CSHSS wells is analyzed in detail. The results indicate that the positive effect of residual heat on cyclic productivity improvement is offset by pressure drop and oil saturation drop. The constant pressure production (CPP) is found to be only a special case of the constant oil production (COP). Both of the cumulative oil production and thermal efficiency increase with the increase of constant oil production rate (COPR). The higher the COPR, the steeper the average pressure curve at its early stage.

This paper presents basic reference for engineers in heated radius evaluations after SHS injection as well as performance estimations of CSHSS wells.

1. Introduction

The heat injection technology has been widely used in thermal recovery for heavy oil reservoirs [1–3], such as steam-assisted gravity drainage [4,5], steam flooding [6,7] and cyclic steam stimulation [8–12]. For cyclic steam stimulation wells, precisely predicting the heated radius after steam injection and the productivity during production period are two foremost tasks for the reservoir engineers. Regrettably, the predicting tasks are never easy due to the complexity of non-isothermal characteristics in the reservoir during the CSHSS process [13,14].

Classical works in this area were firstly developed by Marx et al. [15], who derived an important expression for heated radius based on the isothermal assumption. Willman et al. [16] proposed an improved model based on laboratory studies. These researches presented fundamental references for later studies [17–21]. Ni et al. [22] applied these methods for heated radius calculation to horizontal wells, and it was further developed by Liu et al. [23] who presented more details in the calculation methods for formation parameters. However, these researches were based on the isothermal assumption. In fact, there exists heat loss from the heated area to its surroundings during the injection process. Therefore, the heated area in the reservoir is obviously non-isothermal and those methods based on isothermal assumption can certainly cause errors. This weakness makes the isothermal assumption less attractive.

To overcome this shortage, Li et al. [24] proposed a concept of the front temperature based on the viscosity-temperature curve and derived a formula for heated radius by using the energy conservation equation. Li et al. [25] proposed a semi-analytical model for predicting productivity of cyclic steam stimulation wells based on non-isothermal assumption. These works presented basic references for later researches [26–29]. Although a lot have achieved in heated radius calculation and productivity prediction, the issues are far from settled.

Moreover, all of these studies were focused on saturated steam and few efforts have been done on SHS [30]. SHS, however, is becoming another good choice for heavy oil recovery in recent years with the progress of technology [31–34]. As SHS flows in the reservoir, its thermophysical properties are constantly changing. More importantly, SHS may undergo phase change to saturated steam or even hot water due to heat loss. Thus, the temperature

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distribution in the reservoir after SHS injection is extremely complex. Therefore, one of the most important tasks in the designing of CSHSS wells is to describe the temperature distribution in the reservoir properly. Zhou et al. [35] and Sun et al. [36] presented different models to predict the heated radius for CSHSS, but their works were also based on the isothermal assumption. In fact, temperature distribution in the reservoir is gradually decreased from the SHS temperature to the initial reservoir temperature. More researches need to be conducted urgently.

A series of researches on predicting heated radius and productivity of CSHSS wells are conducted in this paper. This study has four main differences from previous works: (1). Considering the non-isothermal characteristics in the reservoir after SHS injection, the heated area is subdivided into three areas: superheated steam area (SHSA), saturated steam area (SSA) and hot water area (HWA). Then a novel concept of the leading edge temperature (LET) is proposed. With the new concept, the non-isothermal characteristics in the reservoir can be modeled by mathematical methods. (2). A novel analytical formula for predicting the heated radius is obtained. (3). An improved productivity model considering seepage characteristics in each sub-areas is proposed. (4). The correlations between CPP and COP are revealed.

This paper provides key references for reservoir engineers to predict the heated radius and productivity of CSHSS wells.

2. Model description

A vertical well is located in the reservoir. When the SHS injection process is finished, the whole reservoir is divided into two areas: the heated oil area (HOA) and the cold oil area (COA). Moreover, the HOA is divided into three sub-areas: SHSA, SSA and HWA, as shown in Fig. 1. Some basic assumptions are made as follows:

(1). The heavy oil reservoir is assumed to be homogeneous.
(2). The SHS overlay phenomenon in the reservoir is neglected.
(3). There is no vertical temperature difference in the reservoir.
(4). The heat conduction process is completed in an instant.
(5). Wellbore radius is negligible compared with heated radius.

2.1. Heated radius model

2.1.1. Heated radius of SHSA

When the SHS injection process is finished, actual temperature distribution in SHSA gradually declines from SHS temperature (T_{sh}) to saturated steam temperature (T_s). In order to model the temperature distribution in SHSA, a novel concept of the LET (T_{shf}) in SHSA is proposed, which ranges from T_s to T_{sh}, as shown in Fig. 2. Then it is assumed that the SHSA temperature declines linearly from T_{sh} to T_{shf}.

Then, the linearized temperature distribution in SHSA can be modeled as:

$$T(r) = \frac{T_{shf} - T_{sh}}{r_{shf}} r + T_{sh}, \quad 0 < r \le r_{sh}. \tag{1}$$

where, $T(r)$ denotes the temperature in SHSA; T_{shf} represents the LET in SHSA; T_{sh} denotes the SHS temperature; r_{shf} denotes the heated radius of SHSA; r is the distance from wellbore.

Classical method proposed by Marx et al. [15] is not applicable to deal with this non-isothermal condition. Therefore, in order to obtain the formula for heated radius of SHSA, the energy balance equation during the SHS injection process must be rebuilt.

According to the principle of instantaneous heat balance, the injection rate of thermal energy is equal to the sum of the heat loss rate to top-bottom layers and the increase rate of formation heat energy. This energy conversion process can be expressed as (Derivation details can be seen in Appendix A):

$$\frac{2}{\sqrt{\pi \alpha_r}} \int_0^t \frac{\lambda_r}{\sqrt{t-\tau}} \frac{\mathrm{d}A'}{\mathrm{d}\tau} \mathrm{d}\tau + \frac{h \cdot M_r \cdot \mathrm{d}A'}{\mathrm{d}t} = i_{sh}(h_{sh} - h_{wr}) \tag{2}$$

where,

$$\mathrm{d}A' = 2\pi r (T(r) - T_i) \mathrm{d}r \tag{3}$$

where, α_r is the thermal diffusion coefficient of top-bottom layers; λ_r is the thermal conductivity coefficient of top-bottom layers; t is the SHS injection time; h is the reservoir thickness; M_r is the

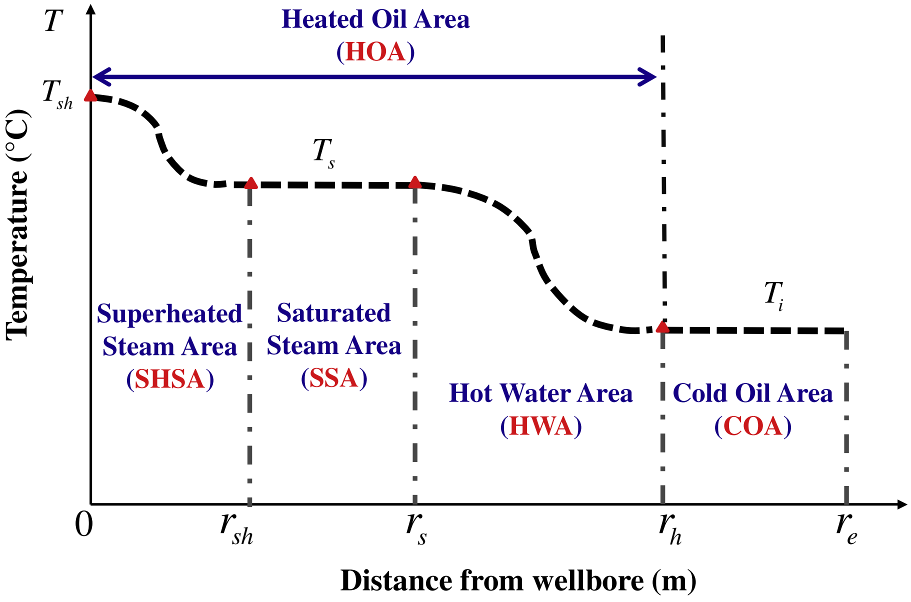

Fig. 1. A schematic of temperature distribution in the reservoir after SHS injection.