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Selection of efficient solvent in solvent-aided thermal recovery of bitumen

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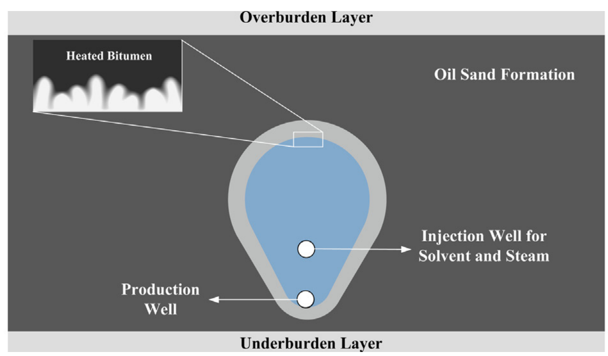
HIGHLIGHTS

- A linear stability analysis of the solvent and bitumen mass transfer is conducted.
- The azeotrope point of solvents/steam mixtures are taken into consideration.
- Scaling relations are introduced to estimate the onset time of instabilities.
- A fast screening method is developed to find efficient solvent.

GRAPHICAL ABSTRACT



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ABSTRACT

In solvent-assisted thermal recovery of bitumen, steam and solvent transfer their latent heat to the oil sands, mobilize the bitumen and co-condense on steam-bitumen interface. The mixing of heated bitumen with solvents further reduces its viscosity and the mobilized oil drains by gravity toward the production well. Co-injection of steam and solvent results in a gravitationally unstable diffusive boundary layer leading to convective dissolution of bitumen and solvent and thereby increases the oil recovery. We present a linear stability analysis to study the growth of convective instabilities and determine the onset of convective dissolution and the initial wavelength of instabilities. The scaling relations obtained from the linear stability are used to find the optimum solvent for solvent-aided thermal recovery processes by taking into account the azeotropic nature of solvent and steam co-condensation. The results show that an n-alkane carbon number range between 7 and 9 leads to earlier onset of convective dissolution, which is in agreement with the results of reservoir simulations. This study provides a fast screening method for selection of efficient solvent for the solvent-aided thermal recovery processes. In addition, the predicted initial wavelengths of instabilities facilitates selection of the proper grid size in numerical simulation of solvent and steam recovery processes.

1. Introduction

The most common enhanced recovery method applied for production of bitumen from oil sands is SAGD (Steam-Assisted-Gravity-Drainage) technique. In SAGD, steam is injected into the reservoir through an injection well and delivers its latent heat to the oil sands. Heating the reservoir leads to reduction of bitumen viscosity and mobilizes it toward the production well placed 5 m below the injector (Butler et al., 1985). However, SAGD has some drawbacks such as excessive energy consumption, greenhouse gas emissions, and environmental footprint. Co-injection of hydrocarbon solvents

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Nomenclature

C	solute concentration [M/L^3]
T	temperature [Θ]
t	time [T]
$\mathbf{v}$	velocity vector (u,v,w) [L/T]
w	vertical component of the velocity vector [L/T]
k	permeability [L^2]
p	pressure [M/LT^2]
g	gravity acceleration [L/T^2]
a	dimensionless wavenumber
a_x	component of the dimensionless wavenumber in x-direction
a_y	component of the dimensionless wavenumber in y-direction
A_l	coefficient in Fourier spectrum of the concentration perturbations amplitudes
B_l	coefficient in Fourier spectrum of the velocity perturbations amplitudes
D	molecular diffusion coefficient [L^2/T]
Ra	Rayleigh number

Greek Symbols

μ	viscosity [M/LT]
ρ	density [M/L^3]
λ	initial wavelength of instabilities [L]
δ	penetration depth obtained from HIM [L]
α	the coefficient of viscosity variation
β	the coefficient of density variation
ξ	unit vector in z-direction

Subscripts

D	dimensionless
b	base state
o	bitumen
sol	solvent
m	mixture
0	heated bitumen at the azeotropic temperature
c	critical (time and wavenumber)

Superscripts

'	perturbed property

with steam has been suggested to minimize these impacts and also to improve the recovery efficiency (Nasr and Isaacs, 2001). In this process, (Solvent-Assisted SAGD), the injected solvent and steam rise in the chamber and condense on the steam-bitumen interface. The mixing of solvent with the heated bitumen further reduces its viscosity and the mobilized oil drains by gravity toward the production well (Khaledi et al., 2015).

Convective mixing of diluents with bitumen was first observed in the experiments of Butler et al. (1985) who studied the process of upwards leaching of bitumen in Hele-Shaw experiments. In their experiments, solvent contacted bitumen from the bottom, and due to the lower density of the solvent compared to bitumen, enhanced mixing due to fingering instabilities were observed. They recorded the advance rate of the front and concluded that this rate is only dependent on permeability and independent of the number of observed convective fingers. Moreover, they stated that using heated solvents can increase the mixing rate, significantly.

To optimize the SA-SAGD recovery process, Khaledi et al. (2015) studied the solvent-steam phase behavior at operating conditions of the process using experimental data and numerical simulations. They stated that the conventional belief of simultaneous condensation of some hydrocarbon solvents (e.g., nC6) with steam does not resemble the real physics of the process in full detail. They indicated that the behavior of the binary mixtures of steam and hydrocarbon solvents with partial pressures close to steam is different in a way that these mixtures have an azeotrope point. For concentrations less than the azeotrope, most of the condensed liquid is comprised of water, and at the azeotrope point, the co-condensation occurs. The results of their numerical simulations suggested that among the studied solvents nC9 leads to the highest bitumen production increase as compared to SAGD.

In order to better understand the evolution of convective dissolution of solvents with bitumen, some authors conducted theoretical studies to predict the onset of this phenomenon. Javaheri and Abedi (2008) applied a linear stability analysis (LSA) to study the convective instabilities in the diluted oil boundary layer in VAPEX (Vapor Extraction) process. Their results showed that in field applications, the Rayleigh number, defined as the ratio of buoyancy forces over diffusion, is less than the critical value required for formation of convection currents and therefore this phenomenon can only happen in lab experiments with high values of permeability. In a more comprehensive study, Javaheri and Abedi (2013) took the effect of heavy oil viscosity reduction into consideration and concluded that convective mixing has the potential to arise in the VAPEX boundary layer in high permeable oil sand reservoirs, and have shown that the onset time of convective dissolution decreases as the viscosity reduction increases. In the most recent study, Rabiei Faradonbeh et al. (2015) performed an LSA for convective mixing at the solvent-steam-heavy oil interface. They considered a horizontal porous layer, saturated with bitumen and subject to heating by steam and solvent from the bottom. The variations of density and viscosity with both concentration and temperature were taken into account, and based on the minimization of the onset times, the efficient solvent was selected. Their results showed that butane and hexane lead to higher degree of instability compared to other solvents. However, the effect of an azeotrope point for mixture of steam and solvents was not considered in determination of the onset of convective dissolution. Moreover, their screening was done at a constant Rayleigh number which does not take into account the in situ thermophysical properties of individual solvents.

In this study, we aim at optimizing the solvent screening process based on maximization of the convective dissolution at the steam-bitumen interface (minimizing the onset time). First, we introduce the governing equations for stability analysis and model the bitumen-solvent density and viscosity based on the co-condensation temperature of steam and solvent at the azeotrope point using the available data in the literature. Then, we explain why the comparison of the onset times at a constant Rayleigh number can lead to incorrect conclusions. Finally, we compare our results with those of Khaledi et al. (2015), which have been obtained using a different approach, and show that the results are in very good agreement. The screening approach developed herein provides a fast method for selection of optimized solvent considering the real behavior of the binary mixtures of steam and hydrocarbon solvents.