In-situ visualization of Steam Assisted Gravity Drainage

with Chemical and Solvent Additives

by

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Abstract

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The introduction of steam-assisted-gravity drainage (SAGD) brought a significant improvement in the recovery of extra heavy oil, bitumen. The viscosity of bitumen being heavily dependent on temperature, makes the steam injection in SAGD highly effective in mobilizing the oil. The porous geometry of the reservoir structure plays an important role in the oil recovery process, along with the multiphase flow that takes place during the oil recovery process. Visualization of SAGD and the addition of chemical and solvents additives were conducted in this thesis at reservoir matching temperature and pressures (0.7-1.3 MPa, 170-210°C). Results of the experiments showed that alkaline additives brought improvement in oil recovery through wettability alteration, and solvents improve oil recovery through combination of mass transport and heat transfer effects. For the hexane-SAGD run, compositional separation of bitumen based on polarity difference was observed.
Dedications

I dedicate my thesis

to my sister,

and my family.
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1 Introduction

1.1 Petroleum Reserves and its classifications

Petroleum is a form of fossil fuel, debris of Earth that was formed from up to 650 million years ago and is in principle, a limited resource. [1] Additionally, oil reserves are only a fraction of the total oil and gas resources, so called original-oil-in-place(OOIP). The proved oil reserves are oil that are economically profitable to extract, and are subject to change. According to the McKelvey Diagram, there are interdependencies between geology, technology, and economics in oil and gas resources. Oil and gas resources can be divided into two main categories: undiscovered resources or discovered resources. Discovered resources are further categorized according to their technical and economical feasibilities.

Both technological advancements and increase in geological knowledge has brought increase in economically recoverable resources, [2] and the possibility of increasing the oil & gas reserves through technological advancements is fundamentally the motivation behind research in petroleum engineering.

The liquid form of fossil fuels, oil reserves, are typically categorized based on API gravity and viscosity into four classes (A to D). API gravity is an indicator of the oil’s density in relative to water, and is expressed as

\[
API \ gravity = 141.5SG - 131.5
\]

where SG is the specific gravity, in other terms, the density of the fluid relative to water.
A Class oil is medium-heavy oil, and the viscosity of this is between 10cP to 100cP. A Class oil is mobile at reservoir conditions and is the least challenging oil to extract. B Class oil is defined as extra heavy oil and generally refers to oil having a viscosity between 100cP and 10,000cP. C Class oil, also known as bitumen has a viscosity higher than 10,000cP and is immobile in reservoir conditions. D Class oil refers to shale, and due to its extremely low rock permeability, it can be extracted by mining techniques. Conventional oil recovery methods are not applicable to either bitumen and shale due to their immobility. Thus, enhanced oil recovery methods must be applied for both C and D Class oils. Examples of enhanced oil recovery mechanisms are thermal recovery mechanisms, gas miscible/immiscible recovery, and chemical recovery such as alkaline, polymer, and foam.

[11,57-60]

1.2 Oil Recovery Methods

1.2.1 Primary and secondary oil recovery

Primary oil recovery is the most basic method of oil recovery that uses the natural flow of oil. Some methods of primary oil recovery are the water drive and gas drive, where in the former, oil is displaced upward by water, and in the later, oil is recovered by the expansion of gas above it. However, the pressure will fall over the lifetime of the well, and eventually there will be insufficient underground pressure to force the oil to the surface. After a natural reservoir's drive diminishes, secondary recovery methods can be applied that rely on the supply of external energy into the reservoir in the form of injecting fluids to increase reservoir pressure. Water injection, also known as waterflooding, is the most extensively used method of secondary oil recovery. However, other fluids (liquids and gases)
can be injected to achieve the same goal. Examples of this are natural gas reinjection and gas lift, which injects air, carbon dioxide, or some other gas. Natural gas can be injected either in the gas-cap to increase the volume of gas that displaces oil downward to the production well, or into the oil bank to displace the oil. [4]

1.2.2 Thermal recovery methods

The two main categories of unconventional oil recovery are thermal and non-thermal methods. Thermal methods are very effective in producing extra heavy oil or bitumen. Bitumen has a viscosity range of $1 \times 10^5$ to $1 \times 10^9$ cP at a temperature of $20^\circ$C, and shows an exponential decrease in viscosity with an increase in temperature. At a temperatures of $80^\circ$C or higher, the viscosity of bitumen decreases to less than 1000 cP allowing the bitumen to be mobile enough to be extracted. [20,74] The relationship between temperature and Athabasca bitumen can be described as below, and this correlation equation was developed by Svrek and Mehrotra, by curve fitting the viscosity measurement data. [74,112]

$$\log(\log(\mu_{bit})) = -3.70015(T) + 9.90602$$

Figure 1-1 shows the correlation graph between temperature and bitumen viscosity using the equation above.
The effectiveness of high temperature in the viscosity reduction of bitumen brought thermal recovery methods by steam usage as steam is capable of transferring large amount of latent heat during condensation. Such thermal recovery methods are cyclic steam simulation (CSS), steamflooding, and steam assisted gravity drainage (SAGD).

Cyclic steam simulation (CSS) is a single well process, and consists of three stages. In the first stage, steam is injected into the well for over a month. Then, the well is shut for few days for heat distribution, which is noted as soak. Afterward, the well is put on the production stage for a few months, during which oil rate rapidly increases, stays at that level for a short time, and declines over the months. This cycle is repeated until the process is rendered uneconomic. Though the recovery factor of CSS is 10-40% oil-in-place (OIP), it is attractive because of quick payout. [15,16]
Steamflooding is another oil recovery process using steam, and its performance is highly dependent on the structure of the reservoir rock and the geology. In steamflooding, steam is injected continuously and forms a steam zone. This reduces the viscosity of oil and mobilizes it so that it can be produced. Additionally, the steam displaces the oil pushing it towards the production well. Typical oil recovery factor is between 50-60%, though excessive heat loss can be a problem. [15]

Steam assisted gravity drainage (SAGD) is an enhanced oil recovery mechanism that was developed by Bulter in the 70s, [16-18] and has been a commercially successful. SAGD not only uses the latent heat of steam but also utilizes a pair of parallel horizontal wells. Steam is injected in the upper horizontal well, and the mobilized oil is produced at the bottom horizontal well through a gravity drainage process. During the oil recovery, steam rises to the top forming a chamber, and the continuous injection of steam allows the steam chamber to grow laterally. [3,16-21] SAGD is particularly effective in low mobility oil as bitumen where the development of steam chamber takes place and not the steam channels. [15] Figure 1-2 is an illustration of a theoretical model of the SAGD process and depicts the steam chamber development through steam injection.
1.2.3 Steam assisted gravity drainage (SAGD)

The theoretical development of the SAGD process is based on a conduction heat transfer mechanism and flow in porous media. The heat conduction transfer mechanism is combined into Darcy’s law, an equation of state often used for flow in porous media, which results in an expression for oil drainage flow as

$$Q = \sqrt{\frac{2\phi \Delta S_o kg a(H - y)}{m v_s}}$$

where $Q$ is the oil production rate, $\phi$ is the porosity of the reservoir, $\Delta S_o$ is the initial oil saturation less residual oil saturation in the steam chamber, $v_s$ is the kinematic oil viscosity, $k$ is the permeability, $m$ is the dimensionless constant established between the viscosity-temperature relationship of oil, $a$ is the thermal diffusivity of the reservoir material, $g$ is
gravitational acceleration, and $H$ is the distance from top to bottom of the reservoir, and $y$ is the height of the reservoir.

### 1.3 Introduction to Microfluidics

Microfluidics is a field of research that presents numerous opportunities in research. First and foremost, it allows for experimental studies to be lab-on-chip scale. [5] The ease of operation in microfluidics and its capacity of flow visualization, along with many natural phenomena being microscale makes the application of microfluidics popular in various fields, as the biomedical research sector, [8] bioenergy research, [89] and in petroleum research. [34-38] Microfluidics holds promises in bringing the possibility of numerous experiments to be performed rapidly with little consumption of reagent. Additionally, the physical characteristics of microfluidics bring advantages in analyzing and manipulating fluids.

In fluid dynamics and in microfluidics, dimensionless numbers express the relative importance of various physical phenomena and is often used to define the different flows types. [5] Of all the dimensionless numbers, the Reynolds number (Re) is most frequently mentioned dimensionless number in fluid dynamics. The Reynolds number compares the relative dominance of inertial forces over viscous forces. The Reynolds number is expressed as

$$Re = \frac{\rho U_0 L_0}{\eta}$$

where $\rho$ is the viscosity of the fluid, $U_0$ is the velocity of the fluid, and $L_0$ is the length of the fluid, and $\eta$ is the viscosity of the fluid. The Reynolds number is used to distinguish between laminar and turbulent flows: systems with Reynolds numbers less than 2300 are considered
laminar, while numbers higher than 4000 indicate turbulent flow. Reynold numbers between 2300 and 4000 classified as transient flow. Furthermore, when the Re is less than 1, as it is often in microfluidics, the flow becomes linear and predictable Stokes flow, where the inertial terms in the Navier-Stokes equation is assumed to be negligible.

The Péclet number (Pe) is another often used dimensionless number which expresses the relative importance of convection to diffusion. The Péclet number is used in mixing phenomena in microfluidics. The Péclet number is expressed as

$$Pe = \frac{U_0 L_0}{D}$$

where $U_0$ is the velocity of the fluid, and $L_0$ is the length of the fluid, and $D$ is the diffusion coefficient. The Péclet number shows the ratio between convection and diffusion. If the Péclet number is higher than 1, the mixing is convection dominant, and if the Péclet number is lower than 1, the mixing is diffusion dominant.

The Capillary number (Ca) is a dimensionless number describing the relative magnitude of viscous forces to interfacial tension. The Capillary number plays a role in in systems with bubbles when the interfacial tension is large enough that it competes with the viscous forces. The Capillary number is expressed as

$$Ca = \frac{\eta U_0}{\gamma}$$

where $\eta$ is viscosity of the fluid, $U_0$ is the velocity of the fluid, and $\gamma$ is the interfacial tension of the fluid. A Capillary number lower than $10^{-5}$ indicates that the flow is dominant by capillary forces, while a high value indicates that the capillary forces are negligible.
The Bond number (Bo) is a dimensionless number to express the ratio of gravitational forces to surface tension forces. The Bond number is expressed as

$$Bo = \frac{\Delta \rho g L^2}{\sigma}$$

where $\rho$ is the density of the fluid, $g$ is the gravitational force, $L$ is the characteristic length, and $\sigma$ is the surface tension. A high value in the Bond number (greater than unity) means that the system is relatively unaffected by surface tension effects, while a low value indicates that the surfaces tension effects are relatively dominant.

1.4 Microfluidics application in Petroleum Engineering

Unconventional oil and gas reservoirs, such as bitumen and shale, have geological structures at micro and nanoscales. Hence, fluid interactions in oil and gas reservoirs require the application of microfluidics/nanofluidics to study the micro/nanoscale phenomena in oil recovery process. However, research in petroleum engineering requires high pressure and high temperature conditions, and the use of harsh solvents. Through the development of glass and silicon chip fabrication, microfluidic chips that withstand high temperature and high pressure conditions, and have compatibility to harsh solvents became available, and this brought the opportunity to use microfluidics to conduct visualization experiments of the oil recovery process. [20,21] Furthermore, the application of microfluidics in petroleum research has been extended to PVT studies, as solubility and diffusivity measurements [36,37], bubble and dew point [38] measurements, and measurement of minimum miscibility pressure (MMP) of heavy oil and CO2. [90] In all regards, microfluidics has shown advantages in drastic decrease in sample volume size and experimental time reduction, and visualization of flow.
1.5 Thesis Overview

The objective of this thesis is to study the oil recovery process of SAGD and its variations through microfluidic applications.

Chapter 2 focuses on the comparison results of alcoholic and alkaline additives in SAGD at elevated pressures (0.7 MPa and 1.3 MPa) and oil recovery results of these comparison tests. Additional advanced IR imaging, fluorescence microscopy and emulsion analysis have been conducted providing further insight into the process of additive-SAGD.

Chapter 3 focuses on solvent-SAGD. Co-injection of solvent along with steam have been carried out in this chapter. Different types of solvents were used, which brought different types of pore scale phenomena and different trends in the oil recovery. Furthermore, the microscopic analysis of the solvent-SAGD run showed a compositional separation of the bitumen based on its polarity due to solvents indicating different components in bitumen, and extending the potential of micromodels to compositional analysis.

Chapter 4 shows the viscosity reduction of solvents due to propane-saturation in bitumen through a viscosity measurement experiment that was performed on a microfluidic chip, validating the impact on the quantity of solvent saturation in bitumen in viscosity reduction.

Chapter 5 presents the conclusion of this study along with future directions and new possibilities of microfluidic applications in petroleum research.
2 Microfluidic Pore-Scale Comparison of Alcohol- and Alkaline based SAGD Processes

This chapter has been submitted for publication. The candidate was the first author in this work and played the primary role in performing the experiments, analyzing the data, and writing the paper. Ali Abedini shares equal contribution to the authorship as majorly contributing to the novelty of the work and in the paper writing. Additional authors for the work include Pushan Lele, Adriana Guerrero and Prof. David Sinton.

Steam assisted gravity drainage (SAGD) is the established method for in situ bitumen extraction. However, natural gas powered generation of steam for the SAGD process results in large economic and environmental costs. Alcohol-and alkaline-based additives are emerging strategies to improve SAGD performance, and micromodels are uniquely well-suited to directly compare and quantify the effectiveness of additives with all other variables tightly controlled. The distinct effects of alcohol- and alkaline-based additives on the pore-scale mechanisms were quantified here using a representative high-pressure high-temperature glass micromodel with both optical and thermal imaging ($P = 0.7$ and $1.3$ MPa; $T = 180$ and $200^\circ$C). Alcohol addition resulted in viscous fingering, some solvency, oil-wet trapping in the mobile zone, and moderate increases in production. In contrast, alkaline addition resulted in water-wet surface condition, emulsification of the bitumen in the mobile zone, and significantly increased production. Temperature profile data combined with optical results were also used to accurately determine the interface and expansion of discrete regions formed during the SAGD including steam chamber, hot water flow zone, mobile zone, and
untouched bitumen zone. Alcohol provided only a slight improvement on the steam chamber growth, while alkaline additive expanded the steam chamber by over 10% and significantly improved the overall recovery.

**KEYWORDS:** Micromodel; Pore-scale; Bitumen; SAGD; Alcohol; Alkaline

### 2.1 Introduction

There is over 160 billion barrels of proven reserves in the form of oil sands known as bitumen, representing over 10% of the world total reserves. [9,10] Bitumen is extracted using either surface mining or increasingly in situ extraction techniques employing heat, solvent, and hybrid heat-solvent processes. Current in situ recovery methods include cyclic solvent injection (CSI), vapour extraction (VAPEX), cyclic steam simulation (CSS), and steam assisted gravity drainage (SAGD). [11-15] The ultimate goal during in situ extraction methods is to reduce the bitumen viscosity either through heat or mass transfer, enabling bitumen production.

The SAGD process has been widely applied for bitumen production in various bitumen reservoirs in Canada including Athabasca Oil Sand, Cold Lake, and Peace River. SAGD employs the horizontal well pair drilling technique to inject steam into the bitumen formations. A large volume of steam near its saturation temperature (i.e., saturated steam) is injected from the upper horizontal well, transferring large amount of heat to bitumen via latent heat generation. [16-18] Consequently the viscosity of bitumen drastically declines, making it sufficiently mobile to drain by gravity to the producer (i.e., the lower horizontal well). [19] While SAGD is effective, the steam generation process is a major source of CO\textsubscript{2} emissions, and many strategies are currently under test to improve both the environmental
and economic performance. One strategy is the use of chemical additives to the steam stream prior to injection. [20-23] The chemical additives can offer a range of benefits including viscosity reduction, wettability modification, interfacial tension reduction, surface property modification, solvency, and increased emulsification.

A range of methods have been applied to understand and test SAGD recovery mechanisms and inform operators, including reservoir modeling and simulation, [24-28] large-scale sand pack flood, [29-33] and micromodel experiments. [19,20,23] Micromodels are particularly well suited to the assessment of chemical/thermal recovery strategies, as they can provide a very controlled test environment with reservoir fluids at reservoir pressures and temperatures. For instance, to evaluate the effectiveness of an additive in isolation from other variables, micromodels can provide side-by-side comparison of recovery mechanisms and displacement efficiency. Micromodels can provide high resolution pore-scale saturation, phase, emulsion, and wetting data not obtainable with other methods and – perhaps most importantly – provide a uniquely well-controlled environment whereby the influence of individual variables can be quantified and compared.

Micromodels and in general microfluidic technologies have been widely used in diverse engineering sectors and recently gained interest to be applied for oil and gas industry. [34,35] Microfluidics has been utilized to measure PVT properties such as bubble/dew points, solvent solubility, and solvent diffusion rate. [36-38] Asphaltene deposition mechanisms and stability of emulsions forming during petroleum processes have been also studied via microfluidic platforms. [39-41] Furthermore, the application has been extended to study the recovery efficiency of various secondary and tertiary oil recovery processes, while majority of them were operated at relatively low pressures and temperatures. [19,20,42-46]
Advantages of lab-on-a-chip techniques are not limited to direct visualization of processes, but also they provide rapid quantification, facile control of temperature and pressure, and operating cost reduction.

In this paper, we use a high-pressure high-temperature micromodel chip to study pore-scale phenomena and recovery efficiency of the SAGD process with additive strategies. The effects of two different types of additive, alcohol-based and alkaline-based are investigated at experimental conditions similar to SAGD field operations (i.e., for our experiments: \( P = 0.7 \) and 1.3 MPa; \( T = 180 \) and 200°C). Advanced imaging tools including bright-field, dark-field, and fluorescence microscopy as well as IR-thermal imaging are employed to quantify pore- and model-scale performance of these processes. In addition to recovery rates, process-critical data including wettability, steam chamber advancement, mobile zone thickness, recovery mechanisms in the mobile zone, emulsion type and emulsion size distribution are presented and compared for both alcohol, alkaline and pure steam control cases.

2.2 Experimental section

2.2.1 Micromodel Design and Fabrication

A micromodel pattern was designed to resemble the pore geometry of a typical bitumen oil sand formation. The micromodel consists of a porous network with posts of various dimensions, arranged in a semi-random pattern to simulate a natural rock pattern. A 10 cm × 10 cm glass micromodel chip was then fabricated by photolithography and wet-etching methods with hydrofluoric acid solution to a depth of 57 µm on a 2.25 mm borosilicate glass (Schott BF33). The physical dimension of the model provided a proper
field of view for monitoring the steam chamber advancement combined with high-resolution pore-scale imaging. The pore network consists of different grain sizes (i.e., in a range of 260–380 µm), pore throat sizes (i.e., in a range of 100–175 µm), and pore body sizes (i.e., in a range of 170–230 µm), all in the range of measured values of unconsolidated oil sands and other micromodel studies. [47-50] The porosity of the model was determined via two different methods including volumetric calculation and image analysis, and calculated to be 0.44 which is in a range typically observed in Athabasca oil sands. [51,52] The permeability of the chip was higher than that of bitumen reservoirs - an artifact of the planar format. The permeability was calculated by the Carman-Kozeny equation [69] and found to be 149.4D (in agreement with previous micromodel studies). [19-21,50] The engraved glass was thermally bonded with a cover glass with drilled holes representing the inlet and outlet of the system. Finally, the micromodel chip was mounted into the PEEK manifold and placed vertically to be attached to the other experimental parts.

2.2.2 Experimental Apparatus

Figure 2-1 depicts the schematic of experimental setup used for SAGD experiments which mainly consist of the micromodel chip, imaging tools, injection pump, steam generator, back pressure regulator, pressure gauges, temperature controllers, two-way and three-way valves, tube lines, and connectors. High-pressure high-temperature steam was injected into the SAGD micromodel chip and the fluid displacement inside the chip was controlled and visualized using different imaging techniques. Water was firstly fed into a custom designed steam generator through a high pressure syringe pump (Teledyne Isco 260D). The steam generator was a coil type one which contains a 1/16” tubing coil being wrapped around an inner cylinder and covered by an exterior cylinder which was wrapped around a ceramic
insulation to prevent further heat loss. The metal cylinder was heated via three cartridge heaters (McMaster-Carr, 3618K413) controlled by temperature controllers (Omega, CNI3222), inserted through the outer cylinder from the base. The metal cylinder showed a high thermal efficiency and was able to well produce a high quality steam. The tubing from the steam generator was then connected to the system directing to the chip inlet. The entire inlet tubing of the system was wrapped with rope heaters (McMaster-Carr, 3641K24) and well insulated to prevent heat loss to the external environment and to aid controlling the steam temperature. The PEEK manifold reduced heat loss to the surroundings as compared to steel manifolds used previously. To enable comparisons between tests, similar thermal conditions were maintained, within experimental error, in all cases. The outlet tubing of the chip was also wrapped with another rope heater and separately controlled to maintain the produced bitumen mobilized up to the back pressure regulator (Equilibar, EB1ZF1). The backpressure regulator was installed at the outlet to maintain the system under the desired pressure and adjust the flowrate through the micromodel. The flowrate of the runs were adjusted to be in a range of 800–1000µl/min to reach the desired test temperature and to reduce the effect of viscous forces. Regarding the balance of convective and gravity forces, gravity is not the dominant force in the micromodel system. Specifically, the Gravity number (i.e., ratio of Bond number to Capillary number [54]) is ~ 0.4 here, indicating that while both play a role, viscous forces are larger than gravity forces in our micromodel runs. The pressure at the back pressure regulator during all steam runs was 0.5–1.0 bar lower than the injection pressure and was consistent during experiments. A bypass line was also designed and incorporated into the experimental setup in order to stabilize and control the pressure and flowrate of the steam before injecting into the SAGD chip. During the run, the time-lapsed
images of steam chamber development were taken by Nikon camera (Nikon D3300), and the corresponding temperature profiles of the chip were recorded by RAR-IR Nano camera. LED strip lights were positioned around the chip to provide a proper lighting to the chip and a 0.005” Teflon sheet was placed between the chip and the manifold from the back to provide more appropriate color contrast for chip image analysis. The pore-scale phenomena in different regions during tests were also visualized and recorded by a digital microscope camera (Dinolite AD-4013TL). Moreover, a post-run analysis on the pore-scale was conducted by a fluorescence microscope (Olympus BXFM, 5x-objective). Due to constraints imposed by the lab space, it was not possible to position a microscope head for live fluorescence (in addition to live visible and thermal imaging of the full model). Consequently, detailed fluorescence pore-scale data were obtained post-run, once the model is depressurized and cooled. Care was taken to depressurize the model slowly using the back pressure regulator in order to preserve the size and shape of the mobile zone as much as possible.
Figure 2-1 Schematic of experimental setup for conducting on-chip SAGD micromodel tests. Both the inlet and outlet pressure as well as steam flow rate are directly controlled, and the additive is premixed in the pump prior to operation.

2.2.3 Experimental Procedure

Prior to each test, the micromodel chip was cleaned with toluene on a hot-plate at a temperature of 90–110°C to remove any liquid or bitumen left over in the model. Then the chip was filled with isopropanol and again was placed on the hot-plate at a temperature of 130°C for 10 min. Once the chip became completely clean and dry, an Athabasca bitumen sample was injected into the chip by a glass syringe at a temperature of 90°C. The chip was then cooled down for 24 hr. Afterwards, the chip was embedded in a PEEK manifold and the inlet and outlet ports were well attached to the lines. The chip was then vertically mounted
and SAGD experiments were initiated according to the aforementioned description. It should be noted that the micromodel was preferentially oil-wet since it was aged through preliminary runs and subsequent chip cleaning protocol with hydrocarbon solvents. Previous studies showed that the surface wettability can change from strongly water-wet to mixed- or oil-wet by aging the rock sample in crude oil. [50-52] For SAGD experiments, saturated steam was injected into the chip. The pressure and temperature data provided in Table 2-1 are the steam pressure and temperature right before entering into the micromodel. As noted earlier, the back pressure regulator was set to a pressure which resulted in the desired flow rate range (~ 1000μL/min). Series of tests at various conditions were carried out to determine the influence of alcohol- and alkaline-based additives on the SAGD recovery performance. Prior to each SAGD-additive test, the specific amount of additive was added and dissolved in the DI water. The solution was then transferred to the ISCO syringe pump and into the steam generator. Table 2-1 summarizes the operating conditions of all on-chip SAGD micromodel tests. The saturation temperature difference due to this addition was calculated to be less than 1°C.

Table 2-1 Operating conditions of on-chip SAGD micromodel tests.

<table>
<thead>
<tr>
<th>Run</th>
<th>Solution</th>
<th>Injection Pressure (MPa)</th>
<th>Injection Temperature (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DI water</td>
<td>0.7</td>
<td>175–180</td>
</tr>
<tr>
<td>2</td>
<td>DIW-1000 ppm alcohol additive</td>
<td>0.7</td>
<td>175–180</td>
</tr>
<tr>
<td>3</td>
<td>DIW-2000 ppm alcohol additive</td>
<td>0.7</td>
<td>175–180</td>
</tr>
<tr>
<td>4</td>
<td>DI water</td>
<td>1.3</td>
<td>195–200</td>
</tr>
<tr>
<td>5</td>
<td>DIW-1000 ppm alkaline additive (pH = 11.7)</td>
<td>1.3</td>
<td>195–200</td>
</tr>
<tr>
<td>6</td>
<td>DIW-2000 ppm alkaline additive (pH = 11.9)</td>
<td>1.3</td>
<td>195–200</td>
</tr>
<tr>
<td>7*</td>
<td>DIW-2000 ppm alkaline additive (pH = 11.9)</td>
<td>0.7</td>
<td>175–180</td>
</tr>
</tbody>
</table>
This experiment was conducted to examine the efficacy of alcohol and alkaline additives in isolation from pressure, temperature, and concentration.

2.3 Results and Discussion

2.3.1 Steam Chamber Development

Figure 2-2 shows lapsed-time images of overall sweep efficiency together with corresponding temperature profiles for SAGD, SAGD-alcohol, and SAGD-alkaline experiments. As steam was injected into the micromodel, it condensed and the generated latent heat was transferred to the cold bitumen. As a result of heat transfer, the bitumen viscosity was drastically declined, allowing the bitumen to flow downward toward the producer/outlet port. During the initial period of the run, rapid steam chamber growth was observed in the chip as the mobile zone was small and heat loss to the surroundings was relatively low, however, chamber growth slowed with time in all runs. As shown in Figure 2-2a and 2b, a thick mobile zone existed in both pure SAGD and SAGD-alcohol tests while for SAGD-alkaline runs (Figure 2-2c), the mobile zone was significantly narrower. Thus the advancement of the steam chamber was larger during SAGD-alkaline compared with pure SAGD and SAGD-alcohol runs. These differing advancement rates are also apparent in the associated temperature maps at each time.
Figure 2-2 Steam chamber development and corresponding temperature distribution map for
(a) pure SAGD run at 0.7 MPa, (b) SAGD-alcohol with 2000 ppm additive
concentration at 0.7 MPa, and (c) SAGD-alkaline with 2000 ppm additive
concentration at 1.3 MPa.
From the image data, the advancement of the lagging and leading edges of the mobile zone, and the mobile zone thickness can be compared directly. Figure 2-3a shows the lagging edge profile (i.e., the line along the start of the mobile zone as shown inset) for all tests. The position and profile of the lagging edge of the mobile zone was very similar for pure SAGD and SAGD-alcohol cases. In contrast the lagging edge, and the steam chamber growth, was very advanced for both SAGD-alkaline cases (i.e., 1000 and 2000 ppm). While both alcohol additive concentration runs matched closely to the corresponding pure steam case (i.e., SAGD test at $P = 0.7$ MPa), the chamber developed somewhat differently in the alcohol case, with more advancement on the upper portion of the micromodel. This result is consistent with expected phase behaviour, with steam condensing sooner than alcohol, preferentially concentrating alcohol vapor at the top.

Figure 2-3b compares the profile of the bitumen-side the mobile zone – the leading edge – for all cases. Unlike the lagging edges of all tests which had a smooth profile, the leading edges were irregular due to viscous fingering of condensed injection fluid (i.e., condensed steam and additive) into the bitumen. Viscous fingering results from instability at the interface of two fluids during a displacement process, mostly due to viscosity contrast, and creates an irregular and fingered profile. [58,59] This irregularity was more pronounced during SAGD and SAGD-alcohol experiments as compared with SAGD-alkaline runs. In addition, comparing the leading and lagging edges of SAGD-additive runs reveals that the edge profiles progressed more into the bitumen (leftward) with increased additive concentration. Figure 2-3c plots the mobile zone thickness for all runs (the distance between leading and lagging profiles plotted in Figure 2-3a and 3b. The mobile zone was thickest for the pure SAGD cases, followed by the SAGD-alcohol cases. Specifically, the average mobile
zone thickness of the alkaline additive runs was 1.55 cm, which is 36% smaller than that of the corresponding pure steam case. In summary, while alcohol showed only subtle differences from pure steam, the alkaline additive cases showed a thinner, more rapidly advancing mobile zone.
Figure 2-3 Final (a) lagging edge profile, (b) leading edge profile, and (c) mobile zone thickness of SAGD and SAGD-additive runs.
2.3.2 Oil recovery factor analysis

Figure 2-4 shows the bitumen recovery data for SAGD and SAGD-additive runs. At early times the steam chamber was developed rapidly. We focus the comparison analysis after this initiation period is over ($t > 40$ min) and the chamber is well developed, as shown in Figure 2-4a (data including the initiation period is shown in Figure 2-4b. With the addition of alcohol (2000 ppm), the bitumen recovery factor increased from 9% in the corresponding pure SAGD test ($P = 0.7$ MPa) to more than 12%. While detectable, the effect was not strong, and the influence of alcohol concentration was likewise very slight (Figure 2-4c). In contrast, the alkaline additive showed a significant recovery improvement over the corresponding pure SAGD test ($P = 1.3$ MPa). Likewise the concentration dependence was significant, with the 19% bitumen recovery coming from the 2000 ppm case.

Figure 2-4 Bitumen recovery factor of SAGD and SAGD-additive tests, (a) Recovery data are normalized and compared after 40 min of the run, (b) Cumulative recovery factor of during entire running time, (c) final bitumen recovery factor as a function of additive concentration.
Figure 2-5a compares the recovery factor of SAGD-alcohol with SAGD-alkaline and pure SAGD at 0.7 MPa in isolation from all other experimental parameters. Injection pressure, steam flow rate and additive concentration were constant for direct comparison. As depicted, the alkaline additive had higher recovery performance and notably increased the bitumen production rate with a final recovery factor of 14% (final recovery factors are shown in Figure 2-5b). In addition, this comparison shows that under the same pressure, temperature and steam injection rate, both alcohol and in particular alkaline additive markedly reduce the steam-oil-ratio over SAGD as shown in Figure 2-5c.

Figure 2-5 Effectiveness of alcohol and alkaline additive in isolation from pressure, temperature, and additive concentration ($P = 0.7$ MPa, $T = 175–180 \, ^\circ\text{C}$, $c = 2000$ ppm) compared with a pure SAGD run, (a) Bitumen recovery factor of SAGD, SAGD-alcohol, and SAGD-alkaline tests after initial steam chamber development, (b) Final recovery factor, (c) steam-oil-ratio relative to SAGD.

2.3.3 Temperature profile analysis

Figure 2-6 shows the final temperature profile of SAGD and SAGD-additive runs. Temperature data along four distinct horizontal lines at different heights of the chip were extracted from IR images of each test in order to accurately determine the ultimate steam chamber border once the steam region is fully developed inside the chip and differentiate it
from lagging edge. Across the steam chamber zone at different locations, the temperature is relatively constant, as is typical in SAGD operations. At the steam boundary, the temperature declines rapidly into the bitumen. The point where the temperature profile deviates from that of the steam chamber is indicated in each case with a line (line format matching other Figures).

For the lower pressure runs, the temperature profile of the steam chamber was in a range of 150–160°C and for the higher pressure runs, it was ranging from 175–185°C. These values correspond to, but are not exactly the pure steam saturation values at the injection pressure ($T = 165°C$ and $191°C$). Some difference between the measured temperature from the chip and the property data are expected due to the slightly lower pressure in the chip, heat loss to the surroundings, and measurement error in IR imaging. The deviation in saturation temperature at elevated experimental pressures due to the presence of additives is not expected to be significant (i.e., 0.9°C for alcohol and 0.7°C for alkaline at the most concentrated values and elevated pressure associated with the tests’ operating conditions). It is noteworthy to mention that the IR images are based on the temperature of the outer surface of the micromodel as glass being largely impermeable to the IR wavelengths used. The IR imaging measures the temperature of the surface, which through calibration tests has been verified to be within 3–4°C of the inner surface of the glass when in the range of 100–200 °C. Thus the temperature contours marking the edge of the steam boundary are likely biased leftward which corresponds to less than 1 mm, a relatively small deviation due to the high temperature gradients in this region.
Figure 2-6 Final temperature distribution of the chip for all SAGD and SAGD-additive tests (the steam chamber border of each test was determined from the point where temperature drops sharply). Select temperature profiles along sections (1)–(4) indicated in (a) are plotted in all cases from 100–200ºC. (Any dark blue region has a temperature equal to or lower than 100ºC).
Figure 2-7a and 7b differentiate the location of the steam chamber boundary and the lagging edge of mobile region in the pure SAGD runs at 0.7 and 1.3 MPa using the optical images combined with IR-thermal images. The line representing the chamber border was determined from IR images (Figure 2-6a and 6d) and the line representing the lagging edge of the mobile zone was determined directly from optical images (Figure 2-3a). As shown, there was a region between the steam chamber border and the lagging edge is made up of condensed hot water (with or without additive). This region was also visually observed during the experiments by the live pore-scale microscopy. The hot water region was initially small and gradually became larger as steam chamber advanced more into the bitumen zone. The liquid layer was not, however, totally impermeable to steam, and some steam bubbles passed through, resulting in transitional steam-in-bitumen dispersions which rapidly condensed and dissipated. The hot water flow zone was comparably larger during the SAGD-additive runs compared with pure SAGD experiments. This liquid condensed region at the lagging edge has not been described in previous SAGD studies, [19, 20] and we expect that we see this here because of a combination of improved imaging, resolution of the pore-scale, and operation at higher reservoir-relevant pressures, favoring early condensation.

We subdivide the entire area of the micromodel during all SAGD and SAGD-additive runs into four regions (from left to right): steam chamber, hot water flow zone, mobile zone, and untouched bitumen zone. The size of each region varies as a function of injected fluid composition and temperature and pressure, as quantified in Figure 2-7c. The steam chamber was significantly larger for SAGD-alkaline runs, and proportionally increased with higher concentration, in step with the improved recovery. As shown in both Figure 2-3c and Figure
2-7c, the final area of the mobile zone during SAGD-alkaline tests is noticeably lower than that of the SAGD and SAGD-alcohol runs.

Figure 2-7 Combined optical and thermal images to show the steam chamber border and lagging edge for (a) SAGD at 0.7 MPa and (b) SAGD at 1.3 MPa; (c) Final areal distribution of four distinct regions occupied the entire chip area during SAGD and SAGD-additive runs. The chamber border is from the IR data (Figure 2-6) and the lagging edge border is from the optical imaging (Figure 2-3).
2.3.4 Pore-scale behavior in the mobile zone

The pore-scale images of the mobile zone during the SAGD, SAGD-alcohol, and SAGD-alkaline runs are shown in Figure 2-8. Figure 2-8a shows the mobile zone of the SAGD test conducted at 1.3 MPa. In that case fingering phenomena dominate in the mobile zone, resulting in significant trapped bitumen. In contrast, during the SAGD-alcohol (2000 ppm, Figure 2-8b) the mobile zone was made up of smaller oil ganglia, and an irregular bitumen boundary again caused by viscous fingering at the leading edge. Some minor solvency effect is apparent in SAGD-alcohol case, as indicated by small, lighter brown residuals; however, the solvency effect was a very minor deviation from that observed in the pure SAGD case. The trapped bitumen ganglia in the mobile zone are a product of viscous fingering and wettability trapping. Wettability trapping is produced as a result of initially oil-wet nature of the micromodel. In contrast, a representative portion of the mobile zone during a SAGD-alkaline run with 2000 ppm concentration is also shown in Figure 2-8c. The mobile region is markedly different from the previous cases, dominated by rapid formation of pore-size bitumen droplets at the interface (negligible fingering) and subsequent drainage with relatively little residual. The pore-scale data also indicated that the alkaline additive results in a more water-wet surface condition (in agreement with previous work at low pressure [20]), which contributes to a faster drainage rate and a thinner mobile zone. [60,61] The glass surface becomes strongly water-wet under the higher pH condition (i.e., presence of alkaline additive in the solution). This wettability alteration provides the chance for water to spread over the surface, vacate the pores, and enclose the oil phase; resulting in formation of discrete oil in water droplets as shown in Figure 2-8c. Notably, the wettability alteration and
subsequent bitumen droplet formation occurs in the mobile zone where only liquid phases (i.e., bitumen and water) are present - in contrast to oil film formation where gas phase is present as a displacing fluid in water-wet rocks. [62] Moreover, the alkaline solution is expected to neutralize the organic acids in bitumen and produce a surfactant effect, reducing interfacial tension and producing smaller emulsions. [63-65] It has been reported that the IFT of water-bitumen systems is a strong function of pH of the solution, reducing from 20 mN/m at pH = 7 to lower than 5mN/m at pH > 10. [66,67] Both of the aforementioned factors (i.e., more water-wet surface and lower interfacial tension) facilitate bitumen extraction and improve the recovery rate during SAGD-alkaline run.

![Figure 2-8](image)

Figure 2-8 Pore-scale phenomena in the mobile zone during the run for (a) SAGD at 1.3 MPa, (b) SAGD-alcohol with 2000 ppm concentration, and (c) SAGD-alkaline with 2000 ppm concentration.
2.4 Conclusion

In this study, the distinct effects of alcohol- and alkaline-based additives on the performance of SAGD process were investigated. A series of carefully-designed micromodel experiments combined with optical and thermal imagings were conducted to quantify the pore-scale mechanisms at reservoir temperature and pressure. According to the normalized recovery data, the alcohol additive showed an improvement in bitumen recovery by 3% over SAGD run while the alkaline additive significantly enhanced the bitumen extraction by extra 7%. Pore-scale visualization showed different mechanisms associated with each of alcohol and alkaline additives. Alcohol addition resulted in viscous fingering, some solvency, and wettability trapping in the mobile zone. Although these alcohol additive impacts were consistently observed, their effect on recovery was minor. However, for the alkaline additive, bitumen emulsification and surface wettability modification towards water-wet condition were the main mechanisms and these contributed to significantly higher bitumen recovery. These results highlight both the pore-scale mechanisms and the recovery impact of both additive types, a comparison uniquely well suited to a micromodel approach that provides uniquely tight control over conditions.

2.5 Post run microscopic analysis

Figure 2-9 provides a post-run analysis of the micromodel chip through dark-field and fluorescence microscopies under 5x-objective magnification for SAGD, SAGD-alcohol (2000 ppm), and SAGD-alkaline (2000 ppm) tests. For the SAGD run (Figure 2-9a), the bitumen mostly occupied the narrower pore throats with well-defined, circular bitumen-water
interfaces. In contrast, with SAGD-alcohol the bitumen-water interface shape was more variable, indicating a minor reduction in interfacial tension (Figure 2-9b), and/or a more mixed wet condition. In addition to the water-in-oil emulsions that generated abundantly, some oil-in-water emulsions were also produced during the SAGD-alcohol run as depicted in Figure 2-9b, beneficial for recovery. [56] Figure 2-9c shows the SAGD-alkaline run with concentration of 2000 ppm.

![Figure 2-9 Post-run analysis of dark-field and fluorescence images at 5x-objective for (a) SAGD at 0.7 MPa, (b) SAGD-alcohol (2000 ppm) with magnified inset showing oil-in-water emulsions, and (c) SAGD-alkaline (2000 ppm) with magnified inset showing water-in-oil emulsions.](image)

Figure 2-10 plots the drop size distribution of post-run in situ water-in-oil and oil-in-water emulsions of SAGD-alcohol and SAGD-alkaline runs both with 2000 ppm additive concentration. The emulsion data was taken from various locations of mobile zone from top to bottom. As compared with alcohol additive, the alkaline produced smaller emulsions. The results also revealed that the type of the additive has a notable influence on the type the emulsions generated during the process. The majority of emulsions produced during SAGD-
alcohol run were water-in-oil emulsions together with minor oil-in-water emulsions. Conversely, for the case of SAGD-alkaline, emulsions were mostly generated in the form of oil-in-water with some water-in-oil emulsions in larger oil droplets. As shown, the alkaline case produced a larger population of smaller oil-in-water emulsions, which contributed to the improved performance. Although it is likely that the size distribution of the emulsions in the mobile zone changed during depressurization, the data collected can provide some insight, and also has relevance to surface facilities. Specifically, the fluid that travels to the surface through the production well experiences a similar depressurization and the resultant emulsions are the inputs for surface separation units.
Figure 2-10 Size distribution comparison of post-run *in situ* (a) water-in-oil emulsions and (b) oil-in-water emulsions in the mobile zone for SAGD-alcohol and SAGD-alkaline tests both at 2000 ppm additive concentration.
3 The role of condensing and non-condensing solvents in SA-SAGD

Highlights

- C6-SAGD run showed the highest enhancement in oil recovery due to its thermophysical properties being similar to steam.
- C4-SAGD run showed high improvement in the oil recovery rate due to the foam layer reducing the viscous fingering phenomena, and the condensation of these bubbles aiding the fast flow of this zone.
- C3-SAGD run showed a foam layer in the mobile zone which reduced the viscous fingering phenomena.
- Fluorescence analysis of C6-SAGD run showed a varying level in fluorescence intensity due to the separation of aromatic components of bitumen.

Petroleum contributes to 33% of the world’s energy supply with one of the major uses being in transportation. [10,75] Though oil is inherently a limited resource, the newly-developed production technologies have increased its supply by increasing the amount of economically recoverable oil, so-called as oil reserves. The introduction of steam-assisted gravity drainage (SAGD) by Bulter in 1970s, where the main mechanism relies on the viscosity reduction of bitumen due to large amount of heat transfer, has significantly enlarged the Canadian oil reserves. While SAGD is effective, it has economic and environmental issues associated with steam generation. Several methods have developed to address the issues as well as improve the bitumen extraction over SAGD. In this regard, use of light solvents to reduce the viscosity of bitumen through dilution, known as vapor extraction.
(VAPEX), has been proposed. [13,14,46] Recently, a hybrid method of co-injecting a minor volume of solvents (5-15vol%) with steam has shown promising results in increasing bitumen recovery and reducing energy costs. [78-83] Laboratory studies on SAGD have been conducted on large-scale sandpack models, [29-33] glass beads, [50] and microfluidic chips. [19-21] Recent development of high-temperature high-pressure glass micromodels in our group has allowed physical modeling of the SAGD and SAGD-solvent processes at conditions similar to the Canadian Oil Sands. This presents an opportunity to study the performance of various solvents on bitumen production under relevant *in situ* reservoir condition. Moreover, the pore-scale mechanisms and displacement efficiency in different regions can be quantified.

### 3.1 Introduction

Steam-assisted gravity drainage (SAGD) is a commercially successful method of extracting bitumen in the Canadian Oil Sands. [15-18] In the SAGD process, a horizontal well is drilled one above the other in the same vertical plane, and large volume of steam is continuously injected from the upper horizontal well, developing a steam chamber and transferring large amount of heat to bitumen via latent heat generation as a result of steam condensation. Consequently, the viscosity of bitumen drastically declines, making the bitumen mobile enough to be drained by gravity towards the producer (i.e., the lower horizontal well) and produced together with condensed steam.

The concept solvent-aided steam assisted gravity drainage (SA-SAGD), also known as expanding solvent steam assisted gravity drainage (ES-SAGD), its name derived from the expansion characteristic of solvents over the steam, has been studied as a method to reduce
the energy consumption in the SAGD process by using the dilution effect of solvents in bitumen. [78-85] The benefits of solvent injection in steam is not only limited to the increase in oil recovery due to viscosity reduction of bitumen, but also that the produced solvent can be recycled and re-injected into the reservoir, and that the produced solvent in the oil phase offsets solvent required to make the bitumen pipelinable which indicates a good opportunity for field application. [81]

During the steam injection process in bitumen reservoirs, the porous structure of the reservoir rock significantly influences the recovery rate. [68-73] The existence of three-phase flow (i.e., steam, water and bitumen) additionally complicates the displacement process. A detailed understanding of the porous media properties such as porosity and permeability together with pore scale physical phenomena can bring methods of enhancement to the oil recovery process and be incorporated in mathematical models numerically simulating the oil recovery process. Macroscopic multi-phase flow is difficult to model experimentally, and two-phase or three-phase relative permeability and capillary pressure data are usually estimated by appropriately averaging the equations describing the physical processes occurring in the pore scale. [70,71] However, this approach requires a thorough understanding of displacement mechanisms on the pore scale and a complete description of the pore space morphology. Direct visual observation of the multiphase flow during SAGD process provides the opportunity to probe recovery mechanisms and pore-scale phenomena that take place in the reservoir.

Though the application of microfluidics for research has mostly been in the biomedical sector, the glass microfluidic chip developed in our lab has provided an opportunity for the visualization of oil recovery processes due to its capacity to work in high-
Microfluidics applications for energy have led to interesting research such as detection of minimum miscibility pressure (MMP) of CO2 in heavy oil, and measurement solvent solubility and diffusion in bitumen. [36,37,90] The application of microfluidics in research brings advantages as many orders of reduction in sample size, rapid quantification, facile control of temperature and pressure, and operating cost reduction. [38]

In this chapter, SAGD micromodel runs were conducted with various solvents at temperatures and pressures (e.g. 1.0 MPa) relevant to in situ reservoir conditions. Visualization techniques were used to analyze the oil recovery factor and pore scale mechanisms, and the effects of different solvents injected with steam were investigated in macroscopic, pore scale and microscopic scales, coinciding with previous conclusions in literature, [78-83] and adding new insights in the solvent-SAGD process through pore scale and microscopic studies.

### 3.2 Experimental Methods

A glass chip was fabricated to resemble the pore geometry of a typical bitumen oil sand formation and a PEEK manifold was used for better insulation during the run. Figure 3-1 shows the overall schematic for the solvent-SAGD tests. DI Water and solvents were first fed into high-pressure syringe pumps (Teledyne Isco 260D) then were co-injected to the steam generator at controlled flowrates. The pressure was manually controlled through the backpressure regulator (Equilibar, EBIZF1) and through the pumps. The flowrate of the runs were set based on the required convection to reach the desired test temperatures. During the run, a Nikon D3300 camera was used to study the oil recovery of the micromodel and a
digital microscope (Dinolite AD-4013TL) was used to study pore scale phenomena in the solvent-SAGD process. An IR camera (RAR-IR Nano camera) was used to read the temperature profile of the chip. After the run was terminated, post run analysis was conducted by a fluorescence microscope (Olympus BXFM 5x objectives). Table 3-1 is a summary of the experimental conditions of the solvent-SAGD runs.

Table 3-1 Operating conditions of SAGD and solvent-SAGD micromodel runs.

<table>
<thead>
<tr>
<th>Run</th>
<th>Pressure (MPa)</th>
<th>Flowrate(ul/min)</th>
<th>Temperature(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAGD</td>
<td>1.0</td>
<td>1000µl/min(DI water)</td>
<td>185</td>
</tr>
<tr>
<td>Condensate-</td>
<td>1.0</td>
<td>1000µl/min(DI water)+</td>
<td>185</td>
</tr>
<tr>
<td>SAGD</td>
<td></td>
<td>100µl/min(condensate)</td>
<td></td>
</tr>
<tr>
<td>C6-SAGD</td>
<td>1.0</td>
<td>1000µl/min(DI water)+</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100µl/min(hexane)</td>
<td></td>
</tr>
<tr>
<td>C4-SAGD</td>
<td>1.0</td>
<td>1000µl/min(DI water)+</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100µl/min(butane)</td>
<td></td>
</tr>
<tr>
<td>C3-SAGD</td>
<td>1.0</td>
<td>1000µl/min(DI water)+</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100µl/min(propane)</td>
<td></td>
</tr>
</tbody>
</table>

*The condensate solvent is not a single component solvent but a mixture of light and heavy hydrocarbons.
3.3 Results and Discussion

3.3.1 Macroscopic Analysis

Figure 3-2 shows the overall chip images of the SAGD and solvent-SAGD runs at three different time frames. At a timeframe of 15 minutes, a rapid steam chamber development had taken place, and the oil recovery process has begun to represent the borderline phenomena of the steam chamber in the oil field reservoir during the SAGD process. The SAGD, condensate-SAGD, and C6-SAGD run did not differ significantly at this time frame. For the C4-SAGD run, the clearing at 15 minutes of the run is quite smaller, compared to the SAGD run. This is primarily due to the gas blanket effect, the solvent gas
chamber dispersing faster and acting as a thermal insulation layer, impeding the heat transfer of steam. [79,80]

At 30 minutes of the run, we can visibly observe major differences in the color of the mobile zone between the SAGD and the solvent-SAGD runs. The pixels of the mobile zone of the SAGD run are in black and white, white being the water region, and black being the bitumen region. However, the mobile zones of the solvent-SAGD runs have a lighter color as a result of dissolution effect of solvents in bitumen. Also, the difference between condensate-SAGD run and C6-SAGD run can be observed from this timeframe. The condensate-SAGD run has a fuzzy boundary at the top region of the micromodel which is thought to due to the lighter hydrocarbons that are in the gas phase. The C6-SAGD run on the other hand, shows an even distribution of the mobile zone, which continues until the end of the run. The C4-SAGD run shows a fuzzy boundary in the interface, and shows a good development of the steam and solvent chamber from the first 15 minutes.

At 85 minutes into the run, there are major differences between all the runs. The SAGD run shows the cleared zone, the black and white mobile zone, and the untouched bitumen zone. Both the condensate-SAGD run and C6-SAGD run show the mobile zone to be thicker than that of the SAGD run. For the condensate-SAGD, the thickness of this mobile zone varying in height can be observed. The mixture of light and heavy hydrocarbons with varying boiling points in the condensate-SAGD run seemed to have various solvents expand at different rates causing an uneven growth of this thick condensation zone. It is speculated that lighter hydrocarbons expanded to the top region and the heavier hydrocarbons dissolved the bottom region of the mobile zone. For the hexane-SAGD run, a uniformity in this mobile region from the top to the bottom is observed, similar to that from 30 minutes of the run. The
expansion of steam and solvent chamber for the C6-SAGD run was noticeably effective as the vaporization temperature of hexane is close to that of water. [78] The C4-SAGD run showed a continuous improvement and a quite steady clearing of oil, indicating a positive effect of the dissolution effect after the initial stages of the run.

Figure 3-2b shows the steam chamber advancement of the SAGD and solvent-SAGD runs. In the temperature scale between 20°C and 160°C, a distinct red zone exists corresponding to the steam chamber of the macroscopic images. As heat transfer is the main mechanism of steam condensation, the significantly higher temperature shown as the red zone corresponds to the steam zone of the micromodel, and its boundary closely matches the condensation line of steam. For the solvent runs, the solvents expanding over this region can be identified as solvents recover oil through mass transport effects as well as heat transfer effects.
Figure 3-2 a) Overall micromodel images of the SAGD, condensate-SAGD, C6-SAGD and C4-SAGD run at different time frames, b) IR images of SAGD, condensate-SAGD, C6-SAGD, and C4-SAGD run at 85 minutes.

Figure 3-3 shows the recovery factor of all the runs. It is noteworthy to mention that the recovery factor point has been adjusted to start from the 5 minutes of the start of the run, due to its rapid channel clearing, and its sensitivity to pressure, temperature and flowrate which was manually adjusted in the first 5 minutes of the run. The condensate-SAGD run, and the C6-SAGD run both showed a continuous improvement in oil recovery factor, especially at the later stages of the run, when oil recovery due to steam condensation was drastically reduced as a thick water and viscous fingering layer has been developed impeding
Further heat transfer to bitumen in the SAGD run. In the case of the condensate-SAGD and the C6-SAGD, the solvents had an effect of reducing bitumen viscosity through mass transfer effects, which allowed oil to be continuously recovered even after the formation of a water layer. For the lighter hydrocarbons, as C3 and C4, the oil recovery in the initial stages of the run was low, due to the difference in the vaporization temperature of water and solvents. The light hydrocarbon gas formed a gas blanket, impeding the heat transfer of steam, also known as the gas blanket effect. [79,80] However, after the initial stage of the run, the lighter hydrocarbons showed an enhancement in the oil recovery compared to the SAGD run, which shows the effect of solvents aiding the bitumen recovery.

Figure 3-3 Oil recovery factor of the SAGD and solvent-SAGD runs.

Figure 3-4 shows the average oil recovery rate for the SAGD and solvent-SAGD runs, from the 40 minutes of the run, when the run was more stabilized and a steady oil recovery
took place. First, it can be noticed that, all the solvent-SAGD runs have an improved oil recovery rate compared to the SAGD run showing the effect of viscosity reduction through solvent dilution in bitumen. The effectiveness of C6-SAGD can be described through the similarity in the thermophysical properties of hexane to water in the conducted experimental conditions (1.0 MPa) relevant to reservoir conditions. Another observation that can be observed is the unexpected effectiveness of the C4-SAGD run. Though the initial gas blanket effect was observed in the C4-SAGD run, a high oil recovery rate was observed in the C4-SAGD run after this initial stage, and a mechanistic study of this phenomena was conducted during the pore scale analysis of C4-SAGD.

![Figure 3-4 Average oil recovery rate(%/min) of solvent-SAGD runs after 40 mins.](image)
3.3.2 Pore scale analysis of the solvent-SAGD runs

Figure 3-5 shows the magnified view of the C6-SAGD run. A magnified view of this zone shows primarily, a change of color gradient throughout this region. This happens as steam and hexane is continuously injected, the inner part of the mobile zone has been washed away by hexane and water, while the mobile zone layer close to the bitumen zone is being diluted by hexane. Hence, the mobile zone shows an increase in the darkness of color as it gets closer to the bitumen zone. Another interesting observation with this zone is the existent of small black particles in the mobile zone near to the steam chamber. These black particles are asphaltenes, component of bitumen that does not get diluted in n-alkanes. [91]

Figure 3-5 Pore scale images into the hexane-SAGD run of the mobile zone.

Figure 3-6 shows the snapshot of the pore scale images during the pure SAGD run, C6-SAGD run and condensate-SAGD run. Figure 3-6a shows the pore scale image of the interface region of the pure SAGD run, where the only black and white region can be observed, and round viscous fingering layer is observed due to the immiscibility of water and bitumen. Figure 3-6b is a pore scale image of the interface region in the C6-SAGD run and Figure 3-6c is a pore scale image of the interface region in the condensate-SAGD run. While a very clear dilution and clearing of the oil zone was observed in C6-SAGD run, some
messier boundaries were observed in the condensate-SAGD run. A fast oil drainage in the mobile zone near the bitumen zone was found in the C6-SAGD run, as hexane expanded over the condensed steam and reduced the bitumen viscosity through mass transport effects as well as heat transfer effects during its condensation. In the condensate-SAGD run, due to the different phases of solvents in the condensate solvent mixture, the mobile zone differed from height. Figure 3-6c depicts the bottom layer of the mobile zone where some wettability alteration is found. The difference between Figure 3-6b and Figure 3-6c is that while hexane expanded over the steam condensation line condensing after steam for the C6-SAGD run, the heavier liquid solvent met with bitumen for the depicted picture in Figure 3-6c, diluting bitumen but not fully clearing it.

![Figure 3-6 Pore scale comparison images of SAGD, C6-SAGD, and condensate-SAGD run.](image)

Figure 3-7a is a magnification of the mobile zone and time lapsed pore scale images taken during the C4-SAGD run. In the C4-SAGD run, the viscous fingering layer of the mobile zone had been cleared, and was mostly occupied by bubbles. However, unlike the C3-SAGD run, the sweeping efficiency of this butane bubbles were high. A closer look in the IR images showed that butane bubble condensed in the mobile zone, and the condensation of butane bubbles and the rapid decrease of volume from it would have brought high flow in this region. The high effectiveness of the C4-SAGD run is thought to be due to the combined
effect of bubbles reducing the mobility of the penetrating fluid and reducing the viscous
fingering phenomena, [44,86] bubble condensation leading to fast flow in the mobile zone,
and the dissolution of butane in bitumen. The pore scale analysis of the C4-SAGD showed a
3.19% recovery improvement over 5 seconds in the captured pore scale region as shown in
Figure 3-7a.

Figure 3-7b is the magnification of the interface region and a time lapsed pore scale
images taken during the C3-SAGD run. Propane bubbles were observed in the interface
region. The flow of the propane bubbles was slow and sluggish, and these bubbles sweeping
the mobile zone was observed. The mobile zone region was better cleared than the other runs,
as the foam bubbles increased the viscosity of the propane water fluid, lowering its mobility
and reducing the viscous fingering phenomena. In Figure 3-7b, the bubbles were clearly
captured in the mobile zone layer in the Nikon images as the flow as slower, as well as in the
pore scale images. The pore scale analysis in the C3-SAGD run showed a 0.58%
improvement in recovery over 5 seconds quite lower than that of the C4-SAGD run.
3.3.3 Fluorescence microscopy analysis

After terminating the runs, microscopic images of the micromodel were taken to further analyze the phenomena that happens during the run. Figure 3-8 shows microscopic images in the interface region of the C6-SAGD run. Figure 3-8a is a darkfield microscopic...
image of the interface region near the bitumen zone of the C6-SAGD run and Figure 3-8b is the corresponding fluorescence microscopic image of it. In Figure 3-8a there are two distinct regions in the bitumen hexane interface, and region A is visually darker in color than region B. Looking at these two regions under the fluorescence microscope as in Figure 3-8b, region B is significantly brighter in fluorescence intensity. This phenomenon can be explained through studies in bitumen microstructure [91-96], and saturate-aromatics-resin-asphaltene (SARA) analysis of bitumen. The SARA components of bitumen have been investigated in their visual observation and their fluorescence signal, [91] showing the aromatics to have a higher fluorescence intensity compared to the other components, and asphaltenes to have basically no fluorescence. The components itself vary in color, from saturates being a clear colorless liquid, aromatics being lighter brown, resins being darker brown, and asphaltenes being black. [76, 91] Hence, the reason why region B in Figure 3-8 has a higher fluorescence intensity can be explained by the higher composition of aromatics in region B, due to its lower polarity and higher solubility in hexane. A quantification along the transition zone is shown in Figure 3-8c, showing region B to have a threefold higher value in fluorescence signal to region A. Additionally, why these fingers were partially diluted is thought to be due to hexane condensation during hexane flow contacting with this portion of bitumen of the viscous fingering layer and diluting a certain fraction of it.

Figure 3-8d-f shows darkfield and corresponding fluorescence microscopic images of the C6-SAGD run near the steam boundary of the interface region. Figure 3-8d shows the darkfield microscopic image of this region and Figure 3-8e shows the corresponding fluorescence microscopic image of it. Black particles that basically showing no fluorescence can be observed in the clear colorless liquid region that shows minor fluorescence. These
black particles labeled Region D are asphaltenes, and the lighter brown region labeled Region C has a significantly higher fluorescence intensity due to a higher fraction of aromatics. Figure 3-8f shows the fluorescence intensity in line fg, and quantifies the higher fluorescence intensity in region C.

Figure 3-8 a) Darkfield microscopic image of interface region near the bitumen zone for C6-SAGD run, b) corresponding fluorescence microscopic image of a), c) quantification of the fluorescence signal along the red marked region, d) darkfield microscopic image of interface region near the steam zone for C6-SAGD run, e) corresponding fluorescence microscopic image of d), and f) quantification of the fluorescence signal along the red line fg.
The post run analysis of C3-SAGD run is shown in Figure 3-9. In this figure, the formation of bitumen residue can be observed along the propane bubbles that was formed during the run. Figure 3-9a&amp;b shows the bitumen residue formed along the trapped propane bubbles in the interface region near the bitumen zone under the darkfield and fluorescence microscopy. Figure 3-9c&amp;d shows the bitumen residue that condensed in a foamy structure close to the steam chamber region of the interface region.

Figure 3-9 a) Darkfield microscopic image of the C3-SAGD run near the bitumen region, b) corresponding fluorescence microscopic image of a), c) darkfield microscopic image of the C3-SAGD run near the steam chamber region, and d) corresponding fluorescence microscopic image of c).

3.4 Conclusion

The micromodel analysis of solvent-SAGD brought various insights to the solvent-SAGD process, some coinciding with previous findings, and also bringing new and useful insights through pore scale and microscopic observations of the solvent-SAGD process. First,
solvent co-injection to steam showed an improvement in the oil recovery due to the mass transfer effect of solvents in bitumen. The phase similarity of solvents to water effected the improvement of recovery from solvent addition to steam, and the C6-SAGD run was most effective as its thermophysical properties was closest to that of water. Lighter hydrocarbon runs eventually showed an increase of oil recovery rate compared to the pure SAGD run after the initial stages of the runs where the gas blanket effect was observed. C4-SAGD run showed a thick layer of fast dispersion of bubbles throughout the run which was effective in clearing the bitumen layer. The effectiveness of C4-SAGD is thought to be due to the clearing of the viscous fingering layer and condensation of bubbles aiding the fast flow in this region. Additionally, the microscopic analysis brought valuable insight into the compositional separation of bitumen that took place in the C6-SAGD run, due to the difference in polarity of the bitumen components and its solubility in n-alkanes.
4 Microfluidic method of viscosity measurement in propane-saturated bitumen

4.1 Introduction

In the solvent-SAGD process, while steam mobilizes bitumen through heat transfer, solvents reduce the viscosity of bitumen through mass transfer. VAPEX is an oil extraction process primarily using the effect of viscosity reduction through mass transfer by injecting light hydrocarbons as propane into bitumen. [33,74] In this chapter, the measurement of bitumen viscosity with propane saturation was conducted using a microfluidic method. Though viscosity measurement through a microfluidic device has been previously done in biological research [98-102], the property measurements of solvent saturated bitumen have traditionally been done in macroscale experimental apparatus. [103-108] The use of the glass microfluidic chip in this work allowed experiments to have advantages in sample size reduction and miniaturization of system design, bringing the heavy duty petroleum PVT research on lab-on-a-chip scale.

There are two steps in the viscosity measurement of propane-saturated bitumen. First, the propane saturated bitumen is prepared in a high-pressure piston cylinder through propane injection in bitumen at a pressure above its saturation pressure. This propane-bitumen sample is left to saturate till it there is no further pressure drop. Then the propane saturated bitumen is pushed through the microfluidic chip and the viscosity of the bitumen is measured by the pressure differences and the imaging of the fluid end, as an application of the Poiseuille’s law.

4.2 Experimental Method
The preparation of propane saturated bitumen was done on a high pressure piston cylinder. Bitumen was filled in one end of the cylinder and water was filled on the other side. Then a certain volume quantity of liquefied propane was injected to the bitumen filled cylinder. Liquefied propane was used to quantify the amount of mass fraction in bitumen. Propane was injected at a pressure quite above the saturation pressure, so that the propane saturation in bitumen could be achieved. Pressure was measured after the propane was injected in bitumen, and saturation was determined when the pressure drop was below the accuracy of the pressure gauges (±1kPa).

The theoretical saturation pressure values were derived from equality of fugacity between the liquid and vapor phases. Assuming that the vapor phase is pure propane, the equation for the saturation pressure $P$ is

$$P = x_c \gamma_c P_{v_c}$$

where $P_{v_c}$ is the vapor pressure of propane in Kpa, and $\gamma_c$ is the activity coefficient of propane in bitumen. According to literature, the best fit value of the activity coefficient was $1.158$. This equation primarily indicates that higher pressure is needed to achieve a higher volume fraction of saturation. [76]

After the propane saturated bitumen sample was prepared, it was pushed to go through the microchannel in the microfluidic chip. The hydraulic diameter of the microfluidic chip was calibrated to be 76 µm by reading the pressure and flowrate of a calibration fluid. The propane bitumen sample was pushed by applying a constant pressure on the other end of the cylinder by the ISCO pump. The pressures were 1.5 and 1.7 MPa, both values above saturation pressures. A backpressure regulator was attached at the end of the chip in run #2 so that the whole system was set above the saturation pressure. Poiseuille’s
law was used to measure the viscosity of the solvent-saturated bitumen through imaging the flow. [101] Poiseuille’s law is described as below:

\[
\frac{dx}{dt} = \frac{\Delta P r^4}{8r^2 \mu x}
\]

where \(x\) is the length of the fluid, \(r\) is the tube radius, \(\mu\) is the viscosity of the fluid, and \(\Delta P\) is the total effective pressure. Figure 4-1 depicts the experimental setup for this process.

![Schematic for the viscosity measurement of the propane-saturated bitumen.](Figure 4-1)

The experimental conditions of the two runs are summarized in Table 4-1 below.

Table 4-1 Experimental conditions for viscosity measurement of propane-saturated bitumen

<table>
<thead>
<tr>
<th>Run#</th>
<th>Bitumen mass (g)</th>
<th>Propane volume (wt%)</th>
<th>Temperature (°C)</th>
<th>Pressure (MPa)</th>
<th>Measured viscosity (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.83</td>
<td>10</td>
<td>20</td>
<td>1.5</td>
<td>65,000</td>
</tr>
<tr>
<td>2</td>
<td>2.83</td>
<td>25</td>
<td>20</td>
<td>1.7</td>
<td>565</td>
</tr>
</tbody>
</table>
4.3 Results and Discussion

In this section, two runs were done with different mass fractions of propane in bitumen. The results showed that higher saturation of propane in bitumen lead to a significant reduction in the viscosity of bitumen. In Figure 4-2 image captures during run #1 and run #2 at different time frames are shown. Run #1 had a significantly slower advancement in the flow, and it took 8-9 minutes for the propane-saturated bitumen sample to completely fill the channel. In run #2, the propane saturated bitumen sample filled the channel in just 7 seconds, resulting in flow speed 2 order of magnitude higher than of run #1, indicating a significantly lower viscosity. The observations are also shown in as graphs in Figure 4-3a and b. Both flows showed a relatively linear trend in its fluid end location of the flow and this linear constant was used to estimate the viscosity of the propane-saturated bitumen sample.

Figure 4-2 Image of propane-bitumen flow captured at different times during a) run #1 and b) run #2.
The measured viscosity was compared with a theoretical model based on the Lobe binary mixing rule. [76, 109] The Lobe mixing rule is expressed as:

\[
v_{\text{mix}} = \phi_A V_A \exp\{\phi_B \alpha_B\} + \phi_B V_B \exp\{\phi_A \alpha_A\}
\]

\[
\alpha_B = 0.27 \ln\left(\frac{V_B}{V_A}\right) + \left[1.3\ln\left(\frac{V_B}{V_A}\right)\right]^{0.5}
\]

\[
\alpha_A = -1.7 \ln\left(\frac{V_B}{V_A}\right)
\]

where \(\phi\) is the volume fraction, \(v\) is kinematic viscosity, \(A\) is the lower viscosity component and \(B\) is the higher viscosity component. Figure 4-4 depicts a graph generated based by the Lobe binary mixing rule and the measured viscosity values of the two runs are also shown there. The difference between the model and measured viscosity values could indicate some escape of propane from the propane-saturated bitumen sample, and the possible difference in the viscosity of the sample bitumen to literature values. [74, 104]
In conclusion, viscosity measurements of propane-saturated bitumen showed a significant improvement in viscosity reduction. This indicates the effectiveness of the alternative method of viscosity reduction through mass transfer as a comparable method or combined method to viscosity reduction through heat transfer. Additionally, the application of microfluidics was important because it brought visualization of the sample flow, reduction of sample size, and miniaturization of the experimental setup.

Furthermore, this shows that microfluidics can be applied for PVT measurements in petroleum research. An important tool of the PVT measurements in petroleum research is a piston cylinder, and a development of a microfluidic piston cylinder that is capable of withstanding the conditions required for petroleum research, such as high temperature and
pressure conditions, [111] and compatibility to harsh solvents would be the next possible
direction to bring the heavy duty petroleum research system to lab-on-chip scale.
5 Conclusion and future direction

The work presented here shows important findings in steam assisted gravity drainage (SAGD) and its variations through microfluidic applications. The high quality visualization experiments of the additive-SAGD and solvent-SAGD at reservoir matching temperatures and pressures brought valuable data in oil recovery, phase distribution, investigation of pore scale mechanisms, emulsion size distribution, and even aspects of compositional analysis.

In the SAGD-additive tests, the alcohol-additive brought wettability alteration and some solvency effects that showed minor improvement in oil recovery, while the alkaline-additive resulted in major wettability alteration that significantly improved oil recovery through the liberation of bitumen by formation of oil droplets. Additionally, the elevated temperature and pressure conditions showed borderline phenomena in the SAGD process, such as a steam condensation and a thick layer of viscous fingering effects.

In the solvent-SAGD tests, various solvents were co-injected with steam at a volumetric ration of 1:10. Condensate and C6-SAGD run a showed a high improvement in oil recovery, as the injected solvents had a vaporization temperature close to that of water and the mass transfer effects of these runs were clearly observed. C4 and C3-SAGD runs showed a gas blanket effect in the initial stages of the run. However, after this initial stage, the co-injection of light hydrocarbon solvents showed a higher oil recovery rate compared to the SAGD run, and a foam layer existed in the mobile zone reducing the viscous fingering.
phenomena. Additionally, the C4-SAGD run showed a fast flow due to condensation of butane aiding the overall oil recovery.

Microscopic analysis of the C6-SAGD run provided insight into the compositional separation of bitumen during the C6-SAGD run, which is thought to be due to the different components of bitumen having varying levels of polarity and solubility in hexane. The microscopic analysis of bitumen showing compositional separation is thought to be the next direction of the micromodel analysis of the solvent-SAGD. The complexity of the bitumen microstructure as a composition of various hydrocarbons, brings unique characteristics to bitumen, and a lot could be obtained from studying this structure. Further research in the bitumen microstructure can be done through spectrometer measurement of the fluorescence signal and through an electron microscopic analysis to visualize the chemical microstructure of bitumen.
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