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Full Length Article

Experimental and numerical study of the convective mass transfer of solvent in the Expanding-Solvent SAGD process

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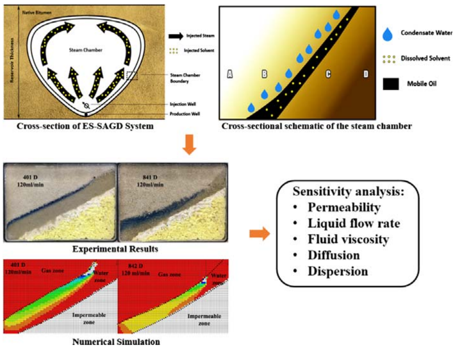
GRAPHICAL ABSTRACT



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ABSTRACT

In the Expanding-Solvent Steam-Assisted Gravity Drainage (ES-SAGD) process, the mass transfer of the dissolved solvent in the steam chamber boundary is critical to the oil production performance. In this study, experimental and numerical simulation approaches are used to investigate the gravity-driven convective movement of solvent in the steam chamber boundary in ES-SAGD. The experiments are conducted in a two-dimensional (2-D) sandpack model, in which a sloping gas-liquid interface in a closed system is developed as an analog of the steam chamber boundary in ES-SAGD. Thus, the flow along the sloping gas-liquid interface is used to represent the flow in the steam chamber boundary in ES-SAGD. Solvent mass transfer is observed by its concentration variation in the direction perpendicular to the flow surface. Later, CMG STARS is used as the simulator to execute the numerical simulations, and the simulation successfully captured the experimental results. In this study, the findings demonstrate the existence of convective solvent movement along the sloping gas-liquid interface. Furthermore, the results show that there is accelerated solvent movement along the interface under high permeability, and slow movement along the interface under high flow rate and high fluid viscosity. Diffusion and dispersion are tested by varying the corresponding coefficients in the physical and numerical models, and results show that these phenomena have negligible effect on the transverse solvent mass transfer process. This study found that gravity-driven convection is the dominant mechanism of solvent mass transfer in the steam chamber boundary in ES-SAGD.

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Nomenclature

c	mole concentration, mol/mol
d_p	particle diameter, cm
D_{AB}	diffusion coefficient of A-B mixture, cm^2/s
F	formation electrical resistivity factor, or simply formation factor
g	gravitational acceleration, m/s^2
j_A	mass flow rate of species A, kg/m^2·s
K	permeability, cm^2
k_l	longitudinal dispersion coefficient, cm^2/s
k_t	transverse dispersion coefficient, cm^2/s
n	mole fraction, mol/mol
Re_k	Reynolds Number of the flow in porous media
t	diffusion time, s
u	flow velocity in the porous media, m/s
U	fluid velocity in the bulk flow direction, cm/s

Greek letters

α	angle of the slope, °
ϕ	Porosity, fraction
$\nabla\omega_A$	gradient of the mass fraction, kg/kg·m
ν	kinematic viscosity, m^2/s

1. Introduction

In in-situ oil sands recovery processes, the extremely high viscosity of bitumen is a significant challenge. In Athabasca oil sands in northeastern Alberta, Canada, the bitumen viscosity ranges from one to six million centipoises under initial reservoir conditions, which makes the bitumen almost immobile [1,2]. Reducing the viscosity of bitumen to the extent that it becomes mobile is the essential requirement for in-situ bitumen recovery. Technically, two methods are primarily used to lower the viscosity of bitumen: heating up bitumen by steam injection, and diluting the bitumen by solvent injection [2].

Steam-Assisted Gravity Drainage (SAGD) is a widely applied technique for in-situ oil sands recovery in western Canada [2]. In the SAGD process, a pair of horizontal wells are drilled near the bottom of an oil sands formation. Steam is continuously introduced into the reservoir through the upper injection well, and the heated bitumen is mobilized and drains downwards to the lower production well. Steam fills up the pore spaces of reservoir as mobile oil and steam condensate move to the production well. The depleted zone established inside the reservoir is called the steam chamber [3]. The latent heat delivered by steam is transferred to the surrounding cold oil sands. Consequently, the mobilized oil drains downwards along the sloping steam chamber boundary to the lower production well, thereby providing more reservoir volume to be occupied by steam. Thus, the steam chamber grows upwards and sideways.

Expanding-Solvent SAGD (ES-SAGD) is an enhanced SAGD process with a small amount of steam replaced by hydrocarbon additives [4]. Fig. 1 displays the cross-sectional view of a steam chamber in ES-SAGD. The vaporized solvent that is injected along with steam into the reservoir dissolves into the bitumen at the steam chamber boundary with the aim of further reducing oil viscosity [5]. Indeed, in ES-SAGD, the oil viscosity is significantly affected by solvent dilution. From Shu's correlation, the viscosity of the mixture of Cold Lake Bitumen and GCOS (Great Canadian Oil Sands) Syncrude at 60 °C is on the order of 10^4 cp, while the viscosity can be decreased to only 10 cp when the solvent volume fraction reaches 0.65 [6]. To study the solvent distribution in an ES-SAGD process, the region in the vicinity of the steam chamber boundary is divided into four zones by occupied fluids properties [7]. As shown in Fig. 2, they are: (A) the non-condensation zone, (B) the steam condensation zone, (C) the mobile oil zone, and (D) the immobile oil zone. In the non-condensation zone, the pore space is primarily filled with a steam-solvent vapor mixture, and the temperature is at the saturation level without condensation; in the steam condensation zone, as the hot steam touches the cool oil sands at the steam chamber boundary, steam starts to condense and deliver its latent heat to the surrounding oil sands; in the mobile oil zone, all the steam has condensed and flows downwards together with heated up bitumen; finally, the immobile oil zone is far from the steam chamber and the oil is at the original reservoir temperature. In ES-SAGD, with a small amount of solvent added into the steam, steam condenses from the vapor phase, but solvent will not condense unless its concentration is extremely high [8]. Therefore, the solvent remains in the vapor phase and some of it dissolves in the oil under gas-oil equilibrium at the vapor-liquid interface. Many studies have demonstrated that solvent movement into the oil in the ES-SAGD process is significantly faster than the previously assumed diffusion-only process [2,7,10,21]. Further mixing of solvent

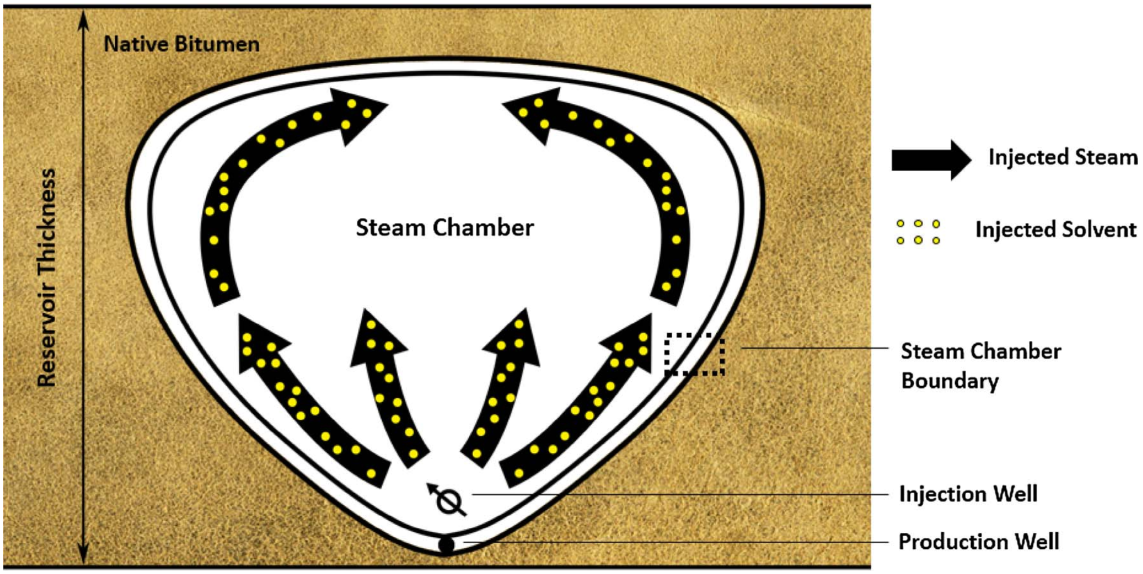

Fig. 1. Cross-section of the ES-SAGD process: the geometry of the steam chamber and flow of oil and condensate.