



Assessment of energy efficiency and solvent retention inside steam chamber of steam- and solvent-assisted gravity drainage process



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HIGHLIGHTS

- Energy efficiency and solvent retention are critical for assessing SSAGD performance.
- A model for property profiles inside the steam chamber of SSAGD is proposed.
- Principles to optimize energy efficiency and solvent retention for SSAGD are given.

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ABSTRACT

Deeply-buried and high-bitumen-content crude oil is one of the most important energy resources. Currently, Steam- and Solvent-Assisted Gravity Drainage (SSAGD) is an attractive, but a high-cost and high-carbon-emitting method for exploiting this type of resource. In order to evaluate the greenhouse gas (GHG) emission and economic performance of SSAGD, it is critical to predict the energy efficiency and solvent retention in the steam chamber. However, the fluid property profiles inside the steam chamber, which are directly related to energy efficiency and solvent retention, have been rarely investigated. In this work, a semi-analytical model is developed for examining the property distributions within the steam chamber, considering the complex interaction of energy and mass transfer along with the effects of phase behavior. Subsequently, the solvent retention and energy-utilization/-saving efficiency are carefully analyzed on the basis of the calculated property profiles inside the steam chamber. The proposed method is mostly based on analytical relationships and is free from certain simplifications that may affect the calculations of energy efficiency and solvent retention in the SSAGD process. Furthermore, the optimal solvent type and injection pressure obtained with the model can reduce the GHG emission and improve the economic benefits of future SSAGD projects.

1. Introduction

Bitumen, which is a crucial petroleum resource, has been proven to be one of the largest oil reserves on earth [1]. It has been confirmed that the global supply of bitumen is more than twice as much of that of conventional oil, of which 80% is buried deep underground [2]. It is estimated that more than 8 trillion barrels of bitumen exists on the earth, of which approximately 900 billion barrels are exploitable by current technologies [3]. Bitumen normally has a viscosity higher than 10,000 mPa·s and a low API gravity in the reservoir condition [4]. The total bitumen reserve in Canada alone is estimated to be 179 billion barrels [5], and Steam-Assisted Gravity Drainage (SAGD) has been one of the most successful commercialized recovery methods for bitumen

reservoirs in western Canada within the past couple of decades [6]. In the SAGD process, steam is continuously injected into a reservoir to form and expand a steam chamber, and a large fraction of the energy injected in the form of steam is unavoidably wasted by heating the overburden [7]. The bitumen is heated only near the chamber edge and drains under the influence of gravity toward the production well a few meters beneath the injection well [8]. Therefore, SAGD is a highly energy-intensive process [9], which not only renders the economics of SAGD susceptible to oil prices [10], but also causes large greenhouse gas (GHG) emission associated with steam generation [11] by the burning of fossil fuels [12].

To save energy and to be more environmentally friendly, the technique of Steam- and Solvent-Assisted Gravity Drainage (SSAGD) has

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Nomenclature

$a, b, \text{ and } c$	coefficients for K-value correlation
$A, B \text{ and } C$	coefficients in Antoine's correlation
C_p	heat capacity, J/(mol \cdot °C)
$CP1\text{-}CP4$	coefficients of heat capacity correlation
D	effective diffusion coefficient of solvent in the gas phase, m 2 /d
H	specific enthalpy, J/mol
H_1	specific enthalpy of the mixture fluid in the vapor phase at the steam front, J/mol
H_2	specific enthalpy of the mixture fluid in the liquid phase at the steam front, J/mol
HVR	coefficient for the calculation of latent heat of vaporization, J/mol \cdot °C $^{0.38}$
K_{sol}	K values of the solvent component
l	horizontal distance between injection end and chamber edge, m
L_v	latent heat of vaporization, J/mol
M	molecular weight, kg/mol
N	segment numbers or data numbers
N_{oL}	mole number of heavy oil in oil phase
P_c	critical pressure, kPa
P_{sc}	pressure in steam chamber, kPa
p^{vap}	vapor pressure, kPa
\dot{Q}	net heat loss rate from the system, J/d
\bar{q}_{hloss}	heat loss rate per unit area, J/(d \cdot m 2)
q_{hloss}^{over}	heat loss rate to the overburden, J/(d \cdot m)
R	universal gas constant, J/(mol \cdot °C)
SR	solvent retention in the chamber, kg
S	saturation of a specific phase
S_{ori}	residual oil saturation defined in relative permeability curve
S_{or}	residual oil saturation
S_{wir}	irreducible water saturation
t	SSAGD production time, d
t'	chamber propagation time at the top of the chamber, d
T_c	critical temperature, °C
T^{edge}	temperature at the steam front, °C
T^{in}	temperature at injection end, °C
T_r	initial reservoir temperature, °C
T_{sat}	saturation temperature, °C
U_1	specific internal energy of fluid in the vapor phase at the steam front, J/mol
U_2	specific internal energies of fluid in the liquid phase at the steam front, J/mol

U_m	chamber propagation velocity at chamber top, m/d
U_ε	velocity of the advancing front of steam chamber, m/d
V	velocity of a specific phase, m/d
V_1	velocity of vapor at the steam front, m/d
V_2	velocity of condensate at the steam front, m/d
V'_2	convective heat transfer beyond the chamber edge in Fig. 3
W_ε	one half of the chamber width, m
x	coordinate parallel to the horizontal plane, m
X_{sol}	mole fraction of solvent in the oil phase
X	steam quality
y_{sol}	mole fraction of solvent in the vapor phase
y_{sol}^{edge}	mole fraction of solvent in the vapor phase at the chamber edge
Z	coefficient of compressibility of the vapor phase, kPa $^{-1}$

Greek letters

α	thermal diffusivity of the formation, m 2 /d
$\alpha_c, \alpha_1 \text{ and } \alpha_2$	coefficient for the calculation of molar density of solvent in oil phase
ρ	molar density, mol/m 3
ρ_L	molar density of oil phase, mol/m 3
ρ_L^0	reference molar density of solvent at the reference pressure and reference temperature
ρ_L^{edge}	molar density of oil phase at the steam chamber edge
ϕ	porosity of the reservoir
λ_c	thermal conductivity in the chamber, J/(m \cdot d \cdot °C)
λ_e	thermal conductivity beyond chamber edge, J/(m \cdot d \cdot °C)
ξ	normal distance to the advancing front of the steam chamber, m
ε	distance to the advancing front of the steam chamber in Fig. 3, m

Subscripts

cap	overburden rock
g	gas phase
L	oil phase
s	steam component
sol	solvent component
ref	reference condition
r	reservoir
o	heavy oil component
w	water phase

been proposed [13] and has attracted increasing attention in recent years. In the SSAGD process, a hydrocarbon solvent at low concentration in the steam is co-injected with steam to further reduce the viscosity of the bitumen owing to the combined effects of dilution and heat [14]. Moreover, the solvent is expected to reduce steam usage in the SAGD process [15] and reduce the heat loss to the overburden [16]; thus, as previous research has shown, the technique also boasts an improvement in the steam-oil ratio (SOR) [17], resulting in a lower energy consumption and GHG emission in comparison with SAGD [18] for exploiting deeply-buried and high-bitumen-content energy resources [19].

Although many results of co-injection cases are promising, specific drawbacks, such as solvent retention and significant energy consumption, may be encountered in SSAGD processes [20]. The sensitivity of economic performance to the solvent retention in the reservoir is substantially greater than the sensitivity to the fuel (gas) cost [21]. Moreover, Dong [22] indicated that moving from lighter to the heavier

solvents narrows the temperature difference between the chamber edge and the injection end, resulting in higher energy requirements both for heating the reservoir and for losses to the overburden. These reasons may explain the small improvements [23] or worse performances of SSAGD compared to SAGD in some cases [24]. In these situations, a large amount of energy from combusted fuel for steam generation is still needed, which results in substantial GHG emission [25]. Therefore, in order to evaluate the economic performance and GHG emission of the SSAGD process, it is necessary to predict the solvent retention and energy efficiency accurately. However, certain simplifications used in most of the existing models neglect significant heat and mass transfer mechanisms in the steam chamber, which may make the predictions of solvent retention and energy efficiency unreliable.

Solvent retention, an essential consideration in the economic performance of SSAGD, was previously investigated through numerical research. Leaute and Carey [26] showed that 80% diluent recovery is attainable through the use of proper separation facilities at the

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