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Efficient oil displacement near the chamber edge in ES-SAGD

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ABSTRACT

Steam-assisted gravity drainage (SAGD) is the most widely used method for in-situ bitumen recovery. Expanding-solvent-SAGD (ES-SAGD) has been proposed as an alternative to SAGD to improve its efficiency. In ES-SAGD, steam is coinjected with a small amount of solvent. Detailed oil recovery mechanisms near the chamber edge are little known due to the complex interaction of fluid and energy flow, and phase behavior. Prior research on ES-SAGD explains that coinjected solvent can further decrease oil viscosity near the chamber edge by dilution, in conjunction with heat.

In this paper, we conduct a detailed investigation on oil displacement mechanisms and the placement of solvent near the chamber edge using fine-scale reservoir simulation. The importance of properly considering both phase behavior and flow to design ES-SAGD is demonstrated. Results show that ES-SAGD can achieve a higher displacement efficiency than SAGD. Oil production rate in ES-SAGD can be two times higher than that in SAGD. As a result, the ultimate oil recovery of ES-SAGD is enhanced by almost 20%, compared to SAGD in this research. The oil saturation reduction results from condensed solvent bank and phase transition near the chamber edge. The condensed solvent bank lowers the oil-component concentrations there. The diluted oil with solvent is then redistributed in the gaseous and oleic phases in the presence of the water phase on the phase transition at the chamber edge. The resulting amount of the oleic phase can be significantly small, yielding lowered oil saturations in the ES-SAGD chamber.

1. Introduction

Efficient recovery of unconventional oil resources, such as heavy oil and bitumen, is becoming more important considering the ever increasing energy demands. The main challenge in in-situ recovery of bitumen is its extremely high viscosity, which makes it essentially immobile at initial reservoir conditions. The most widely used method for bitumen recovery is steam-assisted gravity drainage (SAGD) (Butler, 1997). SAGD takes advantage of the strong temperature dependency of bitumen viscosity. Viscosity of a typical bitumen falls several orders of magnitude over the temperature range of 10–200 °C. In SAGD, steam of a high quality is injected using a horizontal injection well, which is located a few meters above a horizontal production well. Bitumen is mobilized by the latent heat released by the steam injected. Gravity is the main driving force for the mobilized oil to drain towards the production well. The disadvantages of SAGD are the costs and CO_2 emissions associated with generation of a significant amount of steam.

Expanding-solvent–steam assisted gravity drainage (ES-SAGD) has been proposed as an alternative to improve the efficiency of SAGD. In ES-SAGD, a small amount of hydrocarbon solvent is coinjected with steam to further reduce the viscosity of bitumen near the chamber edge (Nasr and Isaacs, 2001; Nasr et al., 2003). Gates (2007) reported that ES-SAGD requires a smaller amount of steam to recover the same amount of bitumen, compared to SAGD.

ES-SAGD, if designed properly, also can exhibit higher oil production rate than SAGD (Nasr et al., 2003; Gates, 2007; Ivory et al., 2008; Li and Mamora, 2010; Li et al., 2011a, 2011b; Yazdani et al., 2011). These studies cover a wide range of solvents (such as pure hydrocarbons from C_5 through C_8 and diluents) and reservoir oils (heavy oil and bitumen). As described in Keshavarz et al. (2013a), the extent of oil rate improvement can vary depending on the reservoir/operating conditions. There is still an ongoing debate on an optimum selection of solvent compounds, solvent concentrations, and operating conditions.

Gates (2007) conducted a simulation study on ES-SAGD with C_6 for the Athabasca bitumen and stated that temperature near the

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Nomenclature

Roman symbols

C_1	methane
C_2	ethane
C_3	propane
C_4	n-butane
C_5	n-pentane
C_6	n-hexane
C_7	n-heptane
C_8	n-octane
C_9	n-nonane
C_{10}	n-decane
C_D	dead-oil component given in Table 2
i	component index
j	phase index
j_o	oil-component molar flux in the oleic phase
k	permeability
k_r	relative permeability
L	oleic phase
u	velocity
V	gaseous phase
W	aqueous phase
x	mole fraction

Greek letters

μ	viscosity
ρ	molar density

Abbreviations

ARC	Alberta Research Council
GCOS	Great Canadian oil sands
LASER	liquid addition to steam for enhanced recovery
SAGD	steam-assisted gravity drainage
ES-SAGD	expanding-solvent–steam assisted gravity drainage
IFT	interfacial tension
VAPEX	vapor extraction

chamber edge in ES-SAGD can be lower than that in SAGD due to gaseous solvents accumulated there. Vapor–liquid phase behavior of solvent–steam systems resulting in such temperature profiles was given in Dong (2012) and Keshavarz et al. (2013a, 2013b) in detail. Higher production rates during ES-SAGD can be achieved only if the dilution effects of the coinjected solvent can offset the temperature reduction effect on the oleic (L) phase viscosity near the chamber edge. This indicates that understanding of the mechanisms in ES-SAGD requires detailed investigation of the non-isothermal multiphase flow near the chamber edge.

A few papers on steam–solvent coinjection indicated that it can reduce oil saturation below a residual oil saturation obtained from SAGD. Nasr and Ayodele (2006) observed that residual oil saturations in their ES-SAGD experiments were lower than those in SAGD. They used a Cold-Lake-type live oil and a C_4–C_{10} mixture as the coinjected solvent. Deng et al. (2010) conducted ES-SAGD experiments with the Athabasca bitumen and a diluent coinjected with steam. They presented figures indicating reduced oil saturations inside the ES-SAGD chamber, but their details were not discussed. Li et al. (2011a) conducted solvent-aided-SAGD experiments with the Athabasca bitumen and two different solvents: C_7 and a mixture of C_7 and xylene. They stated that theoretically, liquid solvent can flush out all residual oil. However, they did not explain how such miscibility can be developed in steam–solvent coinjection for bitumen. Yazdani et al. (2011) investigated numerical simulations of coinjection of n-alkanes ranging from C_3 to C_7 with steam for the Athabasca bitumen. They stated that lowered oil saturation could be attributed to the interfacial tension (IFT) reduction between phases during steam–solvent coinjection and the solvent amount in the residual oil phase. They recommended modifying the end-point saturations of relative permeability curves according to laboratory tests to capture IFT reduction in the dynamic coinjection simulation. Jha et al. (2013) explained the reduced residual oil saturation as a result of the partial evaporation of the condensed solvent that was mixed with bitumen. They reported that the residual oil saturation at a given point in the reservoir was correlated to the historic peak of the solvent concentration at that location. However, detailed mechanisms for the enhanced local displacement efficiency were not presented in their paper.

There are also field observations of improved production rates by coinjection of solvent with steam. In EnCana's Solvent Aided Process (SAP) in 2002 at Senlac, oil rate was improved by 50% shortly after butane was coinjected with steam in phase-C well pairs, which had been operated under SAGD. Similar improvement was reported after applying SAP in their Christina Lake project (Gupta et al., 2005; Gupta and Gittins, 2006). In another application of solvent–steam coinjection by Imperial Oil in Cold Lake, diluent was coinjected with steam in selected wells in their last cycles of cyclic steam stimulation (CSS). This application of coinjection was called Liquid Addition to Steam for Enhanced Recovery (LASER) and resulted in about 100% incremental oil production rates (Leaute, 2002; Leaute and Carey, 2005).

Interpretation of field pilots for this non-isothermal solvent process can be complicated by the complexities that exist in bitumen reservoirs. The heterogeneities of Athabasca bitumen reservoirs were described in Redford and Luhning (1999). As reported in the literature extensively, the local geology and petrophysics played a major role in SAGD operations (Edmunds et al., 1989; Redford and Luhning, 1999; Kisman and Yeung, 1995; Le Ravalec et al., 2009).

Edmunds et al. (1989) stated that low vertical permeability can damage the vertical rise of the chamber. As a result, the neighboring chambers may coalesce before reaching the top of the reservoir, leaving greater residual oil saturations in the top portion of the reservoir. Hosseininejad Mohebati et al. (2010) speculated that the vertical permeability can affect the heat transfer to the bitumen and the overburden when a gas layer forms near the chamber boundaries during the coinjection of non-condensable gases.

The generally isotropic McMurray oil sands are randomly interspersed with irregular shale bodies (Edmunds et al., 1989). The impact of shale barriers depends on their locations relative to well pairs. Barriers located between the injector and producer can inhibit the local steam-chamber development, even when they are small and discontinuous. For such a case, fractions of the well-pair horizontal section do not effectively contribute to the production for a long period (Le Ravalec et al., 2009). The effect of small and discontinuous barriers in other locations of the reservoir is likely less severe. They can be bypassed by the steam. Also, they can increase the contact area between the steam chamber and bitumen. A continuous barrier with only a few breaks may still allow for steam transport through these breaks; however, it can severely restrict the drainage of the L phase (Edmunds et al., 1989).