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Full Length Article

Analytical solution for steam-assisted gravity drainage with consideration of temperature variation along the edge of a steam chamber

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ABSTRACT

Steam-assisted gravity drainage (SAGD) is a widely-used method for heavy-oil and bitumen recovery. Analytical SAGD models presented in the literature often overestimate bitumen-production rate substantially. Although bitumen-production rate and steam-oil ratio (SOR) depend significantly on temperature near the steam-chamber edge in SAGD, previous analytical models assumed the injected-steam temperature to uniformly distribute along the edge of a steam chamber. The main objective of this research is to develop the first analytical SAGD model that takes into account temperature variation along the edge of a steam chamber.

Local material balance and Darcy's law are applied to each cross section perpendicular to the edge of a steam chamber. Then, they are coupled with the global material balance for the chamber geometry that is an inverted triangle. New analytical equations are presented for bitumen-production rate and SOR, in addition to associated variables as functions of elevation from the production well, such as oil-flow rate and temperature along a linear chamber edge. Bitumen-production rate and SOR can be calculated for a representative chamber-edge temperature at a certain elevation from the production well.

Comparison of the analytical model with numerical simulations shows that bitumen-production rate and SOR can be accurately estimated when the new model is used with the temperature taken from the midpoint of the edge of a steam chamber. The chamber-edge temperature used for the new analytical model that gives accurate results can be up to 100 Kelvin lower than the injected steam temperature for a given operating pressure in the cases tested. The previous assumption of the injected-steam temperature at the chamber edge gives overestimated oil-production rates for SAGD. The constant temperature along the edge of a steam chamber gives Butler's concave interface of a steam chamber that is detached from the production well. For a chamber to exhibit a linear interface, temperature must vary along the chamber edge, which occurs in reality mainly because of heat losses to the over- and under-burden formations.

1. Introduction

Steam-assisted gravity drainage (SAGD) is a widely-used method for in-situ recovery of bitumen. In SAGD, high-quality steam (e.g., 90%) is injected into a bitumen reservoir through a horizontal well. The injected steam forms a steam chamber, and condenses near the edge of a steam chamber, where latent heat is released upon steam condensation. Along the edge of a steam chamber, the heated, mobile bitumen and hot water flow toward another horizontal well, which is located approximately 5 m below and parallel to the injection well.

Bitumen is extremely viscous, and usually not mobile at original reservoir conditions. However, bitumen viscosity is highly sensitive to temperature; e.g., it can decrease from several million centipoise (cp) at original reservoir temperatures to below 10 cp at 400 K [1]. This sensitivity of bitumen viscosity to temperature makes SAGD applicable for in-situ bitumen recovery. Recently, coinjection of steam and solvent has been also studied to improve thermal efficiency of SAGD [2–4]. In such coinjection processes, operating steam-chamber temperatures are lower than those in SAGD, because vapor-condensation temperature becomes lower in the presence of volatile solvents at a given operating pressure. This tends to reduce the amount of heat conduction to the overlaying formation rocks during bitumen recovery. Hence, chamber temperature plays an important role in in-situ bitumen recovery in terms of oil-production and energy efficiency.

Many analytical studies have been conducted to understand primary factors affecting bitumen production, and to estimate bitumen-recovery

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Nomenclature

SAGD	steam-assisted gravity drainage
SOR	steam-oil ratio

Greek Symbols

α	thermal diffusivity of reservoir
β_θ	parameter used to describe the extent to which flow direction deviates from steam chamber edge
θ	angle between steam chamber edge and horizontal
θ_{ave}	average angle of oleic flow along the chamber edge
μ	dynamic viscosity
ν	kinematic viscosity
ξ	distance normal to the steam chamber edge
ρ	density
τ	term defined by Eq. (A.8)
φ	porosity of reservoir
ω	acentric factor

Roman Symbols

a	an empirical constant used in Reis' model
a_1, a_2, a_3, a_4	density correlation constants in Eq. (12)
g	gravitational acceleration
H	vertical distance from reservoir top to the production well
h_i	equals to one-meter in this paper
I_o	integration of kinematic viscosity of oil phase in the cross-section perpendicular to steam chamber edge
k	permeability
k_{rave}	average value of relative permeability in each cross-section ahead of steam chamber
l	distance starting from production well in the direction along steam chamber edge
M	volumetric heat capacity
N_L	number of one-meter layers used in the calculation of SOR with Eq. (9)
q_o	oil flow rate
$q_{oil\text{-}prod}$	oil production rate at the production well
ΔS_o	reducible oil saturation of reservoir
T	temperature
U	chamber edge advancing velocity that is normal to the edge
U_o	flow velocity of oleic phase along steam chamber edge
v	chamber edge advancing velocity in horizontal direction
v_{max}	chamber edge advancing velocity at the reservoir top
W_s	width of steam chamber at reservoir top
x	mole fraction of a component in the L phase
Δy	unit length in the direction along the production well
z	elevation

Subscript

ceiling	contact area between steam chamber and overburden layer
D	dimensionless
e	steam chamber edge
L	the point where the perpendicular line from steam chamber edge ξ intersects with production layer
R	under reservoir condition
s	at steam temperature
o	oleic phase
over	overburden formation properties

efficiency in SAGD. Butler et al. [5] presented the first analytical SAGD model by combining material balance and Darcy's law as

$$q_{oil\text{-}prod} = 2\Delta y\sqrt{2kg\alpha\varphi\Delta S_o H/(m\nu_s)},$$

where $q_{oil\text{-}prod}$ is the oil production rate; Δy, k, g, α, φ, ΔS_o, H, and ν_s are the unit length of the horizontal production well, permeability, gravity constant, thermal diffusivity, difference between initial oil saturation and residual oil saturation, reservoir thickness and oil kinematic viscosity at the steam temperature, respectively. m is a constant reflecting the sensitivity of kinematic viscosity to temperature, and is defined in $\nu_s/\nu_o = [(T-T_R)/(T_S-T_R)]^m$ [6], where ν_o, T_S, and T_R are oil kinematic viscosity, steam temperature and initial reservoir temperature, respectively. The value of m is considered to be 3–4 for bitumen and heavy oil. Butler et al. [5] assumed the chamber-edge temperature (T_e) to be the steam temperature (T_S) at the operating pressure. Furthermore, T_e was assumed to uniformly distribute along the interface of a steam chamber. This assumption yields a concave edge of a steam chamber that extends to infinity at the reservoir top, and is detached from the production well.

Butler and Stephens [6] presented the "Tandrain" model by changing the constant 2.0 to 1.5 inside the square root in the equation given above, assuming that the bottom of a steam chamber was fixed at the production well. Later, Butler [7] proposed another model called "Lindrain" by changing the constant to 1.3, assuming a straight steam-chamber edge tangent to the production well. Calculation results from these revised models were more accurate than the equation given above. However, they still overestimated bitumen-production rates in SAGD.

Reis [8] proposed another SAGD model with a linear steam-chamber edge, which has been widely used:

$$q_{oil\text{-}prod} = 2\Delta y\sqrt{kg\alpha\varphi\Delta S_o H/(2am\nu_s)},$$

where the constant "a" was empirically set to 0.4, which is equivalent to replacing the constant 2.0 by 0.8 inside the square root in the equation of Butler et al. [5]. With the assumed chamber geometry of an inverted triangle, Reis applied material balance globally to the entire mobile-bitumen zone. Although Reis' equation gives a lower bitumen-production rate than the equation of Butler et al. [5], Tandrain, and Lindrain, it still tends to overestimate SAGD's bitumen production.

Various prior models added different considerations by making various modifications to the models of Butler et al. [5] and Reis [8]. Some modified the fluid model in Butler et al.'s models [5–7]. Bharatha et al. [9] considered the effect of dissolved gas on bitumen viscosity. Sharma and Gates [10] took into account a relative-permeability distribution ahead of the edge of a steam chamber. Mojarad and Dehghanpour [11] considered emulsion flow ahead of the edge of a steam chamber. Some studies modified Butler et al.'s model [5] in terms of reservoir properties. Cokar et al. [12] considered the effect of volumetric heat expansion on production in their analytical model. Irani and Cokar [13] considered the dependence of reservoir properties on temperature, and used local reservoir properties in their calculation. Studies based on Reis' model [8] include Akin [14], who considered the effect of asphaltene deposition on the oil-phase viscosity, and Azad and Chalaturnyk [15], who considered permeability heterogeneity in their analytical model.

All prior studies assumed that the chamber-edge temperature is equal to the injected-steam temperature at an operating pressure. However, observations from simulation results and field data [16,17] indicate that T_e varies along the edge of a steam chamber. Then, the main objective of this research is to develop the first analytical SAGD model that accounts for a temperature variation along a linear steam-