



Full Length Article

Pore-scale analysis of steam-solvent coinjection: azeotropic temperature, dilution and asphaltene deposition

Lining Xu^{a,1}, Ali Abedini^{a,1}, ZhenBang Qi^a, Mira Kim^a, Adriana Guerrero^b, David Sinton^{a,*}

^a Department of Mechanical and Industrial Engineering and Institute for Sustainable Energy, University of Toronto, 5 King's College Road, Toronto, ON M5S 3G8, Canada

^b Suncor Energy Inc., 150 – 6 Ave SW, Calgary, AB T2P 3E5, Canada

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ABSTRACT

Steam assisted gravity drainage is the main technologically and economically feasible method for *in situ* bitumen extraction. However, SAGD is energy intensive with economic and environmental challenges. Steam-solvent coinjection has proposed to improve SAGD performance, where hydrocarbon solvent is simultaneously injected with steam to increase the production rate and lower the steam-oil-ratio. The addition of solvent, however, complicates an already complex multicomponent thermal-chemical process. Microfluidics is well suited to quantify the pore-scale of steam-solvent coinjection with a tight control over experimental parameters. In this study, a high-pressure high-temperature micromodel combined with optical and thermal imaging is used to probe the pore-scale of steam-solvent coinjection process at relevant reservoir conditions. The effects of butane and hexane, as well as two industrial solvents, condensate and naphtha, on the pore-scale mechanisms are quantified and compared. The *in situ* thermal data is used to profile and analyze the condensation zone behavior and steam-solvent azeotropic temperature for all steam-solvent cases. We find that overall performance depends on the difference between steam-solvent azeotropic temperature and steam saturation temperature, the degree of solvent-bitumen dilution, and the degree of asphaltene precipitation in the condensing zone. In contrast with pure solvents and condensate, naphtha results in the highest recovery due to a higher steam-solvent azeotropic temperature, effective dilution, with minimal asphaltene deposition.

1. Introduction

Steam-assisted gravity drainage (SAGD) is the main *in situ* thermal recovery for bitumen extraction. SAGD includes injecting steam and producing bitumen via a pair of parallel horizontal wells drilled in the bitumen formation [1–5]. Saturated steam is injected from the upper well and condenses at the steam boundary, which in turn, delivering the latent heat to the bitumen. The bitumen viscosity significantly reduces as a result of heat transfer; allowing bitumen to flow toward the lower well (i.e., producer) under gravity force. While SAGD is effective with high production rate, it has significant economic and environmental challenges. Natural gas powered steam generation and associated CO₂ emissions are the major economic and environmental costs [6,7]. Some alternatives have been proposed to increase the performance of SAGD on both fronts, including steam-solvent coinjection, steam-additive coinjection, and pure solvent injection [8–13]. Among the aforementioned scenarios, steam-solvent coinjection is a hybrid approach that is attracting the most current interest [12,14–17]. This approach combines the advantages of steam in terms of delivering intense latent heat

at the oil interface, with solvent dilution, and promises a reduction in steam-oil-ratio (SOR) with and associated cost and emission reductions. It has been reported that small addition of solvent into the steam improves the recovery efficiency by ~25% and reduces the SOR by ~40% [14]. The addition of solvent, however, complicates an already complex multicomponent thermal-chemical process, necessitating careful planning and analysis.

Steam-solvent coinjection involves complex flow dynamics with a complex multi-component phase behavior occur under extreme operational conditions. A variety of methods have been used to assess the performance of steam-solvent processes, including large 3-D physical modeling [15,18–21] and numerical simulations [14,20,22,23]. With steam as the major component of the injected mixture, the challenge is to select a solvent whereby the solvent-steam condensation temperature – the azeotropic point – is matched that of pure steam. In this way the solvent travels effectively through the vapor chamber, and then condenses at the oil interface where it can provide dilution. While solvents with phase transitions close to that of pure steam (such as hexane) have been recommended for this process, recent numerical simulations have

* Corresponding author.

E-mail address: sinton@mie.utoronto.ca (D. Sinton).

¹ L.X. and A.A. contributed equally to this work.

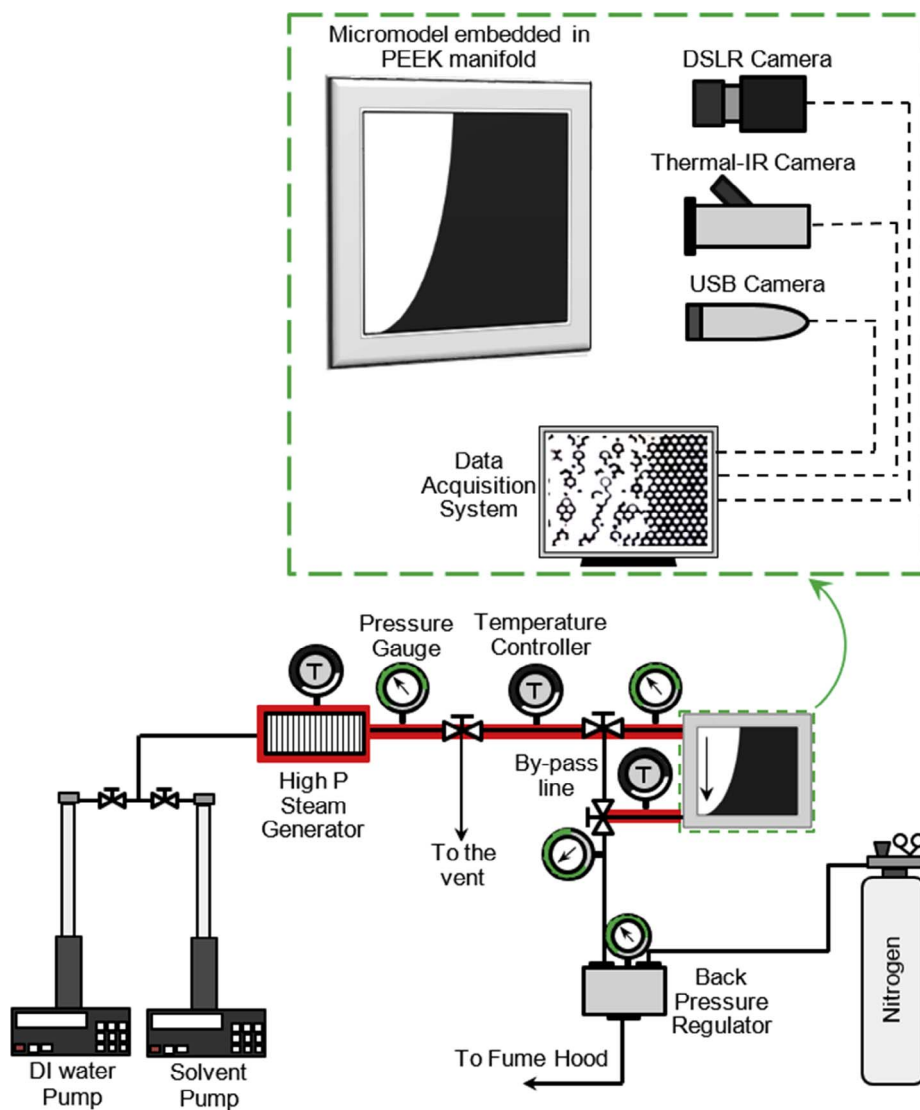


Fig. 1. Schematic diagram of the micromodel apparatus used for pore-scale analysis of steam-solvent coinjection, with the imaging system shown expanded on top. The red shading indicates the heating elements covered by insulations.

shown heavier hydrocarbon solvents (e.g., C_8 – C_{10} s) perform more effectively due to better match between the steam-solvent azeotropic temperature and the steam saturation temperature [12,24]. Large sand pack models also provide insight into overall effectiveness, showing for instance cumulative oil production as a function of total pore volume of injected phase, and overall size of steam chamber with some local temperature measurements [15]. While insightful, past experimental and simulation methods cannot resolve the full combination of condensation, dissolution, asphaltene precipitation and recovery at the oil interface – insight essential for this complex process.

Microfluidics-based approaches have been developed to probe the details of fluid interactions in various chemical and petroleum processes [25,26]. One important application is the measurement of phase properties of solvent-oil systems at relevant reservoir conditions [27–39]. There is also precedent for the application of microfluidics in phase measurement and recovery assessment of bitumen extraction processes. A T-junction pattern was employed to measure the diffusivity of a toluene-bitumen mixture using the variation of fluorescence intensity at the interface [40]. A similar chip was developed to measure the diffusion coefficient of CO_2 in Athabasca bitumen at pressures up to 5.0 MPa [41]. The solubility and diffusivity of propane in bitumen were measured using a microchannel version of a conventional PVT cell [42]. Likewise rheology of heavy oil during capillary driven flow has been

studied on-chip [43]. An associated body of work involves micromodels – microfluidic chips designed to mimic the reservoir rock pore geometries – to analyze the pore-scale dynamics of enhanced oil recovery processes [44–49]. Relevant micromodel studies of bitumen recovery include (i) pure steam and steam injections with alcohol- and alkaline-based additives [50–52], (ii) condensing solvent injection [53], and (iii) steam-solvent coinjection [54]. The latter one visualized the steam-solvent condensation at the bitumen interface with associated asphaltene precipitation and phase entrapments at atmospheric pressure using n-pentane and n-hexane as injected solvents with steam. The variety of previous micromodel applications points to the importance of pore-scale investigation of recovery processes. In addition to the direct observation of the fluid transport, micromodels provide a tight control over operating conditions (i.e., pressure, temperature, and saturation) with fast quantification, ease of operation, and low experimental cost; all stemming from small volume of fluid samples required for experiments.

In this paper, we quantify the pore-scale mechanisms of steam-solvent coinjection for bitumen extraction through optical and thermal imaging of a micromodel. Series of tests (i.e., pure steam and steam-solvent coinjection tests) were conducted with different pure and industrial solvents under relevant reservoir conditions. A suite of optical, thermal, and pore-scale microscopy tools are employed to capture the

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