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STUDY OF SOLVENT-ASSISTED IN SITU BITUMEN RECOVERY

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DISCLAIMER

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Abstract

*Solvent assisted in-situ heavy oil and bitumen recovery technologies, such as the solvent assisted gravity drainage process, offer the potential for high recovery factors using less energy and water than do established thermal technologies. The production rate of heavy oil/bitumen in a solvent assisted recovery process depends on the rate of mass transfer of solvent into oil in porous media. Therefore, solvents with the potential to exploit mass transfer mechanisms through all phases (oil, water and gas) might offer the potential for enhanced oil production rates. Comparative experimental tests of vapor solvent assisted bitumen recovery by different solvents, i.e. propane, n-butane and DME (dimethyl ether), were undertaken in a lab physical model, using a 4 Darcy water-wet sandpack saturated with Athabasca bitumen. Relative to propane and butane, DME achieved 3 to 4 times higher oil drainage rates in these experiments. Detailed numerical evaluation of the test with DME revealed that the solubility and diffusion of DME in water improve significantly the effective diffusion of DME in bitumen in the water-wet sandpack and enhance the rate of dilution of bitumen and thus its drainage rate. Preliminary field scale simulation studies predict that a vapor DME assisted gravity drainage process, with a well configuration similar to that of SAGD in a typical Athabasca bitumen reservoir will have an average bitumen production rate of ~0.048*m^3*/day/m (well length) at an average bitumen-to-net DME ratio of ~5.3* m^3 *(bitumen)/ton (DME) over 14 years. A preliminary assessment of the availability and supply cost of DME indicate that, assuming abundant natural gas, the longer term supply cost for DME is expected to be about 65% of the WTI price. A brief evaluation of the environmental and safety aspects of using DME in an in-situ recovery processes show that DME is, apart from its high volatility and associated flammability concerns, relatively benign.*

Introduction

Solvent assisted in-situ heavy oil and bitumen recovery technologies, such as the solvent assisted gravity drainage process, are viewed to offer the potential of high recovery of heavy oil and bitumen using less energy than do thermal technologies such as the SAGD process, thus less environmental impact by the oil recovery process.

The solvent assisted gravity drainage process, also known as the Vapex process[1], was invented as an analogy to the SAGD process. In this process as originally conceived, solvent vapor at ambient temperature is injected into the reservoir to dilute the bitumen such that a bitumen-solvent mixture with low viscosity can flow to the production well under gravity.

Production rate of heavy oil/bitumen in the solvent assisted recovery process depends on effective mass transfer of solvent into oil in porous media, which is affected by molecular diffusion, convective dispersion of solvent and capillary mixing via the three phases (oil/water/gas phases) fluid system. The significance of different mass transfer mechanisms that influence the oil production rate in a solvent injection process is relevant to the solvent type and the operating conditions.

Comparative experimental tests of vapor solvent assisted bitumen recovery by different solvents, i.e. propane, n-butane and DME (dimethyl ether), were undertaken in a lab physical model, using a 4 Darcy water-wet sandpack saturated with Athabasca bitumen, to provide insight into the impact of solvent selection on the oil drainage behavior of solvent vapor assisted gravity drainage. The parameters monitored in these experiments were oil drainage rate, solvent intake, composition of the produced oil, and residual oil saturation.

The results of the comparative tests showed significantly different oil drainage behavior between DME and the normal hydrocarbon solvents propane and n-butane.

Numerical analysis was conducted to assess the key mechanisms inducing the significant different oil drainage behavior of the test with vapor DME injection as compared to those tests with propane or n-butane injection.

Measurement of fluid properties, including the solubility of DME in bitumen and water, and the viscosity reduction effect to bitumen of DME dilution at the test conditions, were conducted to support the numerical simulation.

Preliminary field scale numerical simulations were performed to evaluate the performance of a vapor DME assisted in-situ bitumen recovery processes. A preliminary assessment of the availability and supply cost of DME was also conducted. Also a brief evaluation of the environmental aspects of using DME in in-situ recovery processes was conducted.

Lab Experiments

The experimental tests were undertaken in a lab physical model using a 4 Darcy water-wet sandpack saturated with Athabasca bitumen. A brief description of the lab tests and a summary of the experimental results follow.

Lab Test Apparatus

A lab physical model (pictured in Figure 1) was used to conduct the experiments. A sandpack model with dimensions of 4.5cm × 4.5cm × 120cm-long packed with sand at close to field condition (4 Darcy), water-wet and saturated with dead Athabasca bitumen was placed in the physical model filled with vapor solvent at near saturation pressure. The upper surface of the sandpack model was exposed to the vapor solvent. The physical model with the oil-saturated sandpack model was positioned at a dip angle of 45° as shown in Figure 1. Diluted bitumen drains downward under gravity and is produced out of the physical model through a production port.

Bitumen Sample

The bitumen used in this series of tests was Athabasca bitumen. The molecular weight of the bitumen was measured as 655g/mole and its density was measured as 1.009 g/cm^3 at 20°C and atmospheric pressure. The viscosity of the bitumen as a function of temperature is presented in Table 1.

Saturation of Sandpack Model

Initially, the sandpack model was water saturated at room temperature and atmospheric pressure to obtain water-wet sand. A volumetric water pump was connected to the bottom port of the model and reverse osmosis water was pumped into the model, the volume of water injected and the weight of water collected were recorded. Next, the sandpack was saturated with bitumen. This was done at warm conditions to reduce the bitumen viscosity. The oil saturated sandpack model was then placed in the physical model. The inflows and outflows of the sandpack model during the saturating processes were used to determine the pore volume and the initial bitumen and water saturations of the sandpack model.

Test Runs

All tests were conducted in a temperature-controlled room. The temperature was maintained at 22°C. After the bitumen saturated sandpack model was placed in the physical model, the solvent injection line and the production station were connected to the physical model. The physical model, including the production station and the associated connection lines, was first evacuated, and then charged to ~10kPaa with the test solvent. This evacuation and charging process was repeated a few times to minimize the amount of air in the system. Then the system was charged to the desired test pressure with solvent vapor and the test started.

During the test, a constant pressure in the physical model was maintained using a volumetric pump to supply solvent to compensate for the solvent intake by bitumen in the porous media through the upper surface of the sandpack model. Cumulative solvent injection was recorded. Incremental production samples were recorded periodically during the drainage period. Drainage rates of the solvent-bitumen mixture and the net bitumen production rates were determined from the incremental production profile.

Experimental Results

Initially three tests were conducted: one with propane, one with n-butane and one with DME as the solvent vapor. Then a second test with DME was conducted to confirm the first test with DME. In all cases, the operating pressure was controlled to be slightly below the selected solvent's saturation pressure.

The initial conditions of the sand pack in the four tests are summarized in Table 2. It is noted that the initial conditions of the sand pack in the four tests were quite similar.

Figures 2 to 5 show the histories of the operating temperatures and pressures of the four tests, respectively. It is noted that the temperatures were well kept at22 ± 0.5°C in all four tests. The saturation pressure of propane is ~880kPa at 22°C. The pressure in the physical model for the test with propane was set at 800kPa (~9.1% below saturation pressure) to assure that propane was always in the vapor phase. The target pressure in the physical model during Test #1 with propane was maintained well (±20kPa around 800kPa). The saturation pressure of n-butane is ~224kPa at 22°C. The pressure in the physical model for the test with butane was set at 200kPa (~10.7% below saturation pressure) to assure that butane was always in vapor phase. The target pressure in the physical model during Test #2 with butane was maintained well (±10kPa around 200kPa). The saturation pressure of DME is ~542kPa at 22°C. The pressure in the physical model for the test with DME was at set 500kPa (~7.7% below saturation pressure) to assure that DME is always in vapor phase. The target pressure in the physical model during the Test #3 with DME was maintained well (±20kPa around 500kPa), and the target pressure in the physical model during the Test #4 with DME was maintained well (±20kPa around 505kPa).

Figure 6 shows the cumulative solvent injection recorded by the pump during each test. The injected solvent compensated for the solvent dissolved into bitumen and drained out of the physical model, and the solvent required to maintain the operating pressure of the physical model and the production accumulators. A total of 180.0g of propane was injected by the end of the test in Test #1 with propane; 275.0g of n-butane was injected in Test #2 with n-butane; 329.0g of DME was injected in Test #3 with DME; and 468.0g of DME was injected in Test #4 with DME. The sampling of the produced fluids in Test #4 with DME were more frequent than that in Test #3 with DME, which resulted in more DME injection.

Incremental fluid production in the tests were sampled frequently (i.e., at 12~24-hour intervals) in the early stage when the recovery factor (RF) was low, and less frequently (i.e. at 48-hour intervals) in the late stage when the RF was high. Figure 7 shows the cumulative bitumen production of the four tests, respectively. It is noted that 538.0g of bitumen was produced by the end of the test in Test #1 with propane, giving 65.2% oil recovery in ~542 hours; 540.0g of bitumen was produced in Test #2 with n-butane, giving 65.4% oil recovery in ~773 hours; 622.0g of bitumen was produced in Test #3 with DME, giving 75.1% of oil recovery in ~449 hours; 620.0g of bitumen was produced in Test #4 with DME, corresponding to 75.1% of oil recovery in ~382 hours.

The average propane-bitumen weight ratio in the production liquid samples was ~0.25 in Test #1 with propane; the average butane-bitumen weight ratio in the production liquid samples was ~0.36 in Test #2 with n-butane; the average DME-bitumen weight ratio in the 10 production liquid samples was ~0.46 in Test #3 with DME; and the average DME-bitumen weight ratio in the 10 production liquid samples was ~0.47 in Test #4 with DME.

After each test was completed, the physical model was discharged to atmospheric pressure. The remaining sand and fluids in the sandpack model were excavated in a 12 × 2 pattern, providing a total of 24 samples. The sample blocks are each 10 cm wide and 2.25 cm high. Selected sample out of the 24 collected samples were analyzed for bitumen, water and solids content. Figures 8 to 11 show the residual bitumen saturations for each of these blocks of the four tests, respectively. The residual bitumen saturation at the top end of the sandpack model is lower than that at the bottom end and that along the sandpack model the residual bitumen saturation increases with vertical depth. Generally the residual bitumen saturation in the tests with DME were much lower than those with propane and butane. These results are consistent with the differences in cumulative bitumen production for the tests, i.e. the more the cumulative bitumen production, the less the residual bitumen saturation.

Summary

Experimental tests were undertaken in a lab physical model, using a 4 Darcy water-wet sandpack saturated with Athabasca bitumen. The tests with different solvents: i.e. propane, n-butane, and DME were conducted at room temperature (22°C). In all tests, the operating pressure was controlled to be slightly below the saturation pressure of the selected solvent. The results show that, to produce 500g of oil (~60% of oil recovery), the test with DME took ~144 hours, the test with propane took about 480 hours, and the test with butane took ~ 576 hours, which correspond to an average oil production rates of 3.47g/hr, 1.04g/hour and 0.88g/hour, respectively. Normalizing for 500g of oil production in all tests, the oil production rate in the tests with DME was ~3.33 times that of the test with propane and ~3.94 times that of the test with n-butane. Therefore, the oil drainage rates in the tests with DME are significantly higher than those with propane and n-butane as shown in Figure 7. Also the test results show the oil production behavior with DME is repeatable.

Measurement of Fluid Properties

To support detailed numerical evaluation of the tests with DME, the solubility of DME in both bitumen and water and the viscosity reduction of bitumen by DME dilution at the test conditions were determined experimentally.

Table 3 shows the measured DME concentration (in weight percent) in bitumen under different pressures at 22°C. The solubility of DME in bitumen increases with the increased pressure. Table 4 shows the measured DME concentration (in weight percent) in water under different pressures at 22°C. DME has significant solubility in water and the solubility of DME in water increases with increased pressure. Table 5 shows the measured viscosity and density of the DME-bitumen mixture at different DME concentration at 22°C. The viscosity and density of DME-bitumen decrease with increased DME concentration in the mixture.

These data were implemented into the numerical simulation model in k-value and viscosity tables' format.

Numerical History Match

To gain an understanding of the contribution of various mechanisms to the observed faster drainage rates with DME, a detailed numerical evaluation of Test #4 was conducted. Computer Modeling Group (CMG)'s thermal reservoir simulator STARS[2] (version 2015) was used in the numerical simulation.

Numerical Approaches

A grid system of 120 × 1 × 5 with grid block size of 1 cm × 10 cm × 0.5 cm for the surface layer and 1 cm × 10 cm × 1 cm for the inner 4 layers, as shown in Figure 12, was used in the numerical model to represent the test model.

The relative permeability curves of the water-oil system and gas-liquid system used in the numerical simulation model are shown in Figures 13 and 14, respectively. The endpoints of the curves depend on the initial/residual water and oil saturations in the test and could be used as tuning parameters for history matching.

The mass transfer of DME in porous media is modeled by diffusion, dispersion and capillary mixing in STARS. A j-function type of gas-oil capillary pressure was used in the numerical simulation: the capillary pressure was 1.8kPa at oil saturation of 0.2, 0.9kPa at oil saturation of 0.9 for the 4Darcy sand[3, 4].

The total mass transfer F_{ijk} of component i in phase j in direction k by diffusion and dispersion is modeled in STARS as formula (1).

$$F_{ijk} = -\phi S_j (D_m + \alpha |U_j|) \nabla_k (\rho_j X_{i,j}) \tag{1}$$

where:

φ: porosity
S_j: saturation of phase j
D_m: molecular diffusion coefficient
α: mechanical dispersion coefficient
U_j: phase j local flow velocity
$\nabla_k(\rho_j X_{i,j})$: concentration gradient of component i in phase j in direction k

The diffusion and dispersion coefficients of DME in water and this particular bitumen are not available thus were selected as the tuning parameters in the history matching of Test #4 with DME. To accomplish a reasonable history match of Test #4 with DME, the following diffusion and dispersion coefficients were used in the simulation.

In bitumen: the dependence of solvent diffusion coefficient on temperature and viscosity follows the empirical correlation[5] of

$$D = D_r \times (T/T_r) \times (\mu_r/\mu)^{0.545} \tag{2}$$

where:

D: diffusion coefficient
D_r: reference diffusion coefficient
T: temperature (absolute)
T_r: reference temperature (absolute)
μ_r: reference phase viscosity

μ: phase viscosity

The reference diffusion coefficient[6] of DME in bitumen was set to 0.00075cm^2/min at the reference temperature of 20°C and reference viscosity of 1 × 10^5 cP. The mechanical dispersion coefficient for DME in bitumen was set to 0.5cm.

In water, the diffusion coefficient of DME was set constant at 0.5cm^2/min, and the mechanical dispersion coefficient was set to zero.

The history matching of Test #4 with DME was conducted with the measured operating pressures as inputs. Quality of the history match was judged by the matching of bitumen production and residual oil saturation at the end of the test.

History Matching Results

Figure 15 shows the history matching input of the operating pressure. The history of the operating pressure in Test #4 with DME was represented in the simulation. Figure 16 shows the comparisons of the simulated and measured cumulative bitumen productions for the Test #4 with DME. It is noted that the cumulative bitumen production in the Test #4 with DME was reasonably matched by the simulation. Figure 17 shows the simulated residual bitumen saturation at the end of Test #4. Comparing to the measured residual bitumen saturation as shown in Figure 11, it is noted that the residual bitumen saturation profile was reasonably matched: low residual bitumen saturation (<0.1) in the top part of the sandpack, high residual bitumen saturation (~0.6) in the bottom part of the sandpack. It suggests that the numerical simulation has captured the major mechanisms of the test.

Figures 18 to 23 show the simulated profiles of oil saturation, DME mole fraction in bitumen and DME mole fraction in water at 24, 48, 96, 144, 192 and 288 hour of Test #4 with DME, respectively. It is noted that the DME has reached the inner-most layer of the sandpack within 24 hours due to its diffusion in both bitumen and water; and that the diluted oil drainage over the upper surface of the sandpack progresses from the top toward the bottom, as was observed experimentally in Test #4.

Discussions

DME is soluble both in bitumen and water as shown in the measured solubility data. Simulation history matching sensitivity studies were conducted to investigate the impact of DME's solubility in water on the oil drainage behavior in Test #4.

Figure 24 show the simulated cumulative bitumen production assuming zero DME diffusion in water. Under such conditions the bitumen production in a long period (~240 hours) is lower than that in the test. Figure 25 show the profiles of DME mole fraction in bitumen and DME mole fraction in water at 24 hour. DME mole fractions are lower compared to Figure 18, thus the oil drainage rate is lower. Figure 26 show the simulated cumulative bitumen production assuming zero DME solubility in water. Under such conditions the bitumen production over a long period (~200 hours) is lower than that in the test. Figure 27 show the profiles of DME mole fraction in bitumen at 24 hour. Because DME mole fraction is lower than this in the test, the oil drainage rate is lower. Therefore, the solubility and diffusion of DME in water improved the effective mixing of DME in bitumen in the water-wet sandpack, which enhanced the rate of bitumen dilution and drainage in the test with DME. To evaluate the improvement of the effective diffusion of DME in bitumen by water in Test #4, a simulation run assuming zero DME diffusion in water but with an increase in the reference diffusion coefficient of DME in bitumen from 0.00075 to 0.02cm^2/min at the reference temperature of 20°C and reference viscosity of 1 × 10^5 cP was conducted. Figure 28 show the simulated cumulative bitumen with larger DME diffusion in bitumen and zero DME diffusion in water as compared to the test results. It is noted the test results were reasonably matched, which suggests that the effective DME diffusion in bitumen in Test #4 with DME could be increased by ~27 times because of DME's solubility and diffusion in water.

The effective diffusion coefficient (0.02cm^2/min) of DME in bitumen at reference conditions in the numerical history match of Test #4 with DME is much higher (~200 times) than the diffusion coefficients[6, 7, 8] of normal hydrocarbons. Further study is required to quantify the diffusion of DME in water and bitumen phases in porous media.

Summary

Test #4 with DME was reasonably history matched by numerical simulation in terms of the bitumen production and the residual bitumen saturation profile. The simulation shows the DME has reached the inner-most layer of the sandpack within 24 hours; and the diluted oil drainage over the upper surface of the sandpack progresses from the top towards the bottom, as observed experimentally. Sensitivity studies show that the solubility and diffusion of DME in water improve significantly the effective mixing of DME in bitumen in the sandpack and enhance the rate of bitumen dilution and thus the bitumen drainage. Further study is required to quantify the diffusion of DME in water and bitumen.

Field Scale Simulation

Preliminary simulation studies were conducted to evaluate the performance of a vapor DME assisted gravity drainage process with a well configuration as in a SAGD process. 2D simulations were performed in a typical Athabasca bitumen reservoir. The reservoir properties are listed as follows:

Pay thickness:	25m
Well spacing:	100m
Well length:	1000m
Vertical permeability:	2.4Darcy
Horizontal permeability:	4.0Darcy
Initial oil saturation:	0.85
Initial water saturation:	0.15
Original-Oil-In-Place (OOIP):	7.2 × 10^5 m^3
Initial pressure:	~500kPa
Initial temperature:	22°C
Initial GOR:	0.74

The 2D simulation model is shown in Figure 29. The horizontal wellpair has a well length of 1000m, the vertical distance between the injector and the producer is 2.5m with the producer placed at the bottom of the reservoir. The grid size used in the simulation is 0.25m (horizontal) × 1000m (wellbore) × 0.25m (vertical).

To facilitate the establishment of communication between the injector and the producer, the initial water saturation in the region between the injector and the producer in the simulation was set to 0.8 thus resulting in lower local bitumen saturation as shown in Figure 28. Also, the reservoir temperature was set to 22°C because data on DME solubility in bitumen and water at other temperatures are not available.

The fluid properties of bitumen and DME, the mass transfer coefficients, the capillary pressure and the relative permeability curves used in the numerical history match of the lab test were implemented into the field scale simulation.

Before running the simulation, translation of the lab test results to field reservoir scale was attempted. As mentioned above, the average bitumen drainage rate was about 3.47 g/hour on a contact area 4.5cm × 120cm (0.054m^2) exposed to vapor DME in the 4Darcy sandpack at a dip angle of 45°. Assuming a chamber developed with two 45° boundaries in the field case of 4 Darcy sand, the contact area exposed to vapor DME is about 35m × 1000m × 2, therefore a bitumen drainage rate of ~167.4 m^3/day is predicted.

The constraints in the simulation of the field DME assisted gravity drainage process were:

- Maximum injection pressure: 530kPa
- Maximum DME injection rate: 5×10^5 (std) m^3/day
- Minimum production pressure: 500kPa
- Maximum gas production rate: 10.0 (BH) m^3/day

Figures 30 to 33 show the simulated chamber development at 1, 4, 9 and 14 year, respectively (the simulation crashed at year 14 due to numerical instability issues). Figure 34 shows the simulated bitumen production rate and cumulative bitumen production. It is noted that the total production is ~2.5×10^5 m^3, corresponding to a recovery factor of ~35% OOIP at the end of 14 year. The maximum bitumen production rate is ~72m^3/day; and the average bitumen production rate is ~48m^3/day over 14 years. The simulation predicts that it takes a long time to develop a sizable vapour chamber. Lower vertical permeability and initial solution gas contribute to the lower average bitumen production in simulation rate than the scaled production rate as mentioned above.

Figure 35 shows the simulated DME injection rate and cumulative DME injection. It is noted that the total DME injection is ~1.6×10^8 (std) m^3 at the end of 14 year. The average DME injection rate is ~3.13×10^4 (std) m^3/day over 14 years. Figure 36 shows the simulated DME production rate and cumulative DME production. It is noted that the total DME production is ~1.3×10^8 (std) m^3 at the end of 14 year. The average DME injection rate is ~2.54×10^4 (std) m^3/day over 14 years. Figure 37 shows the simulated net DME injection (injection – production) rate and net cumulative DME injection. It is noted that the net total DME injection is ~4.6×10^4 tons at the end of 14 year. The average net DME injection rate is ~9.0 ton/day over 14 years. Therefore, the average bitumen-to-net DME ratio is ~5.3 m^3 (bitumen)/ton (DME).

Summary

Preliminary simulation studies show that a vapor DME assisted gravity drainage process, with a well configuration similar to that of SAGD, in a typical Athabasca bitumen reservoir at a temperature of 22°C and operating pressure of ~530kPa will have a recovery factor of ~35% OOIP and an average bitumen production rate of ~48m^3/day over 14 years; the average bitumen-to-net DME ratio will be ~5.3 m^3 (bitumen)/ton (DME).

DME Availability and Supply Cost

Current global production of high purity "propellant grade" DME is about 150,000 MT per year and is used in a range of consumer and industrial products. In addition, there is approximately another 200,000 MT per year of DME produced in China and India for blending with liquefied petroleum gas (LPG), primarily for use as a clean cooking fuel. Currently, there is renewed interest in DME as a clean burning additive or substitute for diesel transportation fuel. The first new North American DME production capacity (20,000 MT per year) is expected to come online in 2019 in Trinidad, using primarily low-cost natural gas as a feedstock. Historically, high purity DME has been produced by dehydration of methanol. Future larger volume demand for DME as a diesel fuel substitute is expected to be met by direct synthesis from syngas (CO and H_2 mixture), which can be derived by gasification from any fossil or bio-based source of carbon or hydrocarbon. However, natural gas is favoured for reasons of process simplicity, ready scalability and the expectation of continued abundance.

Various studies[9, 10] from the late 1990s and early 2000s predict that in the large volumes required for the transportation fuel market, DME supply cost should be similar to that of diesel on an energy equivalent basis. Other studies from the early 2000s indicate that DME was slightly lower in cost than LPG (principally composed of a blend of propane and butane) on an energy equivalent basis. There are continuing R&D efforts ongoing around the world aimed at simplifying both methanol and DME synthesis and eliminating the production of CO_2 as a by-product. If successful, these efforts should also provide for lower costs of supply.

In considering the proposed use of DME in oil sands applications, including for solvent based in-situ recovery of bitumen, it must be noted that currently DME is not commercially available in Alberta. However, there is significant production of methanol, for example at the Methanex plant in Medicine Hat (560,000 MT per year) and, reportedly, addition of dehydration capacity or modification of existing methanol synthesis reactors at existing methanol plants for the production of DME is not a major challenge. Therefore, it seems reasonable to assume that supply could develop readily to meet any newly emerging oil sands related demand. Presumably, premium pricing may apply initially but should evolve (assuming a competitive supply market) to costs and pricing that conform to the above noted longer term prediction of DME priced at approximate parity to diesel on an energy equivalent basis. Given that on the basis of lower heating value the energy value of DME is 27.6 MJ/kg while that of diesel is 42.5 MJ/kg, the projected longer term price, on a mass basis, of DME equals 0.65 times the expected diesel price. Based on historic pricing patterns, the projected whole sale price of diesel can be taken to approximately equal that of light sweet crude oil, i.e. the WTI price for the Alberta market. Therefore, given that the specific gravity of WTI and diesel are approximately equal, for this preliminary analysis the projected long term DME supply cost is 0.65 times WTI price on a mass basis.

Environment Impact

DME (Dimethyl ether: CH3-O-CH3), has a molecular weight of 46.069 and a normal boiling point of -24.8°C. It has a high vapor pressure at room temperature: 534 kPa at 21°C. It is very soluble in water, 34 wt% at 21°C under autogenous pressure conditions[16] and 5.7 wt% at 20°C and 1 bar [15]. It is a highly flammable gas and a dangerous fire hazard. Its explosion limits are from 3.0 ~17 vol% in air[15].

Even though DME is biologically easily degradable, large amounts of DME should not be allowed to enter any wastewater system as its evaporation above the surface of water can lead to the formation of an explosive mixture.

The US EPA (under 40 CFR 180.910) exempts DME from the requirements of a minimum tolerance level when used in accordance with good agricultural practice as an inert component in pesticide formulation applied to growing crops or to raw agricultural commodities after harvest.

DME is atmospherically benign with respect to its ability to affect global climate. It has a short atmospheric lifetime of 5.1 days[13].

DME has an estimated soil organic carbon-water partitioning co-efficient (Koc) value[14] of 27 and is expected to have a very high mobility in soil. Volatilization of DME from soil or from water surfaces is expected to lead to its rapid removal from the soil or water because of its very high vapor pressure. Biodegradation in the soil is expected to be very slow; this is based on an analogous study in an aqueous process.

DME is relatively non-toxic; experiments conducted on rats using concentrations up to 20,000 ppm (2 vol% in air) over a period of 8 months did not lead to any deaths[11]. DME inhalation at concentrations of 50% by human subjects showed that its acute toxicity was very low with the principal physiological effect being anesthesia[12]. Contact with DME is also not irritating to the skin[15], even though it is slightly irritating to the eyes and to the respiratory tract. DME is not classifiable as to human carcinogenicity.

Summary

Comparative experimental tests on the bitumen drainage behaviors in a 4 Darcy water-wet sandpack saturated with Athabasca bitumen with different solvents: propane, n-butane, and di-methyl ether (DME) were undertaken under operating pressure close to respective saturation pressures at room temperature (22°C). The test results showed that the bitumen production rates in the tests with DME were significantly higher than those with normal hydrocarbon: the oil production rate in the tests with DME was ~3.33 times that of the test with propane and ~3.94 times that of the test with n-butane, normalized on 500g bitumen production in all tests,

Fluid property measurements show that DME has considerable solubility in both bitumen and water and that dilution with DME significantly reduces the viscosity of bitumen.

Test #4 with DME was reasonably history matched by numerical simulation in terms of bitumen production and the residual bitumen saturation profile. The simulation shows the DME has reached inner-most layer of the sandpack within 24 hours; and the diluted oil drainage over the upper surface of the sandpack progresses from the top towards the bottom of the model. Sensitivity studies show that the solubility and diffusion of DME in water improve the effective diffusion of DME in bitumen in the water-wet sandpack and enhance the rate of dilution of bitumen thus its drainage rate. Further study is needed to quantify the diffusion of DME in water and bitumen.

Preliminary field scale simulation studies predict that a vapor DME assisted gravity drainage process, with a well configuration similar to that of SAGD, in a typical Athabasca bitumen reservoir at a temperature of 22°C and operating pressure of ~530kPa will have a recovery factor of ~35% OOIP and an average bitumen production rate of ~48m^3/day over 14 years. The predicted average bitumen-to-net DME ratio will be ~5.3 m^3 (bitumen)/ton (DME).

Assuming that the demand for DME as a cleaner substitute for diesel fuel evolves as expected and that supplies of natural gas (the primary feedstock for DME production) remain abundant, longer term DME supply cost is predicted to equal that of diesel on an energy equivalent basis. On a mass basis this translates to a DME price that is approximately 65% of the diesel price, which historically has equated well with the WTI light sweet crude oil price. Therefore, longer term pricing for DME is expected to be about 65% of the WTI price.

The projected longer term price, on a mass basis, of DME equals 0.65 times the expected diesel price. Based on historic pricing patterns, the projected whole sale price of diesel can be taken to approximately equal that of light sweet crude oil, i.e. the WTI price for the Alberta market. Therefore, given that the specific gravity of WTI and diesel are approximately equal, for this preliminary analysis the projected long term DME supply cost is 0.65 times WTI price on a mass basis.

DME is biologically easily degradable. However, large amounts of DME should not be allowed to enter any wastewater system due to its high vapor pressure and resultant risk of explosion. The US EPA (under 40 CFR 180.910) exempts DME from the requirements of a minimum tolerance level when used in accordance with good agricultural practice. DME is atmospherically benign with respect to its ability to affect global climate. DME is expected to have a very high mobility in soil. DME is relatively non-toxic. Contact with DME is also not irritating to the skin but it is slightly irritating to the eyes and to the respiratory track. DME is not classifiable as to human carcinogenicity.

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Temperature (°C)	Viscosity (cP)
20	517300
40	28710
60	3533

Table 1: Bitumen viscosity versus temperature

Test Run	Solvent	Pore Volume (cm^3)	Oil Saturation (%)	Water Saturation (%)
#1	Propane	854.0	94.5	5.5
#2	n-Butane	854.0	94.5	5.5
#3	DME	854.4	95.0	5
#4	DME	854.4	95.0	5

Table 2 Initial conditions of the sand packs

Pressure (kPa)	450	500	530
DME Concentration (wt%)	14.8	34.0	58.1

Table 3 Solubility of DME in bitumen at 22°C

Pressure (kPa)	450	500	530
DME Concentration (wt%)	25.1	31.5	37.2

Table 4 Solubility of DME in water at 22°C

DME Concentration (wt%)	10	35	45	55
Viscosity (cP)	379.5	5.0	1.9	0.9
Density (g/cm^3)	972.2	887.8	829.6	799.1

Table 5 Viscosity and density of DME-bitumen mixture at 22°C

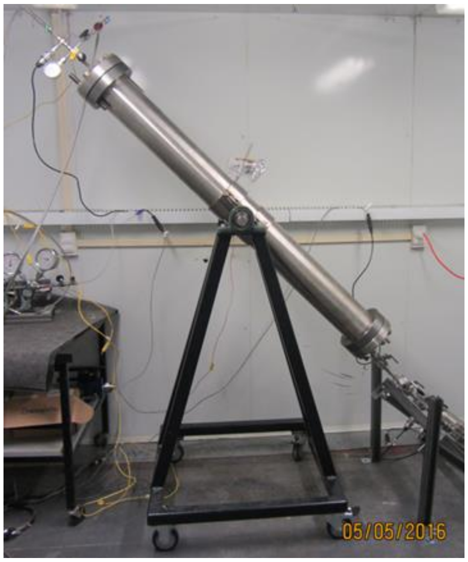

Figure 1 The assembled test apparatus

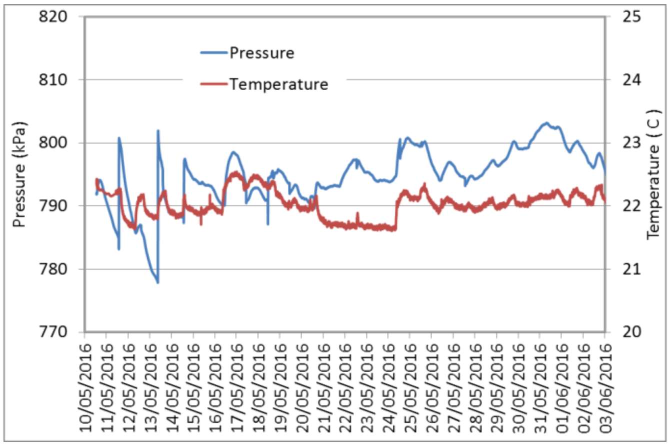

Figure 2 Temperature and pressure during Test #1 with Propane

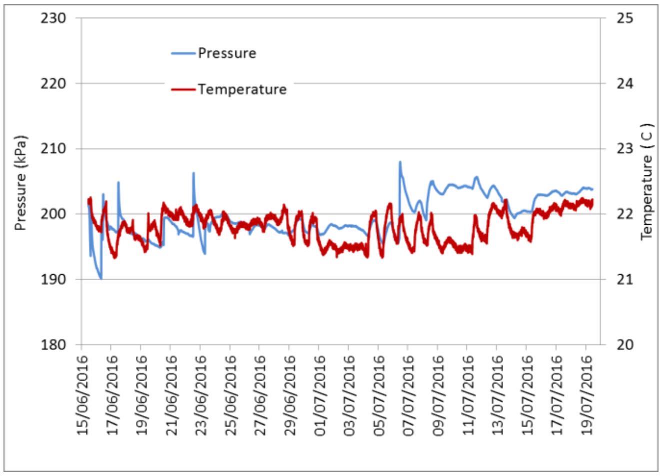

Figure 3 Temperature and pressure during Test #2 with n-Butane

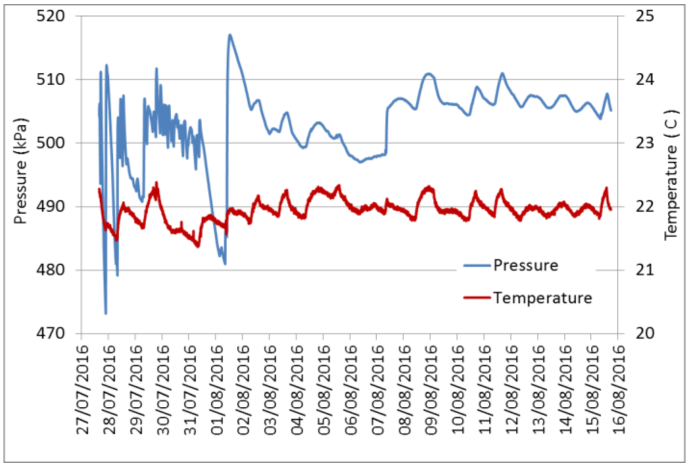

Figure 4 Temperature and pressure during Test #3 with DME

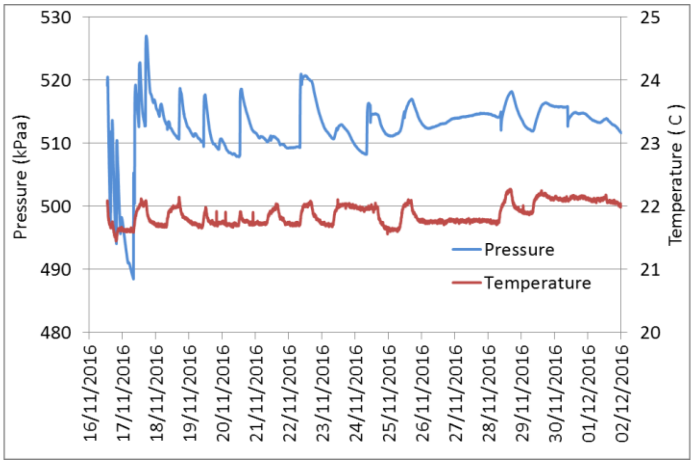

Figure 5 Temperature and pressure during Test #4 with DME

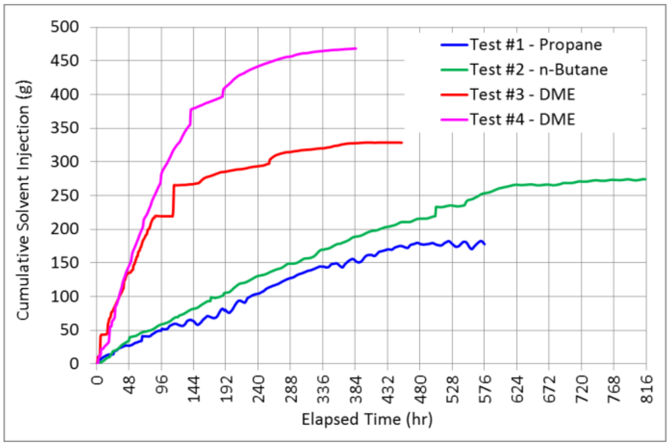

Figure 6 Cumulative solvent injections in the tests

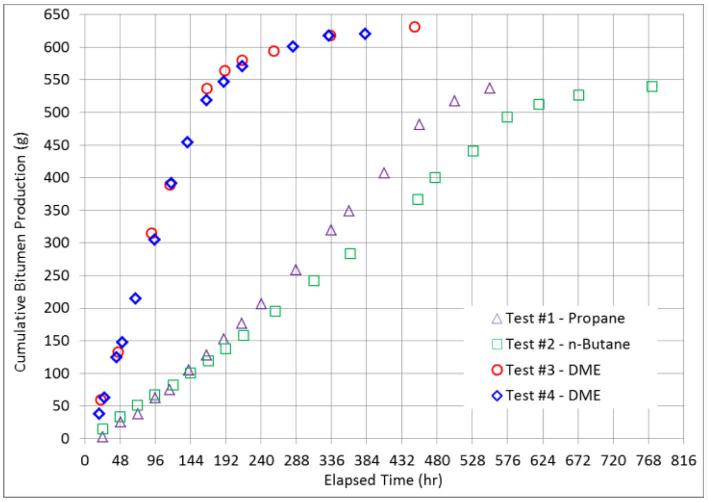

Figure 7 Cumulative bitumen productions in the tests

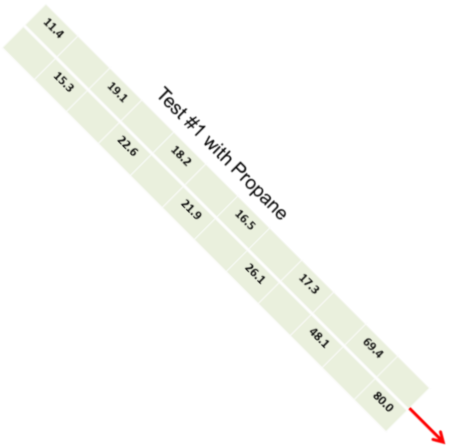

Figure 8 Residual bitumen saturation (%) of Test #1 with propane

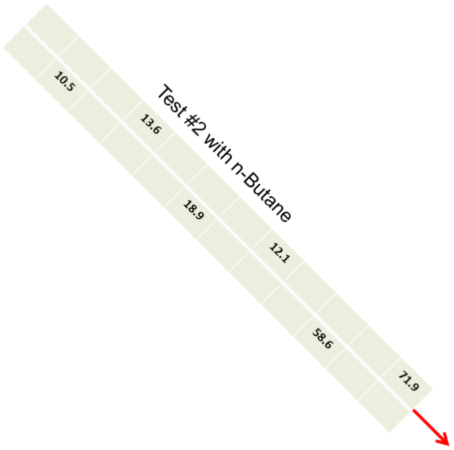

Figure 9 Residual bitumen saturation (%) of Test #2 with n-butane

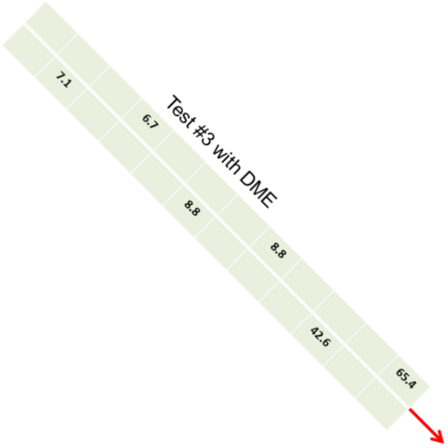

Figure 10 Residual bitumen saturation (%) of Test #3 with DME

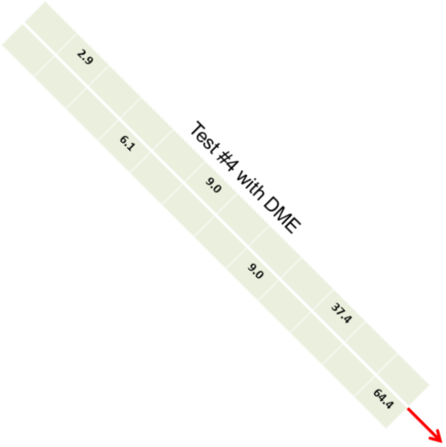

Figure 11 Residual bitumen saturation (%) of Test #4 with DME

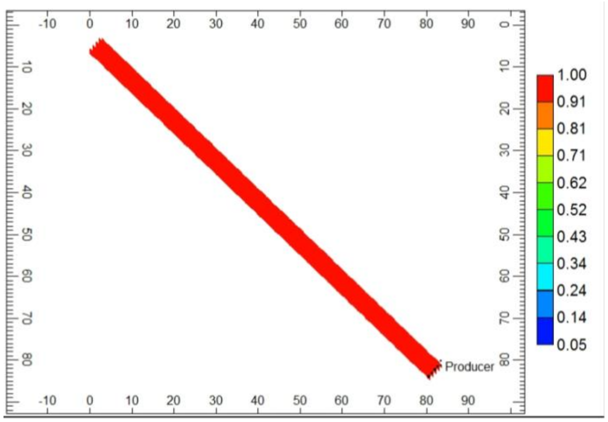

Figure 12 Residual oil saturation of Test #4 with DME

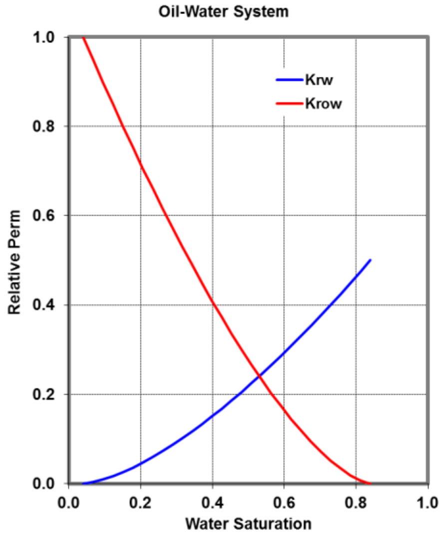

Figure 13 Relative permeability of the water-oil system

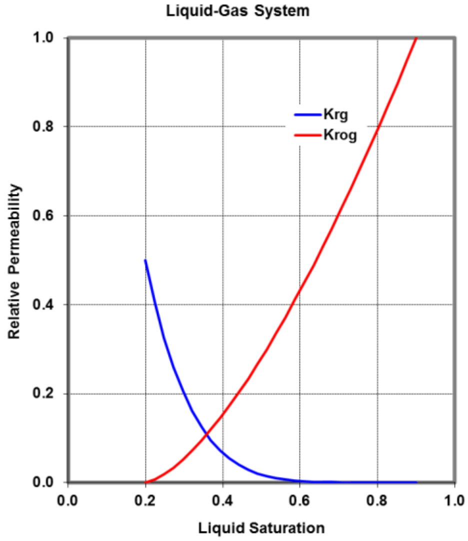

Figure 14 Relative permeability of the liquid-oil system

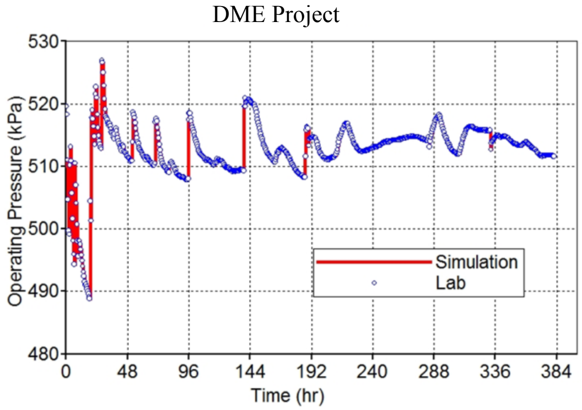

Figure 15 History matching input: operating pressure

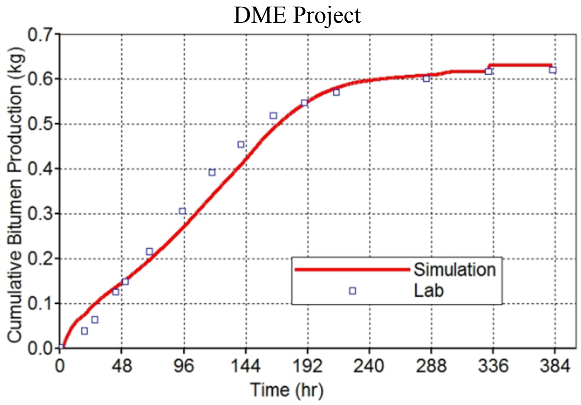

Figure 16 History matching output: cumulative bitumen production

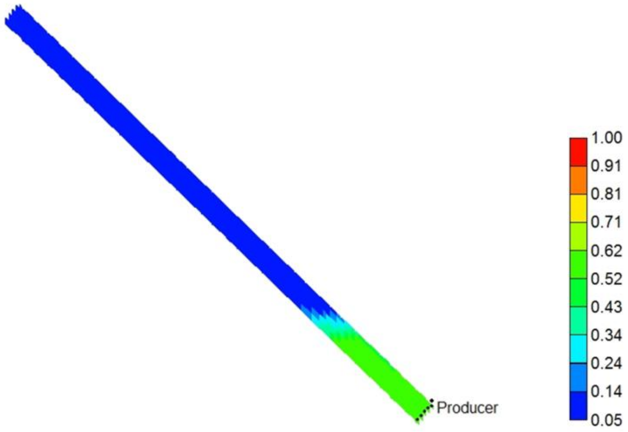

Figure 17 History matching output: residual bitumen saturation

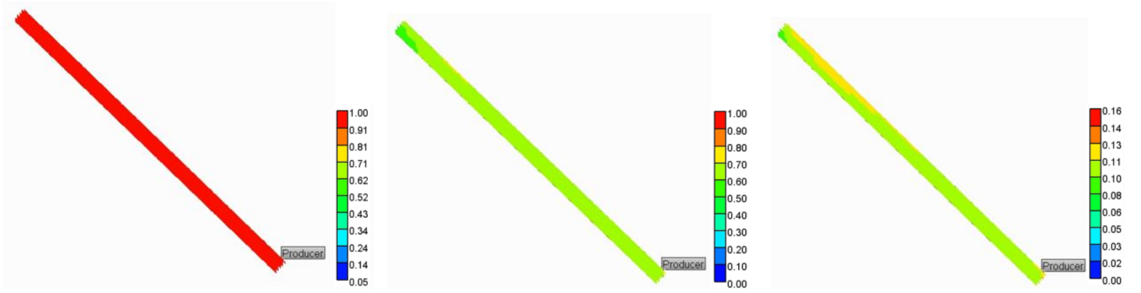

Figure 18 Simulation results: oil saturation (left), DME mole fraction in oil (middle), DME mole fraction in water (right) at 24 hour

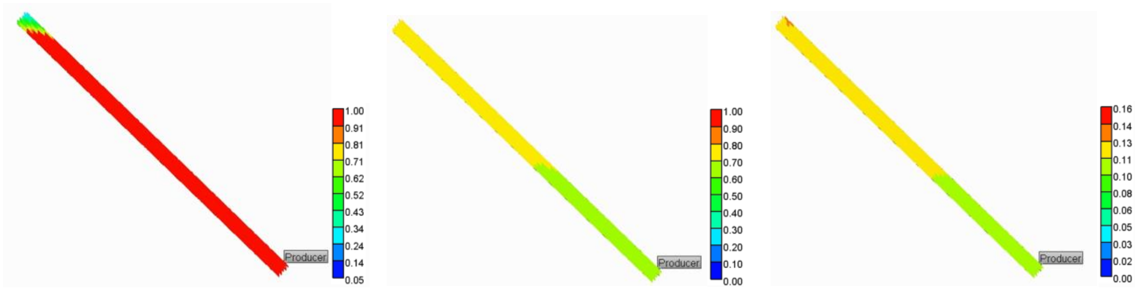

Figure 19 Simulation results: oil saturation (left), DME mole fraction in oil (middle), DME mole fraction in water (right) at 48 hour

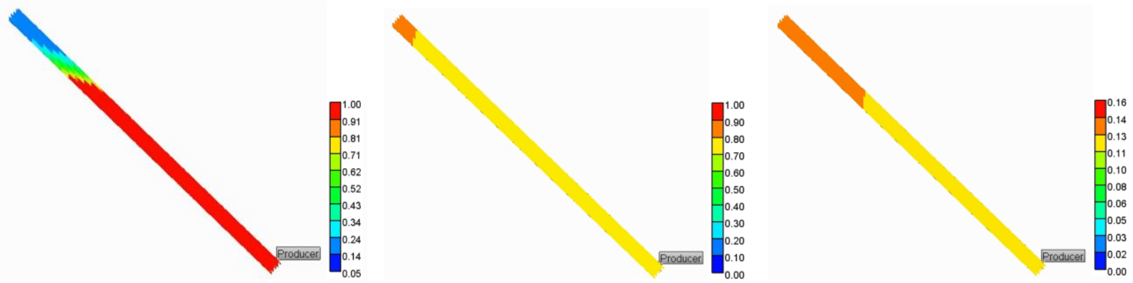

Figure 20 Simulation results: oil saturation (left), DME mole fraction in oil (middle), DME mole fraction in water (right) at 96 hour

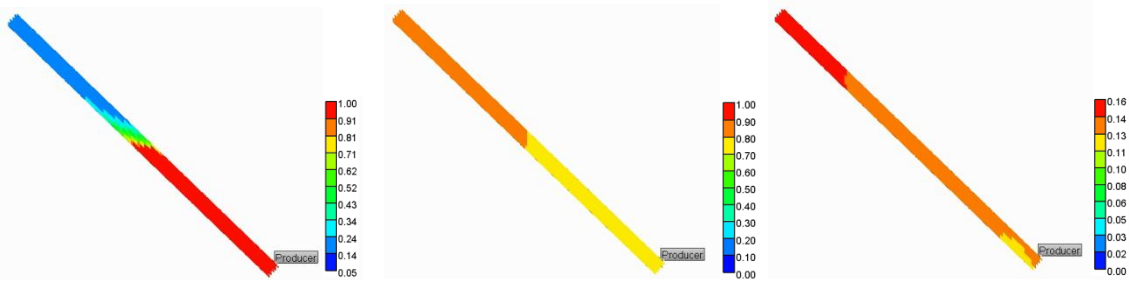

Figure 21 Simulation results: oil saturation (left), DME mole fraction in oil (middle), DME mole fraction in water (right) at 144 hour

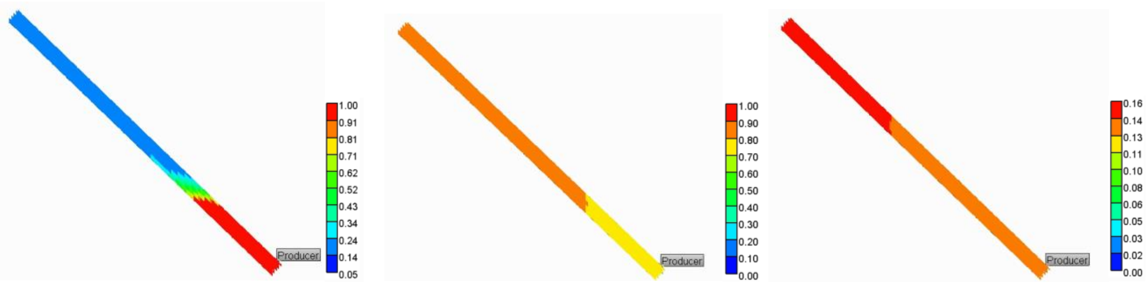

Figure 22 Simulation results: oil saturation (left), DME mole fraction in oil (middle), DME mole fraction in water (right) at 192 hour

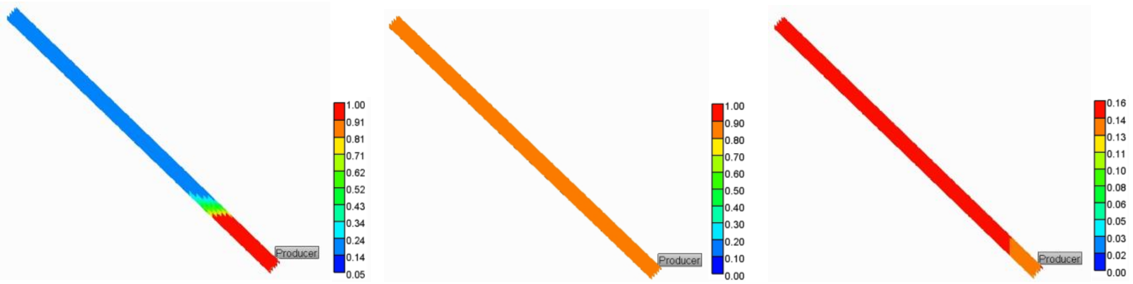

Figure 23 Simulation results: oil saturation (left), DME mole fraction in oil (middle), DME mole fraction in water (right) at 288 hour

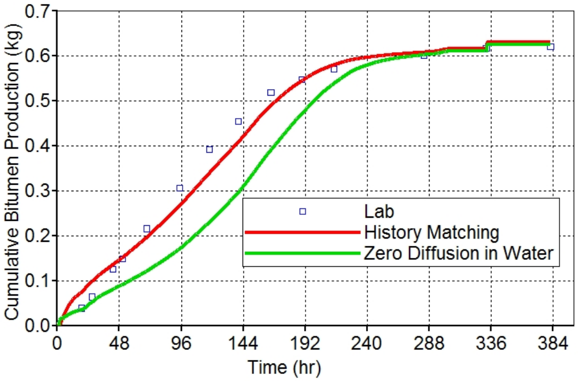

Figure 24 Sensitivity study: cumulative bitumen production with zero DME diffusion in water

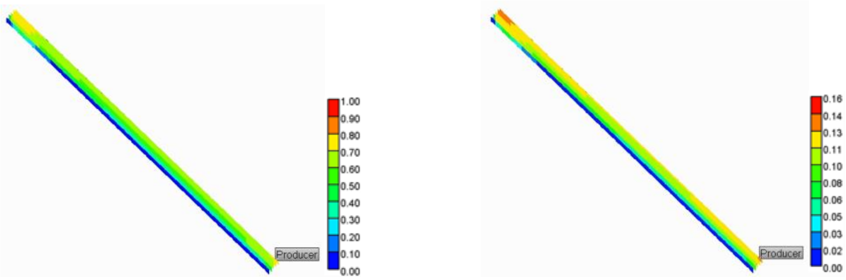

Figure 25 Sensitivity study: DME mole fraction in oil (left), DME mole fraction in water (right) at 24 hour with zero DME diffusion in water

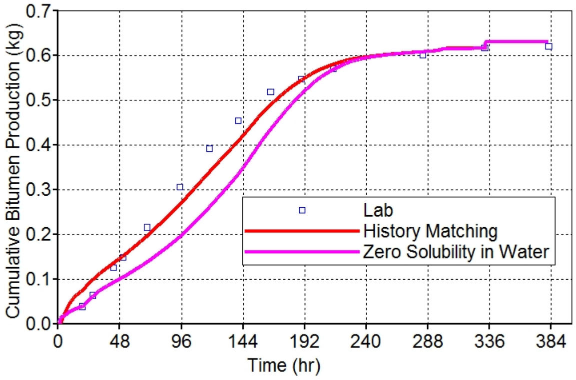

Figure 26 Sensitivity study: cumulative bitumen production with zero DME solubility in water

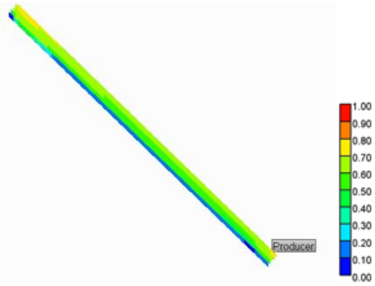

Figure 27 Sensitivity study: DME mole fraction in oil at 24 hour with zero DME solubility in water

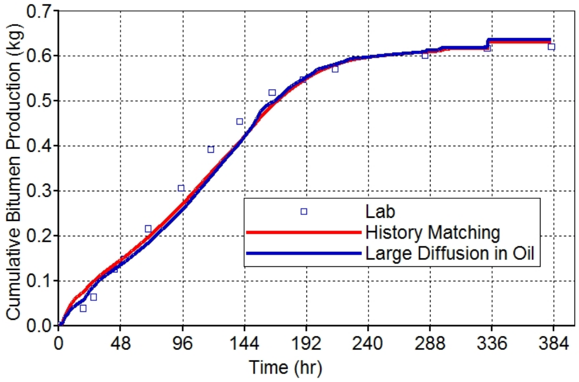

Figure 28 Sensitivity study: cumulative bitumen production with large DME diffusion in bitumen and zero DME diffusion in water

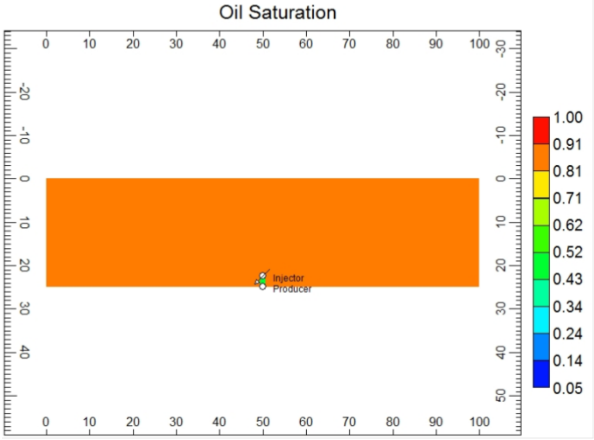

Figure 29 2D field scale simulation model

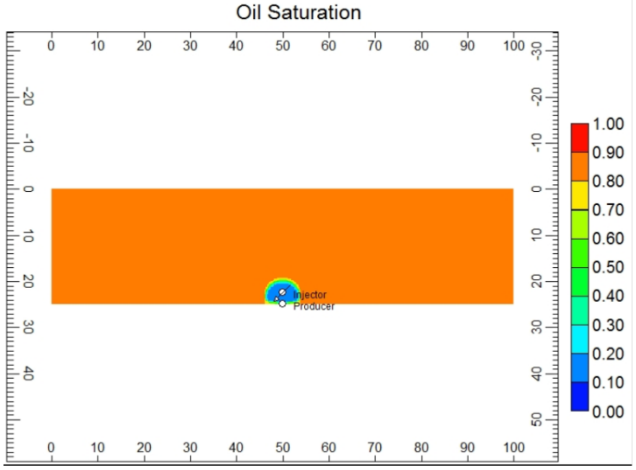

Figure 30 Field scale simulation results: oil saturation profile at 1 year

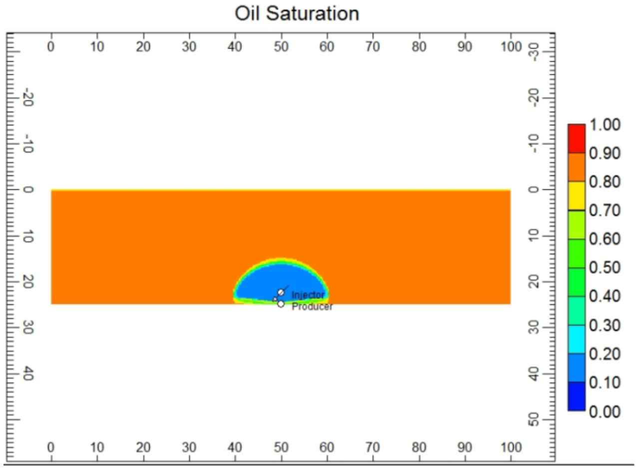

Figure 31 Field scale simulation results: oil saturation profile at 4 year

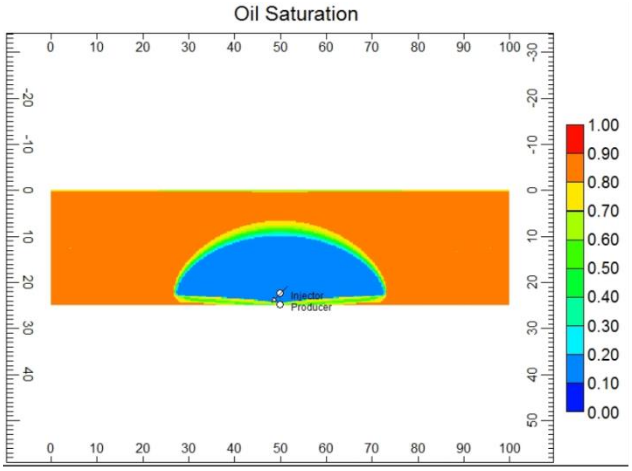

Figure 32 Field scale simulation results: oil saturation profile at 9 year

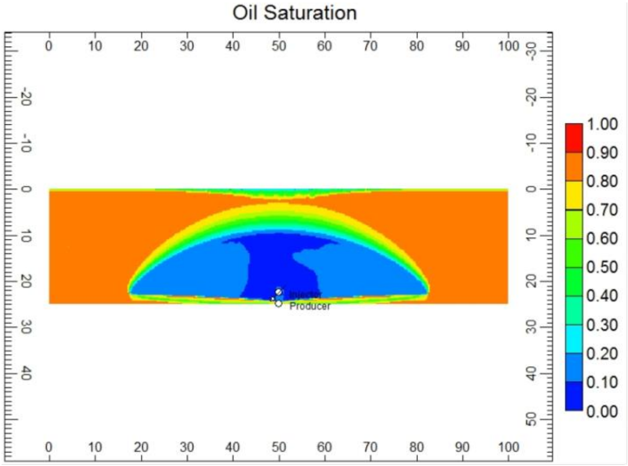

Figure 33 Field scale simulation results: oil saturation profile at 14 year

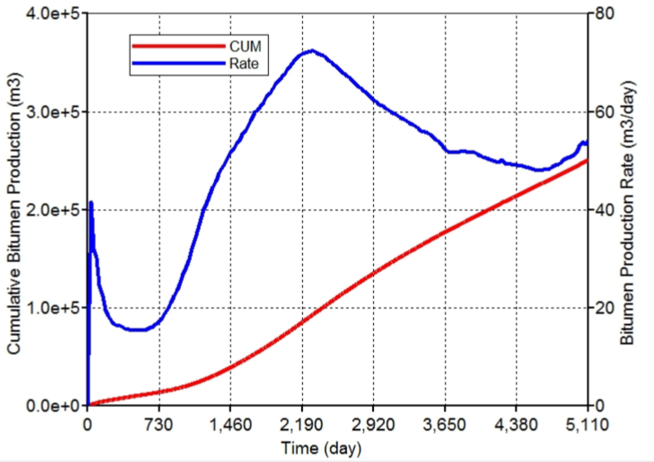

Figure 34 Field scale simulation results: bitumen production rate and cumulative bitumen production

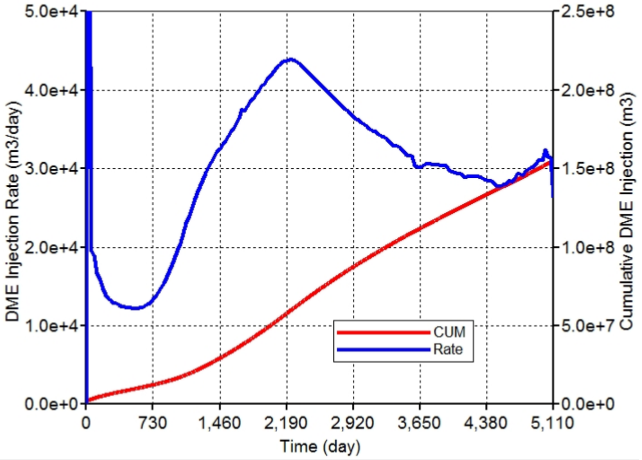

Figure 35 Field scale simulation results: DME injection rate and cumulative DME injection

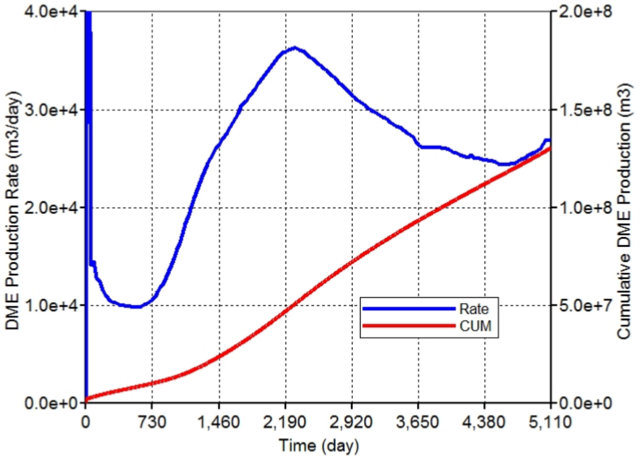

Figure 36 Field scale simulation results: DME production rate and cumulative DME production

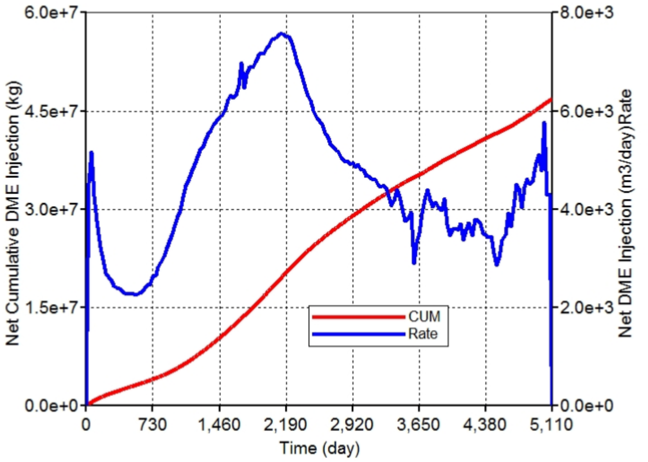

Figure 37 Field scale simulation results: net DME injection rate and net cumulative DME injection