Role of Bitumen-Water Interfacial Tension in Steam Assisted Bitumen and Heavy Oil Production; Solvent versus Surfactant Co-injection with Steam Processes

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ABSTRACT
Over 80% of Athabasca, Alberta, Canada oil sands deposits are suitable for bitumen production by thermal in-situ recovery processes, such as SAGD and CSS processes; by which bitumen is produced over 1,500,000 barrels/day capacity. Oil industry needs novel methods to improve thermal efficiency, improve profitability and reduce environmental footprints of these processes. For this purpose, solvent (light hydrocarbons) co-injection with steam is studied by oil industry, speculating that it would reduce bitumen viscosity and increase bitumen mobility as predicted by Darcy's Law; which resulted in limited commercial success. Interestingly, these studies neglected the effect of solvent on bitumen-water interfacial tension. At our laboratory, surfactant, such as biodiesel (fatty acid methyl esters) co-injection with steam is being developed as an alternative method to solvent co-injection with steam process. Steam assisted bitumen recovery tests were operated in continuous and batch (pressure cooker) modes, and high temperature-high pressure bitumen-water interfacial tension measurements were performed using pending drop method. Core samples from SAGD reservoirs, bitumen and process affected water recovered from bitumen-water emulsions produced by SAGD processes which were untreated with any chemical additive, were used in these tests. Bitumen recovery tests were made by operating the test unit as a pressure cooker, and showed that pentane addition into steam, at 5% and 15% of bitumen mass, reduced bitumen recovery efficiency by 39% and 61%, respectively, which contradicts expectations of solvent co-injection EOR methods. Our research findings suggest that solvent co-injection with steam further decreases bitumen viscosity, which is already reduced by thermal heating, but increases bitumen-water interfacial tension and causes slip of water at bitumen-water interface; which results in increase in water and decrease in bitumen mobilities. Experimental data on surfactant behavior of biodiesel and mathematical analysis of two phase immiscible fluids flow with slip boundary condition at bitumen-water interface will be discussed.

Key Words: Surfactant and solvent co-injection with steam, interfacial tension, bitumen recovery efficiency.

1 BACKGROUND

The Northern Alberta, Canada oil sands resources presents world's one of the vast hydrocarbon deposits, which extend over 77,000 km^2, distributed in three principle regions: Athabasca, Cold Lake and Peace River. The estimated crude bitumen in-place volume and ultimate potentials for recovery are $270x10^9$ m^3 ($1.6x10^{12}$ bbl) and $50x10^9$ m^3 ($300x10^9$ bbl), respectively. About 85% of these resources are in deeper formations, where the crude bitumen is not mobile because of high viscosity, over 10^4 mPa.s. Thermal in-situ production methods, such as Steam Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS) methods are commercially used for bitumen production. Existing bitumen production capacity by thermal in-situ methods is over $1.5x10^6$ barrels/day, which is projected to exceed $3.5x10^6$ in the next decade.

Efficiency and profitability of the steam assisted bitumen production processes are measured by the steam-to-bitumen S/B (by mass). Commercial experience of bitumen production in Alberta, Canada by steam assisted production methods showed that S/B are in the range of 2.3 to 5, even higher, depending on the reservoir characteristics. To reduce S/B ratio, enhanced oil recovery (EOR) methods are being developed based on different physical-chemical methods and principles.

The main obstacles to produce bitumen from deep formations are low reservoir permeability, in the order of 0.1 to 1.0 Darcy, and high bitumen viscosity, over 10^4 mPa.s. Viscosity of bitumen could be reduced by heating the reservoir by steam injection, in-situ combustion of bitumen, electrical or electro-magnetic heating methods. Another method to reduce bitumen viscosity is co-injection of solvents, such as light hydrocarbons, with steam. Based on these principles, several EOR processes, such as Steam Assisted Gravity Drainage (SAGD), Expanding Solvent-Steam Assisted Gravity Drainage (ES-SAGD), Cyclical Steam Stimulation (CSS), Toe to Heel Air Injection (THAI), Vapour Extraction (VAPEX), and N-Solv processes, were studied (Al-Bahlani & Babadagli 2009; Nenninger & Gunnewiek 2009; Butler & Mokrys, 1989). Among these processes, SAGD and CSS methods have proven to be reliable processes for commercial applications (Butler, 1998, 1991).

Commercial experience over three decades showed that SAGD process is the most efficient and economical process to produce bitumen. In this process a pair of parallel injector and producer wellbores, five meters apart, with 20 to 50 centimeters in diameter and 1,000 to 1,500 meters long is drilled into the oil sands reservoir of 150 to 700 meters deep. High pressure and temperature steam at above 90% saturation is injected into upper wellbore which results in the formation of a steam chamber.

SAGD reservoirs are heated mainly by steam, where thermal energy introduced by steam is transferred in the reservoir mainly by thermal conduction mechanism. In these applications, a saturated steam zone is formed in the neighbourhoods of the steam injection well. Steam condenses into hot water at the edge of this steam zone because of large temperature gradients. Saturated steam zone expands into the reservoir, at a slow rate, a few millimetres an hour, and the condensed steam (hot water) and bitumen flows together in a narrow zone (10 to 20 cm thick) in the neighbourhoods of the edge of the steam zone, under the influence of external pressure and gravitational forces.

The nature of the flow of two immiscible fluids, bitumen and water, in the reservoir is low Reynolds number creeping flow; because of which Darcy's law could be used to express bitumen and water mobilities in terms of permeability, fluid viscosity, and gradient of pressure and gravitational force fields:

$$\underline{v} = \frac{D}{\mu} \nabla P \quad (1)$$

where, $\underline{v}$, D, μ and ∇P are the fluid mobility (*m/h*), Darcy permeability (*m^2*), fluid viscosity *(Pa.s)* and gradient of pressure and gravitational force fields (*Pa/m*). Darcy law is the fundamental equation for reservoir development and oil production engineering (Farouq Ali, 2013; Hubbert, 1963).

Development of EOR methods for steam assisted bitumen production methods in Alberta, Canada are mostly based on solvent co-injection with steam methods. These studies are originated from the fact that solvent would be dissolved in bitumen and reduce bitumen viscosity, by which Darcy mobility of bitumen would be increase, as predicted by the Darcy law (Jha et al. 2013; Gupta & Gittins, 2012, 2006; Nasr & Ayodele, 2006; Nasr et al. 2003; Sharma & Gates 2011; Ayodele et al. 2009; Zhao et al. 2005).

In all these studies effect of solvent co-injected with steam on Darcy mobility was ignored. Darcy permeability depends on the wettability between the fluids, and between the fluids and reservoir rock. In fact, Darcy law is formulated from experimental observations of water flow in a porous media; which is related to Hagen-Poiseuille law for the laminar flow of incompressible, Newtonian fluids in tubes. Hagen-Poiseuille law is the solution of the approximated form of the Navier-Stokes equation for very slow, low Reynolds number flows, where inertia forces are neglected compared to pressure and viscous forces and using no-slip fluid velocity on the tube wall boundary condition (Bird et al. 1960). In steam assisted bitumen production processes, solvent co-injection with steam reduces bitumen viscosity; however, it increases interfacial tensions (IFT) between the fluids, and between the fluids and reservoir rock, which could reduce bitumen mobility (Berg et al. 2008; Ozum, 2018).

Recovery of solvent co-injected with steam into the reservoir is a sincere challenge for solvent based EOR processes; which remains an unsolved issue for the profitability of solvent based EOR processes.

Our research showed that surfactant co-injection with steam could be an alternative to solvent co-injection with steam processes; provided that surfactant is chemically stable under high temperature-high pressure (such as 200 ^oC temperature and 1.6 MPa pressure) reservoir operating conditions, and its use is safe, environmentally friendly and cost effective. Our research showed that biodiesel (*BD*) could be used as surfactant additives to improve the efficiency of steam assisted bitumen and heavy oil production, CHOPS (cold heavy oil production with sand), Post CHOPS, heavy oil production with cold water flooding and tertiary oil recovery processes.

2 USE OF BIODIESEL AS A SURFACTANT ADDITIVES IN SAGD AND CSS PROCESSES

Since 1930s, it was known that reduction of bitumen-water IFT promotes bitumen liberation from oil sands ore, thereby boosting the bitumen extraction efficiency in oil sand ore-water slurry-based extraction processes. Because of this reason, caustic *NaOH* was used as an additive to activate naphthenic acids naturally present in bitumen, which reduces bitumen-water IFT and improves bitumen recovery efficiency. It was also known that naphthenic acids naturally present in bitumen are activated under slightly alkaline water involved in steam assisted bitumen production processes contribute bitumen production efficiency.

The use of surfactants as additives, sometimes along with non-condensable gases, were tested during 1980s to boost the heavy oil production by steam drive and cyclic steam injection processes (Castanier, 1989). However, until recently, to promote steam assisted bitumen production processes, reduction of bitumen viscosity by solvent co-injection with steam attracted more attention than surfactant co-injection with steam to reduce bitumen-water IFT (Guerrero et al. 2018; Jonasson et al. 2018; Taylor, 2018; Zeidani & Gupta, 2013).

At our laboratory use of biodiesel (*BD*) as a surfactant additive in oil sands ore-water slurry-based extraction processes was investigated (Ozum & Scott, 2010). Similarity between the mechanisms of bitumen production in ore-water slurry extraction and SAGD processes was the driving force for the initial phase of our work on the use of *BD* as a surfactant additive in steam assisted bitumen and heavy oil production processes, such as SAGD and CSS processes. (Babadagli et al. 2009).

Biodiesel (*BD*) is the commercial name of fatty acids methyl esters, which are of chemical formula: $C_nH_mCOOCH_3$; $m < 2n + 2$). The hydrocarbon chain, C_nH_m, is of hydrophilic, and the methyl ester group, $COOCH_3$, is of hydrophilic characteristics; therefore, *BD* has attractions to oil and water, because of which *BD* can be used as surfactant additives for enhanced oil recovery (EOR) processes. *BD* is commercial commodity which could be produced from a wide range of vegetable oils and tall oil (by-product of bleach Kraft paper mills) fatty acids by simple chemical processes. *BD* could be supplied for EOR applications under \$2,000/ton, which could be used for commercial applications in simple, cost effective and safe manners.

At our laboratory, surfactant behavior of two *BD* samples produced from two different fatty acids were tested. These *BD* samples were of about 0.8 g/mL density, TAN (total acid number acid numbers) of 0.14 mg-*KOH*/g-*BD*), boiling temperatures were over 325 ºC; possessed sufficiently high vapor pressures (0.64 kPa and 1.67 kPa) for their use in steam assisted bitumen and heavy oil production processes. At 20 ºC, *BD* surface tension (γ_{BD}) and *BD*-water IFT ($\gamma_{BD/W}$) were measured as 28.6 and 9.7 mN/m. Fundamental characterization data generated on *BD* samples at our laboratory are consistent with the data generated at other laboratories (Castellanos-Diaz, 2012; Yuan et al. 2005, 2003).

When *BD* is co-injected with steam as a surfactant additive, it evaporates in steam, penetrates through the reservoir with steam, condenses with steam and produces stable *BD*-water micro-emulsions, while fraction of the *BD* dissolves in bitumen; by which it reduces bitumen-water IFT ($\gamma_{B/W}$) and promotes bitumen mobility (Berg et al, 2008; Ozum, 2018). Formation of BD-water micro-emulsions also promotes solubilization of bitumen in water (condensed steam) phase, which increases bitumen production sweeping efficiency.

Our laboratory scale high temperature (200 ºC)-high-pressure (1.6 MPa) steam assisted bitumen production tests generated encouraging results. Use of *BD* as a surfactant additive at about 2.0 g/kg-bitumen dosages (corresponds to 0.320 kg/bbl-bitumen or 0.667 kg/ton-steam assuming plants are operating at S/B ratio of 3:1), signiificantly increases bitumen production efficiency. In the first set of tests *BD* was sprayed on high grade oil sands ore at 2 g-BD/kg-bitumen dosages; while in the second set of tests *BD* was injected into high pressure steam line at the same dosage; results of which are presented in Figures 1 and 2 (Babadagli & Ozum, 2012).

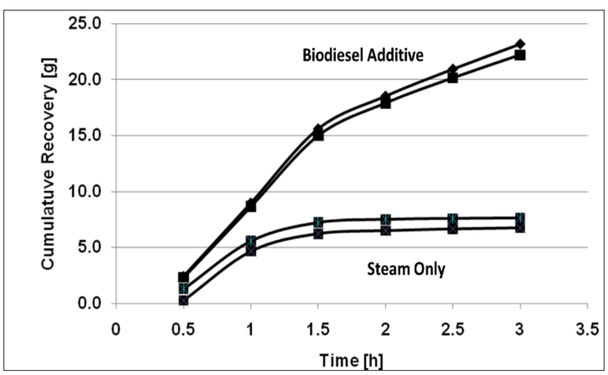

Figure 1. Steam assisted bitumen recovery test; *BD* was added on ore sample before placed in the steam chamber (Babadagli & Ozum, 2012).

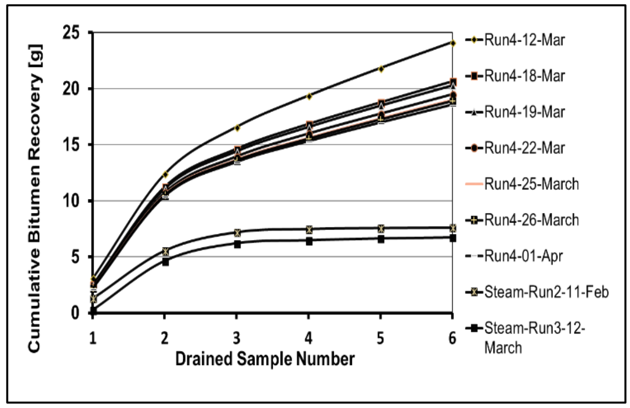

Figure 2. Steam assisted bitumen recovery test; *BD* was added into high pressure steam line (Babadagli & Ozum, 2012).

2.1 Bitumen Production Tests using Solvent (Pentane) and *BD* (Surfactant) Additives

Effects of solvent (such as pentane) and surfactant (such as *BD*) co-injections on the efficiency of steam assisted bitumen production processes were evaluated using SAGD reservoir core samples received from Devon Canada Corporation, using a high-pressure vessel operating in batch mode at about 3 days long (Naderi et al. 2015a). It is believed that these tests simulate the saturated steam zone of a SAGD reservoir. Bitumen and process affacted water characterization tests were made on bitumen and water samples, which were recovered from bitumen-water emulsion sample (without using any chemcial additive), also received from Devon Canada Corporation (Argüelles-Vivas et al. 2012).

Results of the tests to evaluate the effects of solvent (pentane) and surfactant (*BD*) on steam assisted bitumen recovery process, operating the high pressure cell in batch mode, are presented in Figure 3.

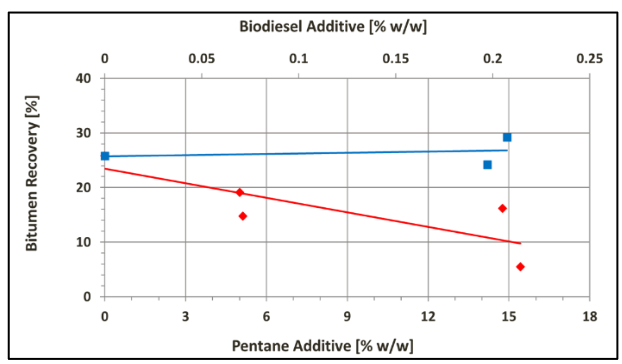

Figure 3. Batch steam assisted bitumen production tests using pentane and *BD* additives (Naderi et al. 2015a).

As seen in Figure 3, pentane addition into SAGD process significantly reduced bitumen production efficiency compared to that of steam only and steam and *BD*. It was interpreted that solvent addition into steam increases $\gamma_{B/W}$ and the slip velocity at bitumen-water interface and supressed bitumen mobility and bitumen production efficiency (Naderi et al. 2015a). These findings contradict the arguments made in the open literature on the use of solvent to promote efficiency of steam asssited bitumen recovery proceses.

After the steam assisted batch bitumen production tests were finalized, the spent reservoir core samples were cut into about eight peaces of about 1.5 to 2.0 cm long and bitumen-water-solids contents were determined by Dean-Stark extration. A plot of a typical bitumen-to-solids ratios as a function of core sample height for steam only bitumen recovery test is presented in Figure 4. Bitumen mobility was calculated from the best fit of the bitumen saturation profile data to the bitumen mass balance for the flow of two immiscible and incompressible fluids ($\nabla \cdot \underline{v} = 0$, $\nabla \cdot$ is the divergence operator, *div* $\underline{v}$), a first order partial differential equation, the wave equation given in Equation 2 (Helfferich 1981; Buckley and Leverett 1942):

$$\frac{\partial S_B}{\partial t} + v_B \frac{\partial S_B}{\partial z} = 0 \qquad (2)$$

where, S_B, z and t are the bitumen saturation of the core sample, distance in vertical direction and time. From the best fit of the experimental data generated by steam only test (non-additive) to the solution of Equation 2, bitumen mobility (v_B) and corresponding Darcy mobility (D_B) were calculated as 1.6x10^{-3} m/h and 0.83 Darcy (8.3x10^{-13} m^2).

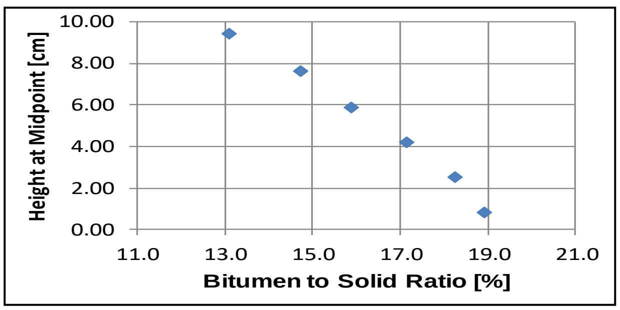

Figure 4. Spent ore bitumen and solids contents at different heights (Naderi et al. 2015a).

Bitumen effective permeability predicted from the steam only batch test results was lower than that of the commercial experience reported in the literature (Cenovus, 2013; Touhidi-Baghini, 1998). Higher bitumen permeability reported based on the commercial experience suggests that major bitumen production happens at the edge of the saturated steam zone and activation of naphthenic acids to surfactant species because of high alkalinity of the process affected water (*pH* of 8.1).

Two major bitumen producers using SAGD process intersted in third party verification tests to evaluate performance of *BD* as surfactant additive. Two tests were made at two different laboratories; however, these tests were performed under water flooding modes, results of which could not provide convincing evidences. Test performed by one of the major chemical company showed that *BD* as a surfactan additive increases steam asssited bitumen recovery efficiency.

Tests made at the University of Alberta, NSERC's IRC on EOR, chaired by Dr. T. Babadagili, University of Alberta, showed that *BD* perfomed the best, increasing oil production efficiency by 23%, among the surfcatans propsoed for EOR processes (Bruns and Babadagli, 2017). Further research are being progressing collaborating with the NSERC's IRC on EOR, University of Alberta on the production of *BD*-water micro-emulsions and its performance to increase efficiency of heavy oil production by cold and hot water floowing methods (at up to 90 ºC tempertaure) (Lee etal. 2018).

2.2 Use of *BD* as Surfactant Additives in CHOPS, Post CHOPS, Cold Water Flooding and Tertiary Oil Production

At our laboratory, performance of *BD* as surfactant additives for cold heavy oil production with sand (CHOPS), Post CHOPS, heavy oil production with cold water flooding and tertiary oil recovery processes has been progressing. FT measurements were made on heavy oil-water-solvent (pentane)-surfactant (*BD*) systems at different *pH* and up to 50 ºC temperature (at atmospheric pressure); where heavy oil and water samples were recovered without any chemical additive from oil-water-sand slurry produced at Baytex Energy Corp.'s CHOPS production plant. Experimental data showed that solvent and acids additions increase oil-water IFT; which promotes slip velocity at oil-water interface and potentially reduces oil mobility.

Use of *BD* as surfactant additive reduces oil-water IFT in the presence of solvent and acidic additives, as shown in Figure 5, Figure 6 and Figure 7 (Naderi et al. 2015b). These experimental observations made us to speculate that use of *BD* as surfactant additives in CHOPS and Post CHOPS professes would cure effects of light hydrocarbons (C_1 to C_5) and acidic gases such as CO_2 and H_2S on the increase in oil-water IFT detrimentally effecting on oil mobility in the reservoir. Our experimental observations showed that *BD* could also be used as surfactant additives for cold (up to 90 ºC temperature) flooding productions too.

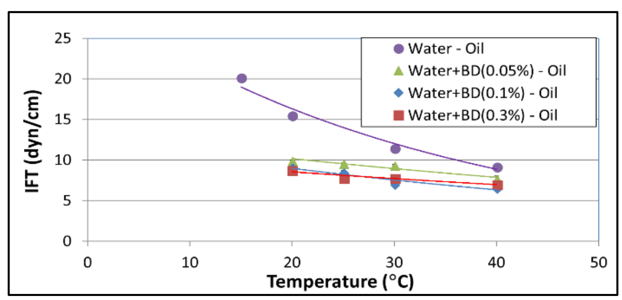

Figure 5. Effect of pentane on oil-water IFT (Naderi et al. 2015b).

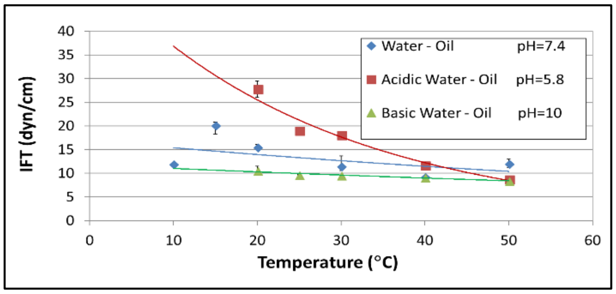

Figure 6. Effect of *pH* on oil-water IFT (Naderi et al. 2015b).

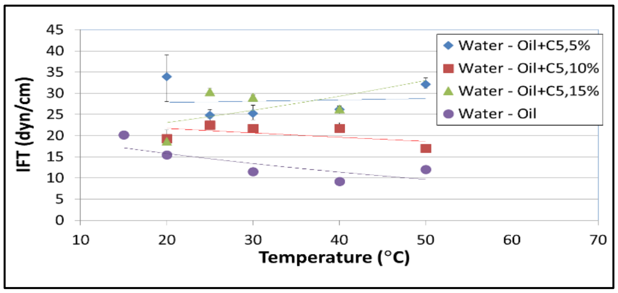

Figure 7. Oil-water IFT, oil-water-pentane-*BD* system (Naderi et al. 2015b).

In all these EOR applications, stable *BD*-water micro-emulsions could be produced by steam distillation of *BD* followed by condensation of *BD*-steam in water, rather than dispersing *BD* in water by high shear mechanical mixing methods. Our laboratory tests showed that *BD* contents of such emulsions needs to be about 0.67 kg-*BD*/ton-water; however, the optimum *BD* concentrations could be different for each reservoir, which would be determined by field trials and commercial experience.

3 CONCLUSIONS

Use of *BD* as surfactant additive could be an alternative to solvent co-injection with steam to boost the efficiency of steam assisted bitumen and heavy oil production methods. In steam assisted process *BD* could be injected into high pressure steam line at about 0.67 kg/ton-steam dosages. *BD* could also be used as surfactant additives to improve the efficiency of CHOPS, Post CHOPS, cold heavy oil and tertiary recovery processes by *BD*-water micro-emulsions flooding, using *BD* at similar dosages. In cold production applications, *BD*-water micro-emulsions should be prepared by steam distillation of *BD* followed by condensation of *BD*-steam mixture. Sufficient data are available for the design, commission and execution of field trials to test performance of *BD* as surfactant additives in EOR applications before its commercial implementations.

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