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Full Length Article

Semi-analytical modeling of steam-solvent gravity drainage of heavy oil and bitumen: Steady state model with linear interface

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HIGHLIGHTS

- Provides a closed-form solution for solvent-aided recovery of heavy oil and bitumen.
- Accounting for the solvent transverse dispersion, interface movement and heat loss.
- Developed solution for spreading and depletion stages of steam chamber development.
- Provides a tool to estimate SA-SAGD performance using SAGD field/laboratory results.

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ABSTRACT

With increasing world demand for energy, greater attention has been given to the exploitation of the huge resources present in the form of heavy oil and bitumen. Although thermal methods such as steam assisted gravity drainage (SAGD) have been successful in recovering heavy oil and bitumen, the low thermal efficiency of the process and the high level of greenhouse gas emissions and water usage remain major concerns.

Co-injection of solvent with steam has shown to be promising in enhancing oil rates as well as in reduction of energy and water consumption with lower environmental impacts. In hybrid steam-solvent methods, there is a balance between the solubility of the solvent and its ability to reduce bitumen viscosity, and the viscosity reduction due to temperature increase. Therefore, proper selection of the solvent for the operating conditions is key to improving the overall efficiency of the steam-solvent process over the steam-only method.

A steady state semi-analytical model is developed to predict the oil flow rate during spreading and depletion phases of steam chamber development in the solvent-aided SAGD (SA-SAGD) process. The model assumes steady state temperature and unsteady state concentration distribution ahead of the linear steam-bitumen interface. It also accounts for transverse dispersion and concentration-dependent molecular diffusion for solvent distribution employing the Integral Method.

The model is validated against CMG-STARS® thermal simulator and also SAGD experimental results for hexane co-injected with steam. It is shown that by adjusting a few parameters using SAGD results, the model can fairly predict the oil production and cumulative steam-to-oil ratio for the solvent-aided process with average absolute deviations up to 7% and 20%, respectively. The results suggest that the steady state model can be used as a screening tool for SA-SAGD. Also, it may be employed to find the optimum solvent candidate and the operational variables to maximize the flow rate of the SA-SAGD process. The model can also be applied for a mixture of solvents provided that the equilibrium experimental phase behavior data are available for a given solvent-bitumen system.

1. Introduction

The most commonly used in-situ thermal recovery methods for heavy oil and bitumen are cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD) where the viscosity of heavy oil or bitumen is reduced significantly by heating the reservoir to

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Nomenclature

B_3	dimensionless parameter
C	solvent concentration, m^3/m^3
C_p	specific heat capacity, J/kg·°C
C_s	equilibrium solvent concentration at the interface, m^3/m^3
D	diffusivity of the solvent into the bitumen, m^2/s
H	formation thickness, m
Pe	Peclet number, dimensionless
S_o	oil saturation
S_{wc}	endpoint saturation: connate water
S_{orw}	endpoint saturation: residual oil for oil-water relative permeability
S_{oirg}	endpoint saturation: irreducible oil for gas-liquid relative permeability
S_{org}	endpoint saturation: residual oil for gas-liquid relative permeability
S_{gc}	endpoint saturation: critical gas
T	temperature, °C
U	interface velocity, m/s
V	velocity vector, m/s
W	half width of the steam chamber, m
a	fitting parameter for temperature distribution
b	fitting parameter for solvent distribution
g	gravitational acceleration, m/s^2
h	drainage height, m
K_{rocw}	oil relative permeability at connate water
K_{rwiro}	water relative permeability at irreducible oil
K_{rgcl}	gas relative permeability at connate liquid
k	permeability, m^2
m	exponent of viscosity function
q	flow rate per unit length, m^2/s
q_R	flow rate ratio
t	time, s
x	coordinate system
x_s	parameter used in mixture viscosity correlation
z	coordinate system

Greek letters

α	matrix thermal diffusivity, m^2/s
δ_C	solvent penetration depth, m
ξ	transformed coordinate direction perpendicular to the interface
θ	inclination angle
κ_t	transverse dispersivity coefficient, m
μ	dynamic viscosity, Pa·s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
ϕ	porosity
χ	steam quality
Δ	difference

Subscripts

D	dimensionless
m	matrix
o	oil, overburden
s	solvent
w	water

steam temperature. In these processes it is necessary to heat the entire reservoir rock matrix and the heat losses to the overburden and underburden become increasingly important as the recovery processes mature. Therefore, such thermal methods may not be sufficiently energy efficient to allow economical production from marginal quality reservoirs such as those with thin pay, high shale content or high water saturation. Low-porosity carbonate reservoirs containing heavy oil and bitumen may also not be economically producible using steam injection. Of particular concern are the requirements for large volumes of fresh water for steam generation as well as the flue gas emissions containing carbon dioxide that result from the burning of fuel for steam generation.

In hybrid thermal-solvent process, steam and hydrocarbon solvent are injected into the reservoir in the vapor phase. The vaporized components condense at the interface between the bitumen and the steam/solvent vapor chamber and deliver heat to the reservoir matrix containing viscous bitumen. Both processes of heating and solvent dissolution act simultaneously to lower the oil viscosity resulting in drainage of bitumen towards production wells by gravity force. As a bitumen layer is removed, new surface of bitumen is exposed to the steam and solvent, and the process is continued until the production rate falls to an uneconomic level. In this process, at a given injection pressure, the operating temperature is lower than that of the steam-only process, which means that lower energy is required and less flue gas is emitted to the atmosphere compared to the SAGD recovery method. Typically, the steam-oil ratio for steam/solvent co-injection is lower than that for steam-only injection and this also reduces the fuel requirements for steam generation and the resulting carbon dioxide production. The solvent employed in the hybrid process with steam is more effective in mobilizing bitumen compared to the solvent-only processes; solvent has higher diffusivity into bitumen at the higher temperature of the hybrid process; also there is higher degree of physical dispersion and surface renewal due to faster drainage of bitumen.

Numerous experimental and modeling studies have been reported in the literature for each of the steam and solvent methods in heavy oil and bitumen recovery [1–7]. Since the upward growth of the steam or solvent chamber is very unstable during early stages of the process, most of the modeling efforts have been focused on the lateral expansion of chamber after it has reached the top of the reservoir. On the modeling side, most of the studies have been focused on the SAGD and VAPEX processes. While there have been a number of SA-SAGD experimental studies and many numerical simulation studies, there have been very limited attempts to model analytically the solvent-enhanced SAGD process.

Butler et al. [1] first developed a model which predicts the oil rate and location of the steam-oil interface in the SAGD process during the lateral expansion of the steam chamber, by assuming a steady-state temperature distribution ahead of the interface. Later, the coefficient of production rate was modified successively by TANDRAIN and then LINDRAIN theory which had more realistic oil rate predictions than the original model. Subsequently, Butler [3] developed a semi-analytical unsteady-state model by using a time-dependent heat penetration depth ahead of the interface. He also introduced a dimensionless group that was a measure of the convective fluid flow to the conductive heat transfer (i.e., the Rayleigh number). In both steady-state and unsteady-state models, the high velocity of the interface at the top of the reservoir provided an infinite surface area of the overburden exposed to heat loss. Butler explained that there are other mechanisms controlling the velocity of the top of the interface, which were not considered in the model.