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A novel model and sensitive analysis for productivity estimate of nitrogen assisted cyclic steam stimulation in a vertical well

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ABSTRACT

Nitrogen-assisted cyclic steam stimulation (NCSS, i.e. huff and puff) is an important alternative to recover heavy oil reservoirs. In order to forecast the production performance accurately and rapidly, a novel model is developed for heated radius calculation and production prediction of NCSS wells. The underlying assumption in this paper is different from the Marx-Langenheim isothermal model, the heated area is assumed to be non-isothermal and the temperature decreases exponentially. A new heated radius calculation equation is then established and solved by the Newton iteration method. Afterwards, an analytical model for production prediction is derived with pseudo-steady state percolation method by considering the variation of temperature, pressure, relative permeability, etc. during the different periods of the huff-n-puff process. After verification by numerical simulation runs, a sensitivity analysis is performed with the consideration of multiple factors, such as injection rate, injection temperature, fluid component and threshold pressure gradient (TPG). The results indicate that the increase of injection rate, injection temperature and nitrogen-steam ratio, or the decrease of TPG will lead to an increase in oil production. This paper provided a reference for heated radius evaluation and productivity estimation in NCSS processes for heavy oil.

1. Introduction

Heavy oil reserves play an important role in meeting the increasing energy demand around the world [1–4]. And in China, the heavy oil reserves widely spread in Liaohe oilfield, Shengli oilfield, Xinjiang oilfield, Henan oilfield and Bohai offshore oil field. Thermal recovery methods, including the steam injection based processes, have been demonstrated among the most successful and commercial methods for recovering heavy oil [5–12]. However, the development effect of steam injection processes becomes worse inevitably during the late periods. The non-condensate gas injection techniques have also been proposed and demonstrated impressive potential in improving heavy oil recovery. The addition of non-condensate gas in steam generates thermal insulating layer in the upper of the reservoir to reduce heat loss due to the density difference between steam and gas and improves sweep efficiency because of the better mobility in reservoir [13–17]. The common non-condensate gases used for assisting steam injection are nitrogen, carbon dioxide, flue gas, air and light hydrocarbon gases, such as methane, etc. Among these gases, nitrogen is inexpensively prepared and easily available, and is safe and clean. Besides, nitrogen has good compressibility and low thermal conductivity [18,19]. Nitrogen has been applied in oilfield to assist steam injection for enhanced heavy oil recovery and acquired satisfying achievements [20,21]. However, few work has been done for production prediction of nitrogen-assisted steam for the development of heavy oil.

To accurately forecast the production of thermal recovery for heavy oil is an important issue that is in close relationship with the development design in oil field. Fig. 1 illustrates a steam huff-and-puff or cyclic steam stimulation (CSS) process [22]. An integral CSS process includes three periods, i.e. injection period, soak period and production period, which are completed in a single well. During the first injection period, the high-temperature steam is injected into the well. Then, the well is shut-in for a certain time to make the steam diffuse to formation and heat the crude oil. Finally, the well is opened and oil is extracted. Previously, the production prediction models for steam injection processes are mainly based on the steam stimulation. During the cyclic steam stimulation (CSS) process, the percolation mechanisms of fluid in porous media become complex because that the temperature is varying in formation. The Boerg-Lantz [23] and Max-Langenheim [24,25] isothermal model that is based on the energy balance equation is adopted in the early production forecasting models for CSS. These

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Nomenclature

T_s	thermal fluid temperature, °C
T_i	initial reservoir temperature, °C
r	the distance from wellbore, m
t	thermal fluid injection time, s
h	reservoir thickness, m
M_R	volumetric heat capacity of reservoir, kJ/(m^3 °C)
Q_i	heat injection rate, J/s
Q_l	heat loss rate to top-bottom layers, J/s
Q_a	heat increase rate of reservoir, J/s
i_s	injection rate, kg/s
H	enthalpy of thermal fluid, J/kg
t_D	dimensionless time
x	steam quality, decimal
L_v	latent heat of vaporization, J/kg
k	formation permeability, μm^2
k_r	relative permeability, μm^2
q	production rate, cm^3/s
R_{os}	flow resistance
V_r	influence factor on radial heat loss
V_z	influence factor on vertical heat loss
t_b	soak time, s
t_p	production time, s
T_a	average temperature at the end of soak, °C
$\overline{T}_a$	average temperature during the production period, °C
p_a	average reservoir pressure at the end of soak, Pa
p_i	initial reservoir pressure, Pa
$\overline{p}$	average reservoir pressure, Pa
B	volume factor
S	saturation, decimal
c	compressibility coefficient, Pa^{-1}
a_0, b_0	constant
Q_r	residual heat, J
H_f	heat extracted by output liquid, J/d
J	production index

Greek letters

α_e	thermal diffusion coefficient of formation, m^2/s
λ_e	thermal conduction coefficient of formation, W/(m·K)
μ	viscosity, mPa s
ρ_o	density of oil at reservoir condition, kg/m^3
λ	threshold pressure gradient
ξ	correction coefficient for temperature drop, dimensionless
β	thermal expansion coefficient, °C^{-1}
φ	porosity

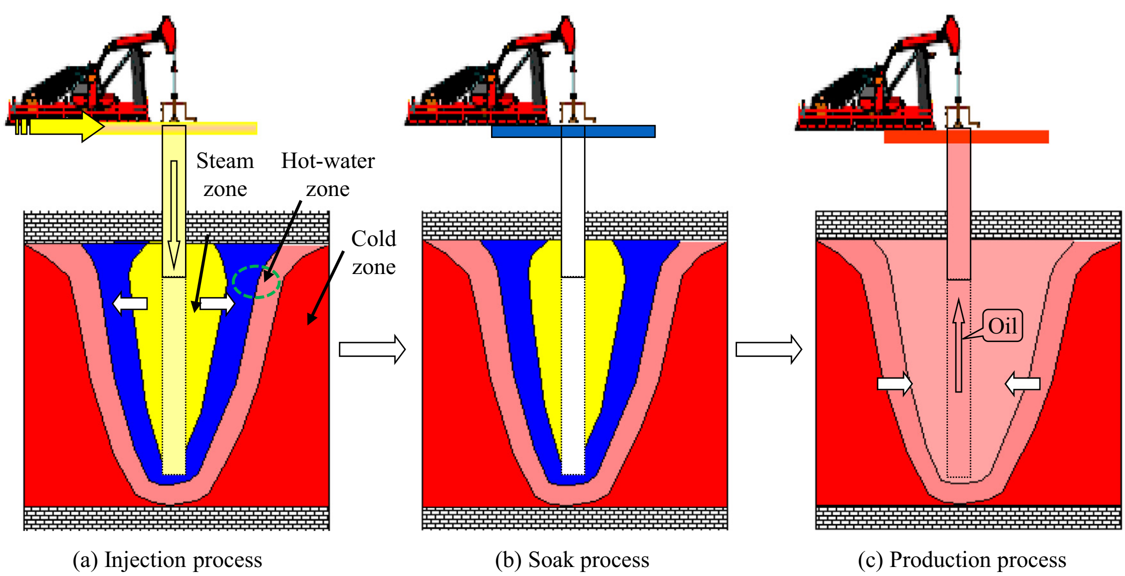

Fig. 1. Schematic diagram of steam huff-and-puff process for heavy oil production.

models assume the oil drainage region is divided into two areas, namely the heated area which is isothermal and the cold area with the temperature of initial reservoir temperature. Since then, these models have been applied for heated radius calculation and production prediction for a long time. However, there inevitably exists heat loss to the surroundings during the CSS process, which makes the heated area in the reservoir non-isothermal. Therefore, the models based on the isothermal assumptions may lead to errors.

In order to overcome the disadvantages above, much work has been done to improve the accuracy of the prediction model. Li et al. [26] and Yang et al. [27] summarized the previous research results, and assumed that the temperature declines linearly in the heated area, and proposed a concept of temperature front of the heated area. Accordingly, the concept of dynamic heated radius was created with the definition of sweep distance of the heated area front at a certain time. On the basis of flowing coefficient and the front temperature of the heated area with the viscosity-temperature curve of the crude oil, an improved equation for the calculation of heated radius was developed. The work provided a reference for the following studies and was applied for productivity prediction for CSS wells. Based on the new heated radius calculation equation, Ni et al. [28] calculated the productivity for a CSS horizontal well, and Sun et al. [29–31] studied the production performance of a vertical well with cyclic super-heated steam stimulation. Sun makes the non-isothermal assumption that the heated zone of the reservoir after super-heated steam injection is