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Performance of Solvent-Assisted Thermal Drainage process and its relationship to injection parameters: A comprehensive modeling

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ABSTRACT

The addition of hydrocarbon solvents to the steam injection, known as Solvent-Assisted Thermal Gravity Drainage (SA-SAGD), has recently been proven to be a more energy saving and environmentally friendly method for heavy oil recovery. Nevertheless, the relationship between injection parameters and heavy oil production in conventional SAGD were always introduced to analysis the performance of SA-SAGD, which makes many confusing in the interpretation. In this paper, the heat lost to the cap rock of the reservoir is determined by taking into account not only the chamber-edge velocity, but also the temperature and mass distributions inside the chamber. Besides, by implicitly characterizing the chamber-edge shape and considering heat and solvent diffusion beyond the chamber edge, the oil rate is calculated. Then, the model couples heat and mass balance equations in the whole oil sand dynamically by considering the effect of liquid pool. This comprehensive method enables us to clearly examine the relationship between the Production-Injection Ratio (PIR) and the height of liquid pool. Lastly, the new model is verified by comparing predicted results with that of numerical simulation. The results show that, the oil rate of SA-SAGD is improved by both of the diluting effect of solvent on bitumen viscosity and a more reasonable chamber shape formed by co-injection solvent with steam. In addition, although heat-loss rate of SA-SAGD is generally smaller than that of conventional SAGD, the Steam-Oil Ratio (SOR) of SA-SAGD may even higher than that of SAGD in the late period of the process if the liquid level is extremely high. Moreover, the liquid-pool height for SA-SAGD is more sensitive to the PIR than for SAGD. Accordingly, when the effect of liquid pool on the production is considered, the PIR of SA-SAGD must be selected carefully.

1. Introduction

Crude oil is still the governing global energy resource, and the demand for crude-oil-extracted fuels such as kerosene and gasoline is increasing continually [1–3]. However, harsh problems, such as unsteady crude oil price, the environmental concerns and over-consumed conventional petroleum deposits, restrain the crude oil exploitation from the underground [4–7]. Therefore, unconventional petroleum sources, e.g., heavy oil reservoir and oil sand, must now be exploited efficiently. The worldwide approximated reserves of viscous crude petroleum is around 8 trillion barrels [8,9], most of which presents in Venezuela, Canada, Russia and China, and is almost six times as that of the conventional oil reserves [10,11]. However, viscous crude petroleum in heavy oil reservoir and oil sand is hard to recover owing to its high viscosity at the reservoir condition. Generally, it can only yield below 8% of the original oil by conventional water flooding [12]. Steam-Assisted-Gravity Drainage (SAGD), has been deemed as one of the most economically successful method for developing oil sands and heavy oil reservoirs [2]. In a normal SAGD process, high-temperature steam is inserted into the reservoir through the top-horizontal well, as shown in Fig. 1(a). After the steam enters into the reservoir and contacts the viscous oil, it will decrease the viscosity of oil by heating and then the low-viscosity oil is able to flow into the production well which is only a few meters below the injection well [13] as shown in Fig. 1(b). SAGD has been proved to be quite effective on Athabasca oil sand which is the largest discovered oil sand on earth [14]. Nevertheless, owing to the difficulties such as the complex water treatment and Greenhouse Gas (GHG) emission control caused by the steam generation [15,16], there are still potentials for the improvement of SAGD.

Solvent was first adopted for heavy oil exploitation in 1974, during which gaseous solvent was continually injected underground into the reservoir [17]. After that, numerous experimental [18,19] and modeling studies [20–22] have been conducted to analysis the recovery mechanisms of this kind of solvent injection process. To rise the production and to cut heat and water consumption in the SAGD process, Nasr and Isaacs [23] invented Solvent-Assisted SAGD (SA-SAGD) which

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Nomenclature

a	coefficient of average velocity
A', B', C', E', F' and G'	the coefficients of the interface velocity function and temperature function
C_p	thermal capacity, kJ/(°C·kg)
C_{si}	highest concentration of solvent in oil phase
D_o	molecular diffusion coefficient of solvent in the oil phase, m^2/d
D_g	molecular diffusion coefficient of solvent in the gas phase, m^2/d
H_i	the vertical distance from ith element to the bottom, m
k	permeability, mD
K	K value
L_v	latent heat of vaporization, J/kg
m	coefficient of viscosity change
M	molecular weights, kg/mol
N_{oL}	mole of heavy oil in oil phase within the steam chamber and at the chamber edge, mol
P	pressure, MPa
PIR	production-injection ratio
Q	heat consumption rate, kJ/day
$\dot{Q}$	net heat loss rate from the system, J/(m^3·d)
q_{in}	steam injection rate, m^3/d
q_o	oil production rate, m^3/d
q_{out}	liquid production rate, m^3/d
$\bar{q}_{hloss}$	the rate of heat loss per unit area, kJ/(m^2·d)
s	parameter in Laplace Transformation
S_g	gas phase saturation
ΔS_o	movable oil saturation
S_{or}	residual oil saturation
S_{irw}	irreducible water oil saturation
T_b	temperature in each part when the chamber top is separated into several parts according to the temperature distribution along it, °C
T_d	dimensionless temperature
T_l	temperature of liquid pool, °C
T_s	steam temperature, °C
T^{sat}	saturation temperature, °C
T_r	initial reservoir temperature, °C
t_b	the time when chamber edge reaches the reservoir boundary, day
t_c	the critical time when chamber edge entering the next part, day
U	the interface velocity, m/d
V	volume, m^3
W_i	the horizontal distance from i-th element to the well pairs, m
W_1	the chamber width at the top of the steam chamber, m
X	steam quality
z	vertical distance from the overburden surface into the overburden, m

Greeks

α_r	the thermal diffusivity of the reservoir, m^2/d
α_L	longitudinal dispersity factor
θ	the angle between interface and horizontal direction
δ_C	solvent-penetration depth, m
δ_T	temperature-penetration depth, m
υ_{os}	kinematic viscosity of heavy oil at steam temperature, m^2/d
υ_o	the kinematic viscosity of heavy oil at temperature T, m^2/d
ξ	length in the direction parallel to the horizontal plane, m
λ	the thermal conductivity, kJ/(m·day·°C)
φ	porosity, %
ρ	the density, kg/m^3

Subscript

cap	overburden rock
g	gas phase
i	index of chamber segment
j	index of component
L	liquid phase
LP	liquid pool
o	oil phase
SC	steam chamber
r	reservoir
w	water
s	steam
sol	solvent

is an improved version of traditional SAGD process by co-injecting a small amount of solvents with steam into heavy oil reservoir. Accordingly, SA-SAGD is regarded as a kind of viscous oil exploiting method with less GHG emission and possibly better economic effectiveness [24–27]. In SA-SAGD process, solvent is maintained at the superheated condition in the steam chamber [28,29]. When the solvent reaches the steam-chamber edge, it condenses and diffuses into the heavy oil to improve oil mobility. Nevertheless, characteristics of heat and mass transfer at the chamber edge is quite complex for SA-SAGD [18,28,30,31]. Specifically, due to the much lower diffusivity of solvent than heat beyond the chamber edge, the oil mobility near the chamber edge is controlled by both of heat and mass transfer, whereas it is dominated only by heat transfer at farther distance away from the edge, as shown in Fig. 1(c). Nasr et al. [32] supposed that the SA-SAGD functions finest if the solvent and steam could condensate simultaneously on the chamber edge when the saturation temperatures of both solvent and water are the same in steam chamber. However, Dong [33] recognized that the bubble-point temperature of the stream at the chamber edge should be achieved if solvent and steam are to condense together. Later, Keshavarz et al. [34] acquired the equilibrium condition at chamber edge for solvent and steam using Dong [33]'s approach. They realized that water is the only component that condenses inside the steam chamber. Besides, the gas-phase solvent accumulates gradually from injection end to chamber edge and condenses together with steam at the edge. By employing Dong [33]'s method, Liu et al. [28] analyzed the phase behavior of solvent–water mixture in the chamber and at the chamber edge. However, Liu et al. [28] didn't relate the phase behavior with the chamber-edge velocity and heat-loss rate, which is important for further analysis of SA-SAGD performance.

For Thermal-Assisted Gravity Drainage process (SAGD, SA-SAGD), energy consumption is intimately related with the heat lost to the overburden, as show in Fig. 1(b) and (c). In order to evaluate the heat-loss rate to overburden, Reis [35] grew a formulation for heat consumption of SAGD with a known chamber width. Edmunds and Peterson [36] also built a model taking into account the heat lost to the overburden. Next, the model was employed to predict the Steam-Oil