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Evolution characteristics of SAGD steam chamber and its impacts on heavy oil production and heat consumption

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ABSTRACT

Currently, Steam-Assisted Gravity Drainage (SAGD) is the most successful commercialized method used to produce bitumen from oil sands and heavy oil reservoirs. Precise description of the steam chamber evolution is important for evaluating the economic effectiveness and Greenhouse Gas (GHG) emission of the SAGD process. In this study, the properties of MacKay River Oil Sands were used in laboratory experiments to compare the chamber evolution and production performance of SAGD under different permeability distributions. Then, a mathematical model was established to predict the steam chamber evolution and the closely related oil production and heat consumption in a heterogeneous formation. Next, the calculated production performance and steam chamber evolution were compared with measured experimental data to verify the accuracy of the model. Finally, the chamber evolution characteristics and their impacts on SAGD oil production and heat consumption are discussed in this paper for formations with different permeability distributions. The results indicate that horizontal permeability controls the evolution of steam chamber such that higher horizontal permeability may cause an obvious convex shape of the chamber edge, whereas vertical permeability has little effect on the chamber shape despite significant influence on the oil production in the early stage of SAGD. Moreover, a convex-shaped chamber interface indicates a higher production rate in the spreading stage and a lower rate in the depleting stage. In addition, this study shows that to minimize the heat consumption of the SAGD process, so that GHG emission can be curbed, a concave-like chamber shape is favorable in the early spreading stage, whereas a convex shape is better in the late spreading stage and depleting stage.

1. Introduction

Crude petroleum is still the dominant worldwide energy source, and the demand for petroleum-extracted fuels such as gasoline and kerosene has increased continually [1]. However, severe problems such as unstable crude oil price, the related environmental concerns and declining conventional petroleum reserves, etc., limit crude oil exploitation [2–4]. Hence, unconventional oil resources such as oil sands and heavy oil reservoirs must be efficiently exploited. The global total estimated reserve of heavy oil and oil sands is approximately 8 trillion barrels of oil in place [5,6], most of which is located in Canada, China, Venezuela and Russia. This total is about six times that of conventional crude oil reserves [7,8]. Nevertheless, heavy oil is difficult to recover owing to its extremely high viscosity in the reservoir. Typically, its recovery yields less than 8% of the original oil in place (OOIP) obtained by conventional water flooding [9].

During the last few decades, Steam-Assisted Gravity Drainage (SAGD) has become the most successful commercialized recovery method for oil sands and heavy oil reservoirs [10–12]. In the SAGD process, steam is continuously injected into a reservoir to expand the steam chamber. The heavy oil is heated near the chamber edge and drains along the interface toward the production well located 2–5 m beneath the injection well [13,14]. Therefore, the economics and environmental issues of the SAGD process depend heavily on the efficiency of oil production and Greenhouse Gas (GHG) emissions associated with steam generation by burning fossil fuels. Both of these issues are directly related to steam chamber evolution owing to the heat and mass transfer along and beyond the chamber edge [14,15]. The steam chamber tends to assume different shapes depending on the formation properties. Therefore, it is important to identify the steam chamber evolution characteristics in heavy oil reservoirs to evaluate the economic effectiveness of the process and to minimize the GHG emission. This is especially

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Nomenclature

a	coefficient of average velocity
A', B' and C'	coefficients of the interface velocity function
$C_{p,r}$	comprehensive reservoir thermal capacity, kJ/(°C·kg)
$C_{p,o}$	produced liquid thermal capacity, kJ/(°C·kg)
$C_{p,cap}$	thermal capacity of the cap rock, kJ/(°C·kg)
eff-effv	flow coordinate system
H_i	vertical distance from the ***i***-th element to the bottom, m
h-v	geological coordinate system
k_h	horizontal permeability, mD
k_v	vertical permeability, mD
l	chamber length in horizontal-well direction, m
m	coefficient of viscosity change
P	pressure, MPa
Q	heat consumption rate, kJ/d
q_o	oil production rate, m^3/d
$\bar{q}_{hloss}$	rate of heat loss per unit area, kJ/(m^2·d)
ΔS_o	movable oil saturation, %
T_s	steam temperature, °C
T_r	initial reservoir temperature, °C
t_b	critical time which the process switches from the spreading stage to the depleting stage, d
ΔT	temperature difference between the steam chamber and the liquid pool, °C
U	interface velocity, m/d
W_i	horizontal distance from the ***i***-th element to the well pairs, m
W_1	chamber width at the top of the steam chamber, m

Greek letters

α_r	thermal diffusivity of the reservoir, m^2/d
θ	angle between the interface and the horizontal direction
ξ_{effv}	distance from the chamber edge, m
δ_T	temperature penetration depth, m
υ_{os}	kinematic viscosity of heavy oil at the steam temperature, m^2/d
υ_o	kinematic viscosity of heavy oil at temperature T, m^2/d
λ_e	thermal conductivity of the reservoir, kJ/(m·d·°C)
φ	porosity, %
λ_{cap}	thermal conductivity of overburden, kJ/(m·d·°C)
ρ	density, kg/m^3

Subscripts

cap	overburden rock
con	heat consumption
cham	in the steam chamber
eff	direction parallel to the interface
effv	direction perpendicular to the interface
h	horizontal direction
liq	liquid
ob	overburden
res	in the reservoir
v	vertical direction

true for the current situation, in which the economic and environmental issues have become critical problems for the upstream petroleum industry and the related downstream fuel extraction process.

Butler et al. [13] derived an analytical model for determining the steam chamber growth rate and oil production rate by combining Darcy's law and heat conduction along with mass balance. However, the lower part of steam chamber edge in this model moves away from the production well, which is not physically realistic. Subsequently, Butler and Stephens [16] improved the previous theory [13] by finding the tangent line from the production well to the original steam interface curve. Their results showed better agreement with scaled laboratory data. By monitoring the temperature distribution of several scaled SAGD experiments, Reis [17] simplified the shape of the steam chamber as an inverted triangle and introduced an empirical equation based on the temperature profile to determine the oil viscosity ahead of the steam zone. The overburden heat loss rate was also calculated by Reis [17], based on the triangle-shaped steam chamber assumption. In addition to the heat loss to the overburden, Edmunds and Peterson [18] and Miura and Wang [19] applied energy balance and material balance equations to determine the heat accumulation inside and outside of the steam chamber during the process.

Although they are based on an assumed inverted triangle steam chamber, these previously mentioned classic studies are significant references for predicting the oil production and heat consumption of SAGD. However, to more effectively accomplish the above two tasks, a critical bottleneck should be resolved: how to accurately estimate the steam chamber shape when expansion is in different formations. This difficult problem has required researchers to assume other shapes of the steam chamber. Accordingly, Azad and Chalaturnyk [20] established a model by assuming the steam chamber to be of circular geometry. In their model, the steam chamber was regarded as a continuously expanding circle, and the oil reservoir was divided into numerous circular slices so that the constant relative permeability was replaced by varying relative permeability in Darcy's equation. Despite a highly accurate prediction of production, the circular model failed to present an accurate curved chamber shape, as shown in the experimental works of Butler and Stephens [16], Butler et al. [21], Chung and Butler [22] and Huang et al. [23]. Based on the previous experimental results, Wei et al. [24] regarded the steam chamber shape to be a symmetric parabola rather than an inverted triangle. Then, a mathematical model was proposed, and the oil production and heat consumption were calculated on the basis of the parabola chamber shape and energy conservation. Later, Sabeti et al. [25] developed a semi-analytical model by adopting an exponential geometry to predict the location of the interface. Although the steam chamber expansion rate is also assumed to be constant in the thermal calculation, which is similar to that shown in previous research [17–19], this model yielded more promising results. Other actual steam chamber shapes have been observed in several laboratory SAGD tests [23,26] and vary in shape according to the formation properties [27,28]. In other words, simplified models do not consider the effects of heat and mass transfer on the shape and are thus only rough approximations.

Therefore, an applicable approach needs to be established for modeling the exact chamber evolution in different formations considering the heat and mass transfer along the chamber shape, which is a key factor in determining the production performance and heat consumption of the SAGD process. In this paper, the steam chamber development and production of SAGD with different permeability distributions were first experimentally compared based on typical MacKay River Oil Sands properties. Then, a mathematical model was established to predict the steam chamber evolution in a heterogeneous formation. Next, the accuracy of the