Emulsification and Emulsion Flow in Thermal Recovery Operations with a Focus on SAGD Operations: A Critical Review

ArianVelayati[1], Alireza Nouri[1]

[1]Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada

Abstract

Steam assisted gravity drainage (SAGD) is a thermal hydrocarbon recovery method by which extra-heavy oil is produced through steam injection and bitumen heating. The presence of emulsions in the produced fluid has been detected from the very beginning of SAGD deployment. However, this phenomenon is still not fully understood. This paper reviews some significant aspects of emulsification and emulsion flow in SAGD operations. Such includes downhole emulsification mechanisms, effect of natural emulsifiers in the emulsion stability, different types of emulsions, emulsion characteristics in terms of viscosity, droplet size distribution, stability, features of continuous and dispersed phases, interactive effects of downhole conditions (e.g., pressure, temperature, and rock properties) and other relevant parameters. Additionally, the paper reviews currently available emulsion modelling techniques. A better understanding of emulsion flow is essential to designing more accurate models for SAGD production, testing sand control devices, and explaining the physics involved in SAGD operations. The focus of this paper is emulsification in thermal recovery methods, particularly in-situ emulsification in the reservoir for SAGD operations.

Keywords: SAGD, Emulsions, Natural emulsifiers, Heavy oil emulsion properties

1 Introduction

An emulsion is a system of mixture fluid in which one liquid phase is dispersed within a continuous liquid phase. Emulsions are a part of a more general system of a two-phase matter referred to as colloids. However, in emulsions, both dispersed and continuous phases are liquids [1-3].

Produced oil from the reservoir is almost always commingled with water in the form of emulsion when produced [4]. The upstream and downstream oil industry deals with many issues associated with the emulsion production from oil wells. Flow deficiencies in the reservoir (emulsion blockage), high-pressure drops in flow lines, upsets in downstream wet crude facilities, crude sales requirements including basic sediment and water (BS&W) and salt are a few examples of the considerations which need to be accounted for when the emulsion is produced [4-6]. A regular type of emulsion observed in the oilfield is "Water-in-Oil" emulsion, with the most common range of emulsified water in light crudes (>20 API) of 5-20 vol% and 10-35 vol% in heavier crudes (< 20 API) [4]. This shows that emulsification is more severe in hydrocarbon recovery from the heavy crude reservoirs.

Steam assisted gravity drainage (SAGD) is a thermal enhanced oil recovery (EOR) technology used for producing bitumen and heavy oil from the reservoir. This method was first introduced and further developed by Butler et al. [7-10]. This technology is an advanced form of steam stimulation in which a pair of wells, one (injector) located approximately 5 m above the other (producer), is used to upgrade the bitumen through a continuous steam injection and heat transfer. The heated oil loses viscosity and is mobilized towards the producer. SAGD is associated with high recovery rates (over 50%) with steam-to-oil ratios 2-5 and is superior to the other commercially applied steamflooding techniques, including cyclic steam stimulation in terms of recovery rate, energy efficiency, number of wells and operational pressure requirements [11,12]. **Figure 1** demonstrates the SAGD concept, schematically.

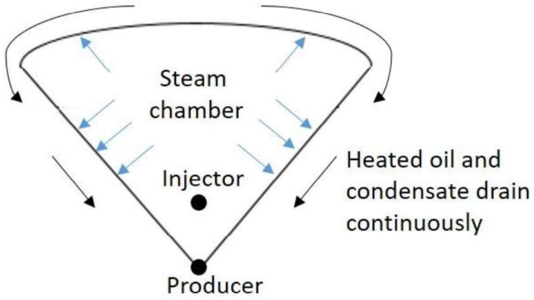


Figure 1- SAGD concept schematic (modified after Butler [10])

The produced fluids in the SAGD recovery method have been reported to be in emulsion form [13]. Characterization of the produced SAGD emulsion shows variable emulsion properties. This is particularly the case for the emulsion type, droplet size distribution, rheological behaviour, emulsified water content, free water phase content, and so on. To the knowledge of the authors, there has been no comprehensive review of the SAGD produced fluid emulsion characterization. Additionally, emulsion flow has been neglected in the SAGD production models presented in the literature.

It is important to understand the emulsification mechanism, emulsion properties, and the complexities associated with this phenomenon in SAGD operations. Such complexities include different emulsion flow behavior that is a result of the change in the viscosity of the emulsion compared to the base oil phase, alteration in the relative permeability of the phases, droplets restrainment in the pore throat, and emulsion blockage among other factors [4-6,13]. These phenomena occur in the reservoir and may affect productivity and productivity issues such as sand production and fines migration.

This review paper attempts to gather, categorize and analyze the SAGD emulsion flow characterization results and identify the type of produced emulsions, downhole emulsification mechanisms, and effective parameters. Also, ranges are identified to bind the emulsion properties, including droplet size. Moreover, numerical and analytical models presented to address the emulsion flow in SAGD have been reviewed, including the effect of emulsification on the relative permeability curves and the residual fluids saturations. Emulsification in the flow lines and downstream is out of the scope of this article. The focus is on the reservoir emulsification.

2 Theory

Colloids are dispersed systems that have at least one dimension between 1 and 1000 nm [5]. Emulsions are special types of colloids that contain immiscible liquids, one dispersed (internal phase) into another (external phase). However, the size of the droplets often exceeds 1000 nm and is in the order of micrometres [1-2]. Some emulsions form spontaneously and are characterized as thermodynamically stable. In contrast, other emulsions are metastable as they require a certain amount of energy to form and need specific properties to remain stable [2]. Petroleum crude emulsion cannot form spontaneously as the phases are most stable when separated (except for microemulsion). There are other mechanisms involved in in-situ emulsification of the crude oil and water in the reservoir.

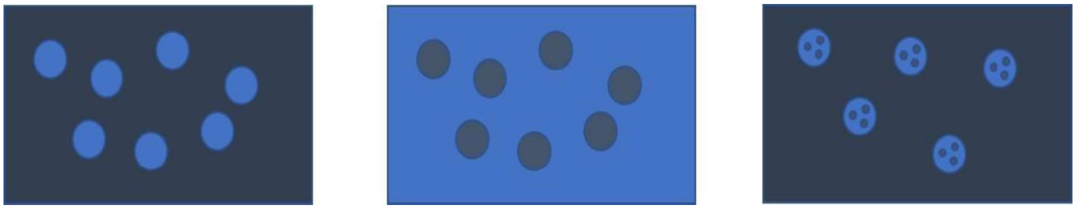
2.1 Emulsions Categorization

Emulsions are often categorized based on their type, droplets size range, and stability. It is common to divide emulsions to microemulsions and macroemulsion based on the droplets (internal phase) size being smaller or larger than 10 nm [1,4]. Although, this classification of emulsions is somewhat arbitrary. Most of the crude emulsions are categorized as macroemulsions and are inherently unstable, ignoring the natural emulsifiers and their role in emulsion stability. The emulsions are classified based on the continuous phase into three major groups [14]:

- Water-in-Oil Emulsion (W/O): Oil is the continuous phase and water droplets are dispersed,
- Oil-in-Water Emulsion (O/W): Water is the continuous phase and oil droplets are dispersed,
- Multiple Emulsions (Complex Emulsion): i.e. Water-in-Oil-in-Water (W/O/W) emulsion, which denotes a multiple emulsion that contains water drops dispersed in oil phase which in turn is dispersed in the continuous water phase.

2.2 Emulsions Stability

Crude oil emulsions are thermodynamically unstable and mainly observed in the W/O emulsion form [4,15-16]. However, the emulsified water content of the emulsion varies significantly from one case to another. The type of emulsion formed relies on several factors. There is a rule of thumb that states the volume fraction of the phases dictate the continuous and dispersed phases [17]. Though this is not always the case, particularly for the crude oil emulsions and other factors are involved, such as type of the emulsifier. Bancroft rule states that the phase in which an emulsifier is more soluble constitutes the continuous phase [18]. This explains why most of the crude emulsions are of W/O emulsion-type as natural emulsifiers which exist in the formations (asphaltenes, resins, organic acids, and bases) are more soluble in oil rather than water. **Figure** 2 displays a basic illustration of different types of emulsions.



(a) (b) (c)

Figure 2- Basic schematic of the different types of emulsions; (a) W/O emulsion, (b) O/W emulsion, (c) complex emulsion

The stability of an emulsion is defined as the emulsion ability in resisting changes in its properties over time [19]. Emulsions tend to be thermodynamically unstable. The reason is emulsification requires a significant amount of energy and the system tends to go back to its former thermodynamic state with lower energy level by phase separation and interfacial area and energy reduction. Gibbs free energy equation can be used to describe this process [1].

$$\Delta G = (\gamma \Delta A) - (T \Delta S) \tag{1}$$

where γ is interfacial tension, A is interfacial area, T is temperature, and ΔS is Entropy.

If ΔG is positive, spontaneous emulsification is unlikely to occur. This is often the case since often $\gamma \Delta A >> T \Delta S$ and the emulsions typically tend to be thermodynamically unstable. When the droplets are dispersed within the continuous fluid interfacial area increases largely and ΔG increases consequently and results in added instability to the system. The only way to resist phase separation then is through the reduction of the interfacial tension. Emulsifiers are used in the emulsions for that specific purpose of stabilizing the fluid mixture. However, this stability is referred to as “kinetic stability,” meaning that the emulsion’s properties will remain fairly unchanged for a certain period. Oil field emulsions are categorized based on their kinetic stability to loose (rapid phase separation), medium, and tight emulsion that can remain stable for days [4]. There are other detailed classifications of the water-in-crude oil emulsions, where emulsions stability is clustered based on their appearance, oil chemical composition, and measured rheology into unstable, metastable and stable emulsions [20-22].

The mechanisms of emulsion instability are characterized by flocculation, creaming/sedimentation, coalescence, Ostwald ripening, and phase inversion phenomena. Flocculation is a result of attractive forces between the droplets, while coalescence is the process of droplets collisions and fusion into larger droplets. Creaming is the rise of the droplets to the top as a result of the buoyancy force. In contrast, sedimentation is the settling of the droplets due to the gravity force and the weight of the droplets. Ostwald ripening is a thermodynamic driven spontaneous phenomenon, where smaller droplets shrink in size due to their higher solubility compared with the larger droplets. Over time, smaller droplets are deposited on the larger droplets, shifting the droplet size distribution to larger values. Finally, phase inversion is the alteration of the continuous phase as a result of several factors that lead to a drastic change in emulsion properties and structure [1-3,23]. **Figure 3** displays the instability mechanisms schematically.

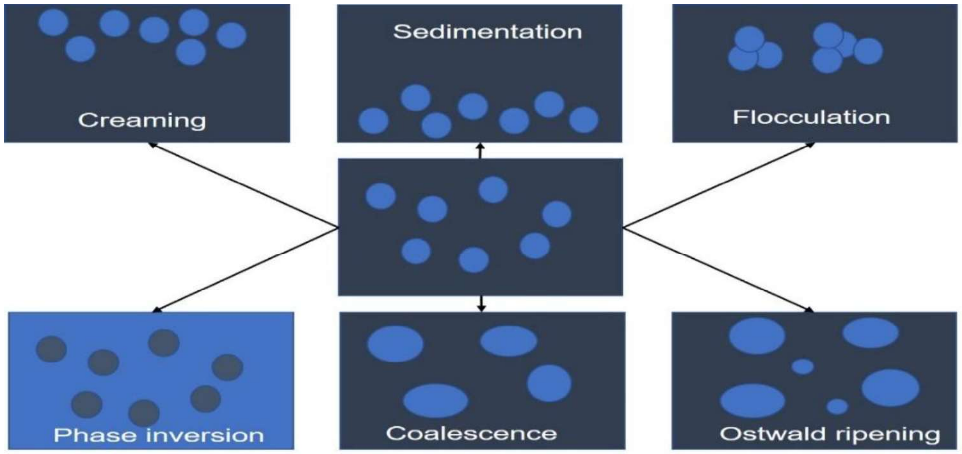


Figure 3- Different breakdown processes in emulsions (modified and reproduced with permission after [23])

Stokes law relates the settling velocity of the spherical particles (v_s) at terminal velocities to the density of the particle (ρ_p) and fluid (ρ_f), radius of the particle (R) and viscosity of the fluid (μ) [24]. According to the Stokes equation (**Equation** 2), the density difference between the particle and the fluid dictates the sedimentation or the creaming of the dispersed phase system inside the fluid mixture system. For heavy oil systems such as in SAGD, where the density difference is minimal between the oil and water, phase separation due to this factor is low.

$$v_s = \frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g R^2 \tag{2}$$

2.3 Emulsifiers

Emulsifiers are substances that promote the dispersion and stability of the emulsions by reducing the interfacial tension, and steric hindrance [1-5]. Surfactants or surface-active agents are a class of emulsifiers. Emulsifiers have two polar (hydrophilic) and non-polar (hydrophobic) components. This molecular structure enables the emulsifier to be soluble in both oil and water phases.

Surfactants are classified based on their polarity to anionic, cationic, non-ionic, and zwitterionic [1]. According to this classification, anionic surfactants carry a negative charge, cationic surfactants positive charge, zwitterionic surfactant both positive and negative charges, and non-ionic surfactants are not electrically charged. Surfactants are either synthetically derived such as fatty acid esters of sorbitol, or natural such as the asphaltenes and resins in the heavy fraction of the crude oil [2-4].

Emulsifiers have an important role in forming the type of emulsion. Bancroft rule is an empirical observation with some exceptions but describes this role clearly. According to Bancroft's rule, emulsifiers with more solubility in oil will form W/O emulsion. In contrast, emulsifiers that are more soluble in water create O/W emulsions. This is explained by the fact that if the surfactant is in the droplets, the interfacial tension gradient cannot form and drops are prone to coalescence upon collision [18]. Therefore, hydrophilic-lipophilic balance (HLB) of a surfactant which is a measure of surfactant solubility in a phase may determine the type of the formed emulsion [3]. **Figure 4** shows the emulsifier structure and how it is oriented in different types of emulsion.

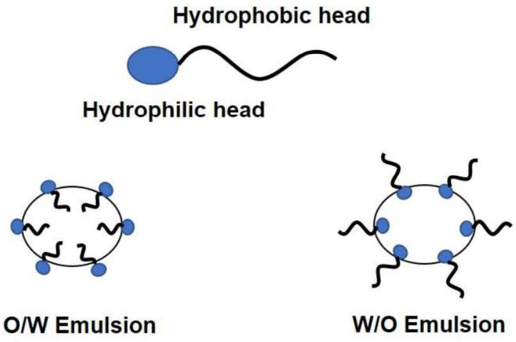


Figure 4- Schematic representation of the emulsifiers and their orientation in different types of the emulsions

3 SAGD In-situ Emulsion

Thermal methods such as SAGD are special types of steamflooding enhanced oil recovery techniques, which are widely used for bitumen and heavy oil production. The viscosity of oil in these reserves is so high that the fluids need heating to be mobilized. In SAGD, steam is continuously injected by a horizontal injector well located approximately five meters above a horizontal producer well. Consequently, a steam chamber is developed, and the latent heat of steam is transferred to the bitumen, causing a reduction in the viscosity of the oil. Therefore, mobilized oil and condensate flow towards the producer well. However, the produced oil is in the emulsion form. The type of the produced fluids has been observed to be, in most cases, a free water phase and W/O emulsion [13,25-27].

3.1 Observations Based on Scaled Laboratory Tests

One of the early studies on the emulsification in SAGD was carried out by Chung and Butler [25]. In their research, they scaled down the physical field parameters to conduct the SAGD test in the lab such that one hour of the lab experiment in the lab model was equivalent to 1.57 years at the field conditions. They designed a reservoir model with pre-set well configurations and installed thermocouples to measure the temperature as a result of steam chamber growth. Cold lake bitumen was used in their experiments and steam was injected at 109 ° C. They detected a free water phase and W/O emulsion in their experiments regardless of the operating conditions. However, they recorded a significant change in the Emulsified Water to Oil Ratio (EWOR), which is the volume fraction of water dispersed in the volume of oil based on the geometry of the injector relative to the producer well. In the case where the injector was vertical, EWOR was relatively constant, with a value of 0.19 in the entire experiment. In contrast, an EWOR value of 0.7 was measured for the case in which the injector was horizontal in the early production stage. This value declined to 0.3 in the late production stage. They concluded that the state of the steam chamber highly influences the emulsification.

Jamaluddin and Butler conducted similar experiments to investigate the emulsification in SAGD operations [27]. They also used a lab model with Cold lake bitumen. However, they employed packing material with different types of wettability. Moreover, they assessed the effect of steam injection pressure and steam quality on the emulsification. They reported that the produced fluids in their experiments included W/O emulsion and a continuous water phase, which contains very little suspended bitumen. EWOR varied considerably for different wetting systems. **Table 1** shows the EWOR for different wetting systems in the early and late production stages at 10 psig steam injection pressure. They observed that EWOR decreases for higher steam injection pressures, which will be discussed in detail in Section 4.

Table 1- EWOR values for different wetting systems (after [27])

Wetting system	**Early production EWOR**	**Late production EWOR**
Oil wet	0.76	0.52
Water wet	0.46	0.32
Neutral wet	0.61	0.34

Sasaki et al. monitored the initial stages of the SAGD operation by the employment of a 2-D scaled reservoir model [28]. A camera was installed to capture thermal-video pictures and record the steam chamber expansion. Synthetic oil (Motor oil) was utilized instead of bitumen with a roughly 1/5 viscosity of the Athabasca bitumen. Nevertheless, viscosity trends as a function of temperature are similar between the synthetic oil and the bitumen. Glass beads were used as the packing material representing the porous media. Dry steam was injected at the saturated steam temperature to the reservoir model. Produced fluid in their experiments consisted of single-phase condensate and a W/O emulsion phase after breakthrough. Single-phase oil was produced for a short period of time before the steam breakthrough. EWOR was reported to be less than one before the rise of the steam chamber but increased to 1.2 and remained fairly constant after steam breakthrough. The oil volume fraction of emulsion produced after a steam breakthrough was 45%. An important observation in these experiments was the change in the free water phase volume fraction. Results showed that the free water phase was about 66 % in the early production stage but increased to 90% in the late production stages. However, these values decreased with the installation of thermal insulators to minimize heat loss.

Several other studies can be found in the literature, confirming the W/O type for the produced emulsion [29-31]. These findings are either based on scaled reservoir high-pressure high-temperature experiments or actual field samples. There are also some reports on the inverse and complex emulsions such as W/O/W or O/W/O emulsions [32-35]. It should be noted that the sampling point matters in the case of field emulsion characterization. Emulsification and change in the emulsion properties may occur in-situ and by flow through the reservoir rock, in the flow lines and production valves, fittings and chokes, and in the surface equipment. So, if it is intended to address the emulsion flow characteristics in the reservoir, surface emulsion samples are not representative and scaled reservoir modelling experiments are more reliable to understand what happens in the reservoir.

To summarize, produced fluids in SAGD operations consist of a single-phase condensate (water), W/O emulsion, and single-phase oil only in a short period before the steam chamber rising to the top. EWOR varies mostly with the wettability of the system and steam chamber growth. The free water phase is relatively pure with a minimal amount of bitumen particles, and the studies show the amount of free water phase changes with time. This is a result of steam chamber growth in the reservoir, and it is shown that when the steam chamber is developed, more condensates are produced. Therefore, emulsification is more severe in the early stages of the production and declines in the late production stages.

3.2 SAGD Emulsion Characterization Techniques

Emulsions are physically characterized by their colour and appearance, droplet size distribution, rheology, emulsion type, dispersed phase volume fraction (emulsion quality), interfacial properties, and stability [1-4]. Various techniques have been proposed to determine emulsion properties. However, emulsions are thermodynamically unstable and prone to change in the properties and phase separation. Hence, it is critical to characterize the emulsion expeditiously. Phase inversion and alteration in the emulsion characteristics should be expected during the sampling and characterization, and one needs to follow the protocols to determine the emulsion properties accurately. Some of the emulsion characterization parameters and techniques are described herein.

Solids Concentration in Emulsion: Produced fluids in the reservoir almost always transport detached fine solids. The particle detachment has been reported to be influenced by several parameters, particularly brine composition and concentration [36-39]. So, the emulsion characterization needs to account for solids concentrations inside the fluid mixture as well. The effect of fine solids on the emulsion properties is described in Section 5.1.

Determination of Continuous Phase: The first step is the identification of the continuous phase. The most basic method to do so is the dilution method, in which a few drops are added to the water [40]. If the emulsion is of the type W/O, it will remain in the form of a drop, otherwise (O/W) drops will spread. Another basic method is dyeing in which the continuous phase can be detected with an oil/water-soluble dyes. This method is most efficient when done under a microscope. If a water-soluble dye is mixed with the emulsion and no change in colour occurs, it means the continuous phase has to be oil. However, colouring methods are not useful in crude emulsions as these types of emulsion are opaque. Electrical conductivity can also be employed to determine the continuous phase since water as a polar substance has more conductivity compared with the oil. Hence, an O/W emulsion potentially has more electrical conductivity. The limitation of this method is the vague results generated when there is a considerable amount of solids in the phases [1].

Emulsion Phase Weight Ratios: The content of the emulsified water, oil and solids within an emulsion is often measured by the modified Dean-Stark procedure. In this method, the emulsion is placed inside a porous thimble above a refluxing solvent [41]. The components are distinguished through a distillation process.

Another existing method is diluting the emulsion with solvent and then centrifuging it for a certain period [42]. This method is fast and reliable and very common for field evaluations. In the SAGD experimental models, practical solutions have been offered before the centrifuge test. Chung and Butler proposed cooling down the samples at 5° C for 24 hours and then removing the separated water phase by a needle syringe [25]. The centrifuge method presented in the ASTM D4007-B1 was then followed to identify the emulsified water content [43]. Other methods are available to determine the dispersed phase contents such as Karl Fischer Titration, and Gamma-ray attenuation, however, these methods have limitations when it comes to the presence of the fine solids in the system or water content [1,44-45].

Emulsions Rheology: Bulk rheology of emulsions can be measured by several methods. Researchers have used different viscometers to determine the viscosity of emulsions at desirable temperatures. Bennion et al. [46] used pressure differential measurements inside a capillary tube to find the dynamic viscosity of the bitumen emulsion using Poiseuille's law. Kumasaka et al. [31] and Olalekan et al. [47] used plumbing type viscosity sensors for the measurement of emulsion viscosity at elevated temperatures. Rotational viscometers have been used in some studies to characterize SAGD emulsions [29,31]. Such measurement techniques can be erroneous as a result of the emulsion instability and phase separation during the measurements. For instance, there is a possibility of the bitumen separation from the fluid system at the rotor-plate interface of a rotational viscometer. It can be useful to try different techniques to determine the emulsion viscosity to minimize measurement errors.

Emulsion Stability: Various techniques can be used to determine emulsion stability, including simple bottle tests, centrifugation, microscopic techniques, light scattering, and electrokinetics methods. The bottle test is the most basic method for emulsion stability determination, where phase separation in the emulsion is monitored with time. The method is vastly popular due to its simplicity. However, when the separation is not distinct, the results are biased and depend on the operator readings. More advanced methods, including centrifugation, light scattering, and optical microscopy, are employed to eliminate the errors associated with the complexities in distincting phase interfaces.

Stability in the emulsion system comes from both the steric hindrance and electrostatic stability. The methods described above measure general stability that includes all the parameters involved in the demulsification process. It is also possible to assess the electrostatic stability of the emulsions directly by electrokinetic measurements. This is achievable through measurement of the zeta potential, which is the potential difference between the mobile dispersed medium and the stationary layer of the dispersion medium attached to the dispersed particle [1-4,48].

The most relevant study in which emulsion stability is addressed as a result of the measured zeta potential is the criteria presented by Riddick and presented in **Table** 2 [49]. However, he was looking into blood cells of typically 7-10 micrometre in size, and SAGD emulsions are somewhat within the size range, but not necessarily with the size distribution. One also needs to consider the fact that electrostatic repulsion is not the only source of stability. Steric hindrance, emulsifier concentration, density differences, droplet size, and many other important contributing mechanisms are involved in the process. There are several studies on the SAGD crude emulsion stability in which zeta potential measurements were used along with other means of the emulsion stability tests [33, 35].

Table 2- Relation between the suspension stability and the measured zeta potential (after [49])

Stability characteristics	**Avg. ZP (mv)**
Maximum agglomeration and precipitation	0 to +3

Range of strong agglomeration and precipitation	+5 to -5
Threshold of agglomeration	-10 to -15
Threshold of delicate dispersion	-16 to -30
Moderate stability	-31 to -40
Fairly good stability	-41 to -60
Very good stability	-61 to -80
Extremely good stability	-81 to -100

Size Distribution of Dispersed Phase: Size distribution of the droplets within an emulsion influences many emulsion characteristics. This includes the stability and bulk viscosity of the emulsions. Several methods exist for the dispersed phase size distribution characterization, such as optical microscopy, laser diffraction, scanning electron microscopy, and Near-Infrared Spectroscopy [1-4,50-51]. Microscopic methods are preferred as they provide visual means by which the dispersed phase size range can be identified. However, results obtained from these techniques are highly sensitive to the sampling method. In the laser diffraction method, the deviation of a light source (laser) from the particle is measured, and the final patterns are analyzed to give the particle size distribution [51]. This method is prone to errors caused by the particle shape since the analysis theory is based on spherical particles.

Interface Properties: It is well documented in the literature that the emulsion characteristics, especially the stability, are severely affected by the droplets film properties [52-54]. Surface rheology and elasticity, interfacial tension and electrical double layer (EDL) can change the stability state of the emulsion. Tensiometers and surface rheometers of different types are used to determine the interfacial tension and dynamic interfacial rigidity modulus (surface elasticity, G'), respectively.

Non-conventional techniques: Non-conventional advanced techniques such as Differential Scanning Calorimetry (DSC) have gained popularity recently in the characterization of the thermal EOR and SAGD emulsions [29,33,55]. DSC is a thermoanalytical method in which the amount of heat or cooling required to increase or decrease the sample temperature is monitored as a function of time or temperature [29]. This method is very useful in SAGD emulsion characterization since the supercooling behaviors of the free phase water and emulsified water are very different. Therefore it is possible to distinguish between the free water phase and emulsified water in this method. However, finer solids in the SAGD emulsions can influence the latent heat and freezing temperature by providing nucleation sites.

Summary: Simple and basic methods like bottle tests, as well as unconventional advanced techniques such as Differential Scanning Calorimetry (DSC), are available for the characterization of emulsion properties. Interpretation of the results from one test seems to be insufficient as each one of these methods has its limitations and sources of errors. Additionally, sampling can be a significant cause of inaccuracy in some of the presented methods. Incorporating several techniques can be useful in the identification and reduction of potential errors and also providing insights on the time and mechanisms of alterations in the emulsion properties.

4 SAGD Emulsification Mechanisms

Emulsions are not present in the reservoir before recovery procedures, and their formation is attributed to the mixing/or changes in pressure, temperature, and presence of natural emulsifiers [15]. Researchers have theorized the existence of a mobile oil phase following this process and as a result of the thermal gradient in the steam bitumen contact region. It is explained that the water droplets are engulfed by this mobile oil phase and "W/O" emulsion is formed in this way [25,27, 30]. Moreover, the presence of emulsions was verified in micromodels visually in SAGD-Solvent injections as well [56,57]. **Figure** 5 shows this phenomenon schematically and visually in a SAGD micro model.

Higher temperature decreases the Gibbs free energy, hence, facilitates the emulsification. Moreover, studies have shown that increasing the temperature leads to a reduction in the interfacial tension of the fluid system, reducing the system energy and magnifying the potential of emulsification [46,58]. Perhaps this is one of the reasons why emulsification is reported to be more severe in thermal EOR operations.

In SAGD, it seems that the emulsification and the amount of water emulsification in the mobile oil-phase are closely linked to the steam chamber growth [13,25,27]. In the very early production stage where the steam chamber is not developed, bitumen is mainly heated by conduction, resulting in the mobilization of single-phase heated oil towards the producer well [59]. This stage of single-phase oil production is short as the steam chamber begins its rise and lateral growth. Lab modelling of SAGD process shows that as the steam chamber is rising (early stages in SAGD production), a counter-current flow of steam and mobile oil (mobilized downward by gravity force) is developing within the steam chamber, magnifying the emulsification. However, when the steam chamber spreads laterally, a stratified two-phase steam-oil flow is formed, where steam flow takes place at the interface, and oil flow occurs below the interface toward the producer well. A lower EWOR is observed under such steam chamber growth profile [25-27]. Additionally, it has been shown that if the process of the steam chamber growth speeds up through higher steam injection pressure, lower EWOR values are obtained [27].

When the steam comes in contact with the cold bitumen, heat is transferred from the steam to the bitumen, reducing the oil viscosity. Jamaluddin and Butler explained that steam needs to be undercooled to form spontaneous nucleation in such a process to result in condensation. If there is a relatively flat steam-water interface, steam most likely condenses at this interface before achieving the degree of supercooling required for nucleation on the oil surface. They concluded that microscopic droplets on the oil surface cannot form under such conditions [27]. However, this logic seems to be incomplete as "spontaneous nucleation," and "supercooling" phenomena are unlikely to occur in porous media.

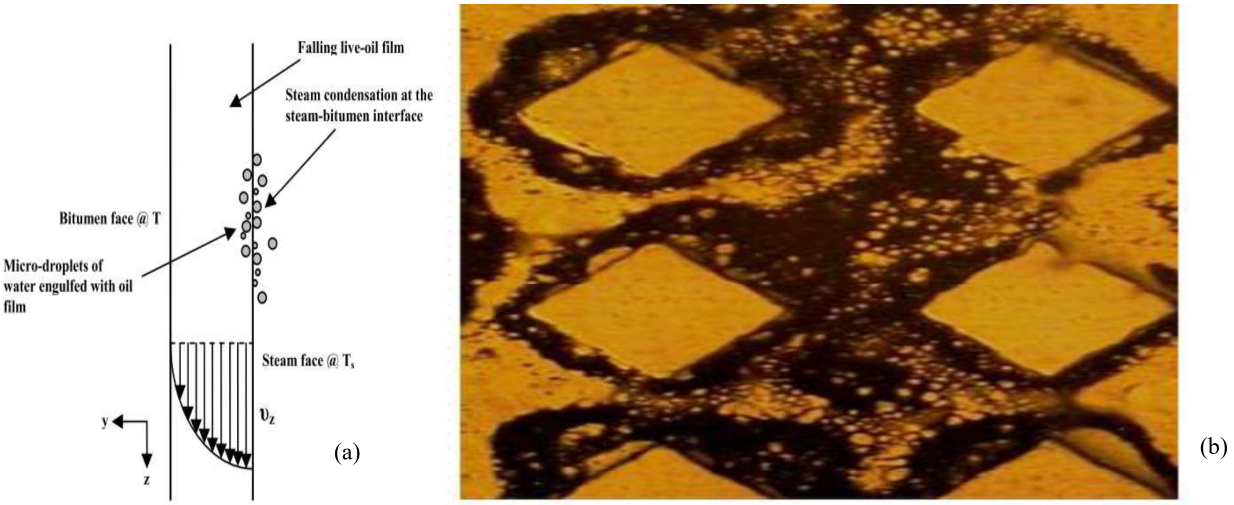
Spontaneous nucleation (homogeneous nucleation) occurs when there are no foreign materials or wall surfaces. Under these circumstances, the phase change is blocked by an activation free energy barrier [60]. This barrier is a result of surface free energy increase, which is caused by the embryos of the more condensed phase. Hence, in the case that no impurities exist, steam may supercool below the dew point until the occurrence of the homogeneous nucleation. However, the prerequisites for such thermodynamic process are not met in SAGD and in porous media. The reasons are the water in the reservoir is saline and polarized, different types of sand and clay fines are packed, and steam is in contact with an impure bitumen interface that contains hetero atoms (ionic). These factors most likely cause a heterogeneous condensation.

On the other hand, the amount of work required to form a water droplet in different wetting systems in a capillary tube has been investigated. It was shown that the work required to have a single drop of water in an oil-wet system is less than in water-wet and neutral-wet systems, as shown by **Equation 4** [27].

$$P_{emuls} = \frac{W_n}{V_w} = \frac{3\sigma}{R} \left(1 + \frac{2}{3}\, Cos\theta\right) \tag{4}$$

where P_{emuls} is the pressure required to disperse water drop in oil phase (Nm^{-2}), W_n is the net work required to disperse water droplets in the oil phase (N.m), V_w is the water drop volume (m^3), σ is the interfacial energy (J m^{-2}), R is the radius of curvature (m) and θ is the contact angle of water phase and capillary wall.

For strongly water-wet systems, the work required to form W/O emulsion can be much more than for strongly oil-wet systems. In stable waterfronts and water films, the condensation will likely take place at the water phase, and this theory can support the reports of less emulsification in the late SAGD production stage. It has been shown that temperature can decrease the interfacial forces and increase the water wetness and relative permeability of the oil over time [61,62]. The resulting condensate drops must be tiny in the beginning [27]. As the steam condenses, the excess energy contained is released to the surroundings in the form of latent heat, causing a reduction in the bitumen viscosity at contact with the steam.



(a)

(b)

Figure 5- Emulsification at the steam-bitumen interface, (a) schematic (Adapted with permission from source [30]), (b) W/O Emulsion formed in a SAGD micromodel, Adapted with permission from source [30]

To summarize, the high steam temperature in SAGD facilitates the emulsification through a reduction of interfacial forces and magnification of the system entropy. These factors decrease the required work for emulsification. Condensation of the steam within the heated (mobilized) oil results in engulfment of water droplets by the oil phase carrier fluid; hence, the formation of a “W/O” emulsion. EWOR is highly sensitive to the steam chamber profile. More emulsification is anticipated due to the extra direct condensation in the counter-current flow of steam-oil while the steam chamber is rising. Lower EWOR is expected when the steam chamber is spreading laterally.

5 SAGD Emulsion Features

In this Section some of the most prominent features of SAGD emulsions are described. These include the effect of physio-chemical factors on the emulsion properties. Such factors mainly influence the stability, viscosity, droplet size, and droplet size distribution of the emulsion. Additionally, conventional emulsion flow models presented in the literature are critically reviewed in this Section.

5.1 Primary Stability Factors

Emulsions are generally thermodynamically unstable (except for the micro-emulsion) and may exhibit kinetic stability in the presence of emulsifiers. Emulsifiers promote the stability of emulsions through steric hindrance, electrostatic repulsion, viscosification, promotion of rigidity of the droplet film, and reduction of the interfacial tension between phases [1-4].

SAGD “W/O” emulsions have been reported to display kinetic stability [25,35,46,63]. Reasonable kinetic stability of the emulsions has been detected visually [28,30], and through produced fluid sampling from the SAGD lab models [25,27]. However, there is mention of the possible instability mechanisms such as coalescence [30] and the indirect effect of temperature in destabilizing the emulsion through a reduction in the emulsion viscosity [46]. Kinetic stability of the emulsions can be considered to be true for all the emulsions formed in the thermal recovery operations due to the presence of a large amount of interfacially active compounds in the heavy oil [64]. Although the temperature is a destabilizing factor for emulsions by reducing the bulk viscosity, this effect seems to be somewhat neutralized by the presence of natural emulsifiers in the heavy oil reservoirs.

Natural Emulsifiers: Natural emulsifiers in heavy oil reservoirs consist of fine solid particles (such as clay, silt, and corrosion products) and surface-active compounds (such as asphaltenes and naphthenic acids) that contribute to the SAGD emulsion stability [4,65]. Most of the natural emulsifiers exist in the heavy fraction of the crude that is made of asphaltenes, resins, and oil-soluble organic acids and bases. **Table 3** shows Saturate, Aromatic, Resin and Asphaltene fractions (SARA analysis) of Athabasca and Cold Lake bitumens in Canada. This table is showing a considerable amount of asphaltenes and resins in the bitumen, which could potentially form micelles and act as the emulsifiers in SAGD conditions.

Table 3- SARA analysis of Cold Lake and Athabasca bitumens in Canada (After [66])

	Athabasca	**Cold Lake**
API Gravity	8.05	10.71
Viscosity at 24 °C (Pa.s)	323	65
Saturates (%wt)	17.27	20.74

Aromatics (%wt)	39.70	39.2
Resins (%wt)	25.75	24.81
Asphaltenes (%wt)	17.28	15.25

Asphaltenes are complex polyaromatic molecules that contain aromatic sheets with alkyl and alicyclic side chains and heteroatoms (Nitrogen, Oxygen, sulphur and trace metals like vanadium and nickel) [67]. The molecular weight of asphaltenes ranges from 500 to over 10,000.

Asphaltenes stabilize the "W/O" emulsions either in the colloidal state (through the formation of rigid films around the droplet) or in a precipitated and aggregated form (through steric hindrance). This fraction of heavy oil can change the wettability of the solids, form rigid films around the droplets after forming micelles with resins and contains heteroatoms that are surface-active materials and adsorb on water droplets [68]. In experiments that replicated SAGD and Expanding Solvent-SAGD (ES-SAGD) operations, it was found that asphaltenes of produced W/O emulsion have a lower zeta potential value in SAGD operations compared to the ES-SAGD operation, indicating lower stability and a higher tendency for precipitation [35]. Kokal and Al-Dokhi showed that crudes with a higher tendency in asphaltene precipitation are more likely to form a stable emulsion [15]. **Figure 6** illustrates the stability mechanisms provided by the asphaltenes.

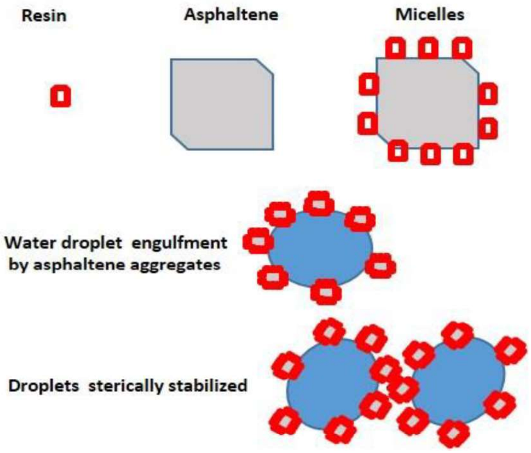


Figure 6- Stability of "W/O" emulsions through steric hindrance and film rigidity provided by asphaltene-resin micelles

Effects of Reservoir Clays: SAGD emulsion can also be stabilized by fine solid particles that have a significant presence in the form of silt, clay, shale particles and corrosion products in the reservoir and near wellbore region [4]. However, the size of these solid particles is very important, so to act as a stabilizing factor. Particle sizes have to be much smaller than the water droplets to form a viscoelastic rigid film around the water droplets [1].

Wettability Effect: Wettability of the particles is extremely important for the solid particles to act as an emulsifier [69]. Wettability of the particles determines the placement of the solid particles in the system such that if the particles are oil-wet or water-wet, particles will be placed in the oil or water phase, respectively. Therefore, neutral-wetting condition favours the potential of solid particles forming a film around the droplets, as schematically shown in **Figure 7**.

Moreover, fine solid particles may contribute to the stability of the emulsion through an electrical charge repulsion. This is the case only if the particles are electrically charged. Contact angle, particle size, solids concentration, and interparticular interaction all influence the solid particles role as an emulsifier [69]. If the conditions permit emulsion stability by fine solid particles, the resulting stabilized emulsion is referred to as Pickering emulsion [70].

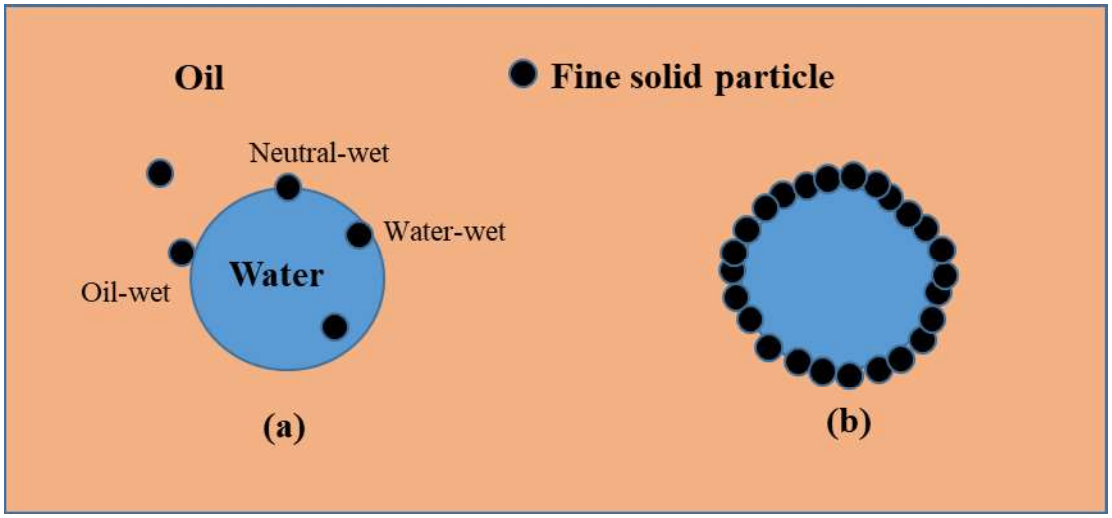


Figure 7- Effect of contact angle on the stabilizing role of the solid particles. (a) Neutral wetting conditions (ɵ=90°) favors the possibility of fine particles acting as emulsion stabilizers (b) Pickering emulsion structure

Effect of Phase Inversion: Phase inversion is another phenomenon that might have a slight chance of occurrence in SAGD operations as a result of an increase in the emulsified water cut. Phase inversion is one of the emulsion instability mechanisms, and emulsion properties alter drastically after this phenomenon. As a rule of thumb, if the volume fraction of a phase in an emulsion is so much larger than the other phase, it will eventually form the continuous phase [1]. The inversion point is also influenced by the presence of emulsifiers and their solubility tendency in each phase. In the literature, it is indicated that the emulsified water cut can reach up to 76% in the early stages of SAGD operations [27]. Hence, the chances of a phase inversion occurrence appear to exist to some extent for a short period of time and probably for some production intervals.

Water and oil density difference is minimal in SAGD operations (heavy oils have high densities), which makes the phase separation more difficult. This adds to the stability of the emulsion [33]. Numerous other factors contribute to the stability of the emulsion, including the shear rate, bulk viscosity, interfacial viscosity, and phase composition among others [4].

Effect of High Temperature: The propensity of the emulsification has been reported to be more severe in thermal recovery [46]. The physical phenomena involved were described in the SAGD emulsification subsection. Not only higher temperature facilitates the emulsification, but it also destabilizes the emulsion because of the reduction in the viscosity of the system. In general, more viscous emulsions have been found to be more stable [52].

pH Effect: There have been reports of a strong influence of pH on emulsion stability in the literature [58]. Whether the interfacial film is formed by asphaltenes, resins or fine solids, the effect of pH can be different such that asphaltene based films are strongest in acidic conditions, resin-based films in base conditions, and solids can become oil-wet by the presence of asphaltene. This process is further supported by the acidic medium. Moreover, it was found that brine composition has an interactive effect with pH such that crude/brine systems have an optimum pH range for which the interfacial films show instability [4].

5.2 SAGD Emulsion Droplet Size Distribution

Droplet Size Distribution (DSD) of the emulsion has a direct effect on other emulsion properties such as viscosity and stability. However, emulsion stability is not necessarily a function of the dispersed phase size [1]. Yet, more stability can be attained for smaller droplets in some emulsions. Emulsions with homogeneous and narrow DSD's toward smaller size typically possess higher viscosities, and an increase in viscosity contributes to the stability of the emulsions as well [52].

Generally, droplet size of in-situ oilfield emulsification is at the macroscopic scale. Hence, the emulsions are categorized as macro-emulsions (>0.1 µm) [1,4]. Typically, a mean size range of 0.1 µm to 10 µm has been reported for the oilfield emulsions [46]. **Figure 8** displays where the SAGD emulsions stand within the classifications of emulsions regarding the droplet size range.

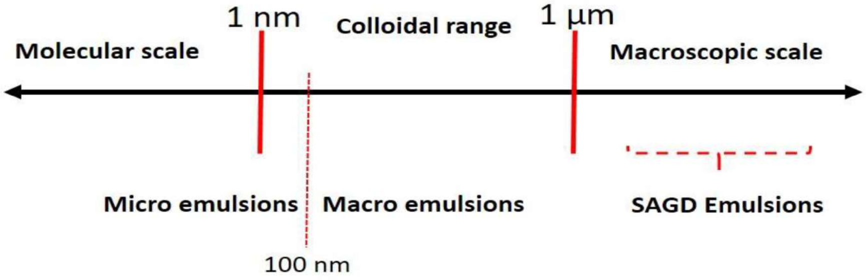


Figure 8- SAGD emulsions classification based on the dispersed phase size

Sasaki et al. (2002) conducted experiments in which they attempted to replicate the conventional SAGD operation using a 2-D scaled reservoir model [28]. A high-resolution optical fiberscope was used in the experiments to capture the micro-phenomena visually. The measured droplet sizes were compared with the same for produced fluids samples, and the results matched reasonably. It was reported that the average diameter of the water droplets changes with time. Further, much larger average diameters were observed after the steam breakthrough. These results support the theory that was previously presented by Chung and Butler [25] and Jamaluddin and Butler [28] that linked the emulsification mechanism to the steam chamber growth. The average diameter of the water droplets changed from approximately 10 µm to 15 µm, and droplet size was measured approximately 30 µm after steam breakthrough.

Kumasaka et al. (2016) used a micro-reactor and a steam generator to mimic the High pressure-High temperature (HP-HT) SAGD emulsification conditions [31]. They ended up with a "W/O" emulsion with droplet size distribution ranging from 2 µm to 15 µm with a mean diameter of a bit over 10 µm. Droplet size distribution in their experiment appears to be more uniform than the results shown by Sasaki et al.. This is most likely a result of the difference in emulsification mechanisms. The effect of porous media was completely ignored in the micro-reactor method of emulsification. However, the flow through the porous medium can have contrasting effects. The effects are flow shearing, which promotes emulsification and at the same time, may cause droplets breaking. They also compared their measured droplet size with the emulsion produced in Hangingstone, Canada. However, it is not clear where the sampling point of the emulsion is as it can drastically change the emulsion characteristics altogether. The droplet sizes of the Hangingstone field samples are comparable to the same for emulsions produced due to extreme pressure drops across choke valves, as investigated by Noik et al. [29] and Dalmazzone et al. [55].

The droplets formed in the SAGD process are not consistent in size. Micron-sizes as small as 1 µm to as large as 60 µm have been reported in the literature. However, the initial size of water droplets has to be tiny in the beginning. Later on, the droplet size likely increases as a result of coalescence. Visual capturing of the droplet formation in SAGD lab models suggest that the mean size of the droplets is probably between 10 µm- 15 µm based on the different results presented in the literature [28-31].

Another important parameter is the dispersed phase droplet size distribution (DSD), which varies case by case and appears to be a dynamic property. This means that the DSD alters with time, as a function of steam chamber growth and motion of the droplets in the porous media. Currently available data from the SAGD experiments show that the DSD in SAGD operations follows a rather multimodal distribution with multiple peaks of type “S” in Galtung’s classification [71].

5.3 SAGD Emulsion Viscosity

At first glance, higher viscosities of SAGD “W/O” emulsions tend to reduce the cumulative production according to Tandrain and Lindrain analytical equations developed for SAGD production [13]. However, more complicated mechanisms are involved as will be explained later in this Section.

While dilute emulsion might exhibit Newtonian behaviour, macromolecular fluids, and concentrated emulsions are typically considered as non-Newtonian pseudoplastic (shear thinning) fluids [1]. In other words, the apparent viscosity of the emulsions decreases at higher shear rates.

In general, the viscosity of the emulsions is influenced by the continuous and dispersed phase viscosities, the volume fraction of the dispersed phase, mean droplets size, DSD, shear rate exerted on emulsions, temperature and presence of emulsifiers [1-4]. Not many emulsion-specific correlations have been developed. Most of the correlations in the literature are defined for the suspensions with assumptions that might not be valid in case of emulsion. Such correlations have been developed for the cases of constant temperature and variable temperature conditions both. **Table 4** shows some of the most important correlations.

Table 4- Viscosity models presented for dispersed fluid systems

Viscosity models of constant temperature			
Model	**Correlation**	**Variables**	**Assumptions/Hypothesis**
Einstein [72,73]	$\mu_r = 1 + 2.5\,\emptyset$	μ_r: Relative viscosity μ: Dispersed system	Derived for suspension of non-deformable spherical

	$\mu_r = \frac{\mu}{\mu_c}$	viscosity μ_c: Continuous phase viscosity $\emptyset$: volume fraction of the dispersed phase	particles at very low concentrations
Taylor [74]	$\mu_r = 1 + [2.5\left(\frac{(k+0.4)}{(k+1)}\right)]\ \emptyset$ $k = \frac{\mu_D}{\mu_c}$	μ_D: Dispersed phase viscosity	Derived for a small concentration of spherical droplets Often used to describe the SAGD emulsion rheological behavior in numerical modelling
Roscoe [75] and Brinkman [76]	$\mu_r = \frac{1}{(1-\ \emptyset)^{2.5}}$	$\emptyset$: volume fraction of the dispersed phase	Developed for a higher concentration of the dispersed phase
Richardson [77]	$\ln\,(\mu_r) = k\ \emptyset$	k: A constant which depends on the system	An exponential increase in relative viscosity is expected with higher dispersed phase volume fraction
Broughton and Squires [78]	$\ln(\mu_r) = k_1\ \emptyset + k_2$	$k_1\ and\ k_2$: Constants which depend on the system	A modification of Richardson equation
Eilers [79]	$\mu_r = \ [1 + \left(\frac{1.25\emptyset}{1 - a_E\emptyset}\right)]^2$	a_E: Empirical constant (range: 1.28-1.30)	Obtained based on the experiments on the bitumen emulsions
Mooney [80]	$\ln(\mu_r) = \frac{2.5\emptyset}{1 - k\emptyset}$	k: A constant which depends on the system	Derived for concentrated suspensions Very popular in the emulsion literature
Krieger and Dougherty [81]	$\mu_r = \frac{1}{(1-\ \emptyset/\emptyset_m)^{[\mu]\emptyset_m}}$	$[\mu]$: Intrinsic viscosity $\emptyset_m$: Maximum packing concentration	Derived based on functional analysis, similar to Mooney's approach
Hatschek [82]	$\mu_r = \frac{1}{(1-\ \emptyset^{1/3})}$		Developed for the concentrated emulsions
Sibree [83,84]	$\mu_r = \frac{1}{[1 - \left(h\emptyset^{\frac{1}{3}}\right)]}$	h: A hydration factor which depends on the emulsion system	A modification of Hatschek equation

Pal and Rhodes [85]	$\mu_r = [1 + \left(\frac{(\emptyset/_{\emptyset_o})}{1.187 - (\emptyset/_{\emptyset_o})}\right)]^{2.49}$	$\emptyset_o$: Dispersed phase concentration at which relative viscosity is 100	The empirical correlation obtained for mono-dispersed emulsions with similar phase densities and low IFT
Viscosity models of variable temperature			
Ronningsen [86]	$\ln(\mu_r) = a1 + a2T + a3V + a4T\emptyset$	ai: Shear rate-dependent coefficients T: Temperature	Empirical correlation derived from the experimental results
ASTM standard [87]	$\ln(\ln(z)) = A - Bln(T)$ $z = v + 0.7 + f(v)$ $\ln(\mathrm{f}(v)) = -1.47 - 1.84v - 0.51v^2$	v: kinematic viscosity Z: Viscosity function T: Absolute temperature A & B: Characteristics of each product	Defined for crude oil and their fractions
Farah et al. [88]	$\ln(\ln(\emptyset + 0.7)) = k1 + k2\emptyset + k3ln(T) + k4\emptyset\ln(T)$	Ki: experimental coefficients	-An extension of the ASTM correlation obtained to include the dispersed phase volume fraction for W/O emulsion -Proposed correlation coefficients must be determined for 2 points (temperature above/below wax appearance temperature)

Phase inversion can occur at very high emulsion qualities (water cuts), which leads to a complete change in rheological behaviour. SAGD emulsions are “W/O” emulsions with higher viscosities compared with the continuous phase (oil) viscosity. This behavior in “W/O” emulsions has been observed in many studies, while “O/W” emulsions have been reported to manifest lower viscosities than the oil phase [1-4]. Chances of phase inversion at high water cuts in SAGD operation are not high as the maximum emulsified water content reported in the literature is 76%, and this is the case only for the early production stages and strongly oil-wet systems [27].

Accuracy of SAGD Emulsion Viscosity Models: Temperature decreases the bulk viscosity of the fluids. This parameter has a significant effect on emulsion behaviour as it facilitates the emulsification and destabilizes the emulsion by reducing the emulsion viscosity. The typical SAGD temperature is about 200 °C (and above). At this temperature, bitumen viscosity is approximately 10 cp for Athabasca oil sands [89]. However, the viscosity of the produced fluid deviates from this magnitude as the water volume fraction increases in the emulsion [90]. Not much research work can be found in the literature in which the viscosity of the emulsion is measured for the actual bitumen-emulsions. Bennion et al. (1993) measured the viscosity of the emulsions at different water cuts for a field oil sample using an HP-HT micro-reactor [46]. Also, Chung and Butler (1988) measured the viscosity of the bituminous emulsions in their scaled reservoir model experiments [25].

Chung and butler's viscosity measurements were carried out for temperatures up to 90 °C. We extrapolated the viscosity value at 200 °C to find the viscosity at SAGD conditions. Power function trend lines were plotted to extrapolate the viscosity values at the desired temperature. Next, we analyzed different viscosity models presented in the literature (**Table** 2) to see which model best describes the emulsion rheological behaviour. The most popular method that has been used for numerical modelling of SAGD emulsion in the literature appears to be Taylor's model. **Figure 9** and **10** show the models plotted against the measured viscosity points in Bennion et al. and Chung and Butler experiments, respectively. **Table** 5 shows the analysis of the statistical results for different viscosity models.

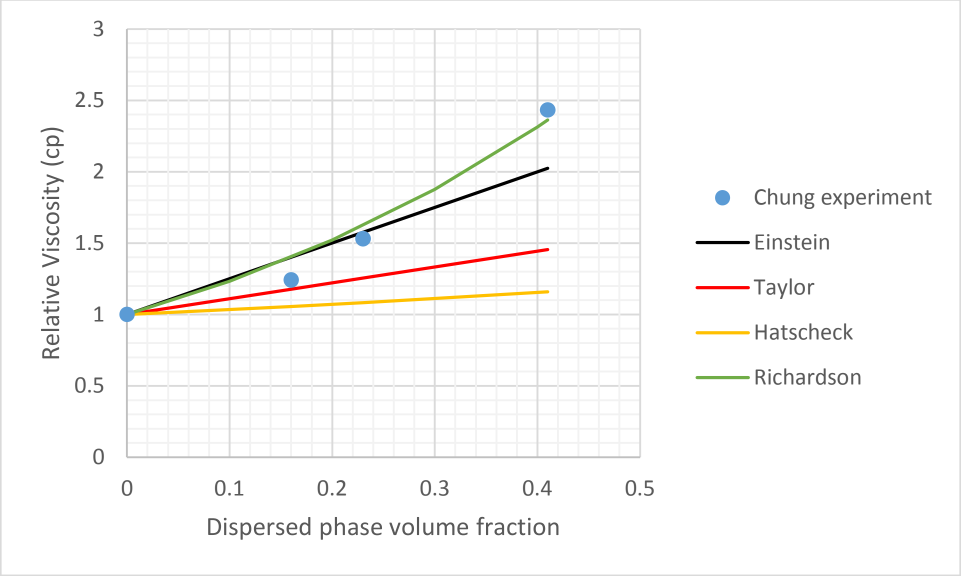


Figure 9- Relative viscosity of different models against the experimental data at 200°C

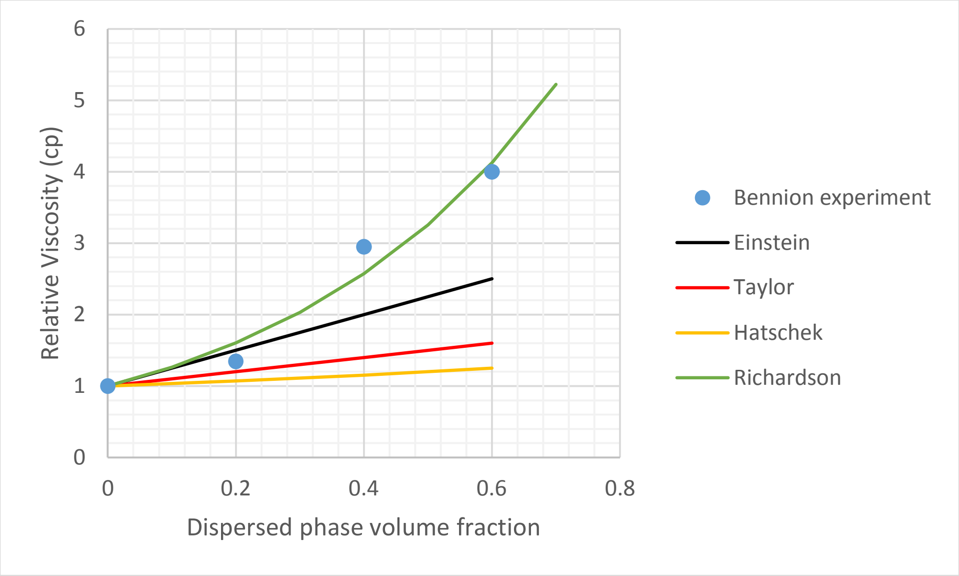


Figure 10- Relative viscosity of different models against the experimental data at 200°C

Table 5- Statistical analysis of the viscosity models performance for each experimental data set

Experiments	**Sum of squared errors (SSE)**			
	Einstein	**Taylor**	**Hatscheck**	**Richardson**
Chung experiments	0.193	1.033	1.858	0.037
Bennion experiments	3.173	8.179	10.859	0.223

The reason **Figure 9** and **10** are plotted separately is the difference in emulsion preparation (emulsification) procedures in the experiments. Further, none of the two papers mention the DSD of the dispersed phase within the emulsion. According to **Figure 9** and **10**, while models such as Taylor and Einstein predict the emulsion viscosity with acceptable accuracy in lower concentrations, they are unable to give reliable results at higher concentrations of the dispersed phase.

Taylor model has been the method of choice in numerical and analytical modelling of SAGD emulsion flow. However, implementation of this model in the simulator results in a false representation of the emulsion viscosity at higher EWORs (and equivalent dispersed phase volume fractions). This is especially the case since SAGD EWOR values are relatively high as shown in Section 3.1. Richardson model seems to be the most accurate emulsion viscosity model for the SAGD emulsions (This applies to modified Richardson models such as Broughton and Squires model that contains two calibration coefficients). However, the problem with Richardson model is the calibration coefficient in the correlation. Experimental results (In-situ emulsion DSD, emulsion viscosity at different water cuts) are not always available to be used for calibration purposes. Other popular models such as Mooney's correlation was examined, and it was observed that this model predicts the viscosity of SAGD emulsion well only at very high concentration and performs poorly at low concentrations of the dispersed fluid. DSD and viscosity might vary case by case as the oil composition and formation properties affect the emulsion properties. Therefore, the authors suggest the following workflow to determine the field sample emulsion viscosity as shown in **Figure 11**.

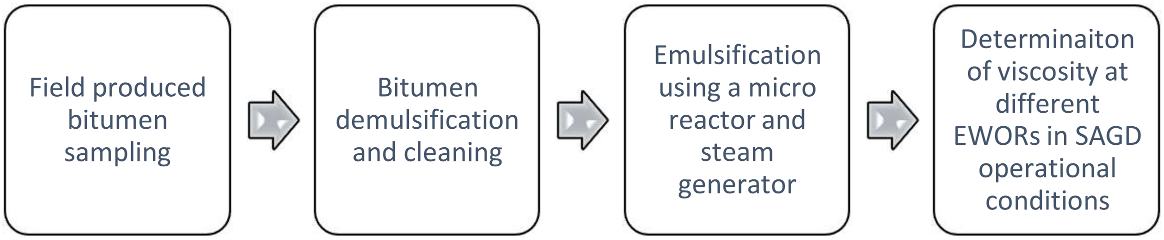


Figure 11- Procedure of field emulsion viscosity determination

5.4 SAGD Emulsion Flow Modelling

The effect of temperature on different reservoir properties has been investigated by many studies [91-93]. It has been found that temperature could potentially decrease the interfacial forces and increase the water-wetness and relative permeability of the oil with time [13,61,62]. Relative permeability curves change with temperature in steamflooding operations, such that relative permeability of oil increases and the residual oil is reduced consequently. Additionally, it was observed that steamflooding conditions tend to lower the relative permeability to water. Butler (1991) discussed that such effects are partially due to the formation of emulsions under steaming conditions. He explained that small droplets of water dilute the residual oil drops. Other researchers also speak of the convective heat transfer under SAGD emulsion flow [59,94]. Water relative permeability could be reduced as some of the water might be tied up with the slow-moving oil phase [13].

Adding to the complexity, emulsion droplets may cause emulsion blockage, and larger droplets can potentially clog the pore throats [90]. These droplets are also prone to breaking up as they pass through these pore throats [95]. A reduction in the permeability in some experiments and more catastrophic results such as complete well failure were reported as a result of emulsion blockage [90].

Developed models for SAGD production rates have been reported to deviate from the field production rates [63]. One of the reasons behind the deviation is linked to the emulsion flow in the reservoir [96]. The lag traceable in the Sasaki et al. experiment was linked to the emulsion flow, particularly in the early stages of the production, in which emulsification was more severe in the experiment [96]. **Table 6** shows the attempts on the modelling of the SAGD production considering the emulsion flow.

Table 6- Presented models considering SAGD emulsions

Model	Remarks
Azom and Sirinvasan [59]	- Coupled an emulsion mechanistic model with SAGD numerical simulation - Emulsion viscosity modeled using Taylor's correlation which is not valid for a high concentration of dispersed phase - Deviation from the experiment production trend
Kumasaka et al. [31]	- Numerical simulation - A viscosity model was developed after experiments on heavy oil - Used hypothetical pseudo-reactions for emulsification which is not supported by sufficient evidence
Ezeuko et al. [63]	- Numerical simulation - Defined hypothetical pseudo-reactions for emulsification - Emulsion viscosity modeled using Taylor's correlation which is not valid for a high concentration of dispersed phase
Mojarad and Dehghanpour [97]	- An analytical model of emulsion flow at the edge of the steam chamber - Emulsion viscosity modeled using Taylor's correlation which is not valid for a high concentration of dispersed phase - Assumptions made based on the experimental work of Noik et al. [30]. One of the assumptions is that all the water is emulsified in the oil phase. In Noik et al. experiments, emulsification was carried out by a flow loop system and a flow restriction. They witnessed full emulsification of water in cases of high threshold energy. That study is meant for emulsification in flow lines, not in-situ reservoir emulsification. Numerous studies using scaled reservoir models illustrate a dynamic range for different wetting systems which depends on the SAGD production stage and steam chamber growth. EWOR can reach as low as 0.19 as shown in some experiments [26] which makes the premise in this study invalid.

In the models introduced in **Table 6**, the emulsion was simplified in the form of a single-phase fluid with an effective viscosity, different from the single-phase oil viscosity. However, this approach is associated with some serious shortcomings that make the assumption invalid. Firstly, not all the droplets will remain as the dispersed phase fraction, and most likely, a significant fraction of the droplets will form a continuous water phase. Moreover, emulsion droplets may be trapped in the pore throats if the size of the droplets is in the same order of magnitude as the pore throats. The latter has shown to have a dependency on the flow rate and capillary number [98-100].

Another viable option of looking into the emulsion flow in porous media would be treating the emulsion as a multiphase flow with apparent relative permeability defined for both dispersed water and continuous oil phases. Experiments show the apparent relative permeability is affected by the flow rate, capillary number and water/oil ratio [101]. Studies indicate that due to the emulsification in porous media, apparent relative permeability of the oil decreases, while at the same increases at higher capillary numbers [101]. In steamflooding operations, a higher relative permeability of the oil can be partially credited to the effect of temperature in reducing the viscosity of the fluid such that the capillary number increases as a result of a magnified flow rate.

6 Summary

This paper reviewed emulsification and emulsion flow in thermal EOR methods with a focus on SAGD. The paper critically reviewed physical properties and other aspects of SAGD emulsion including the emulsion type, dispersed phase volume fraction, free fluid phase volume fraction, emulsion stability, emulsion viscosity, emulsion droplets size and DSD, emulsification mechanisms and the relevant thermodynamical concepts, effect of the reservoir wetting system on the emulsification, interactive effect of the parameters, methods of emulsion characterization, reservoir engineering aspects of emulsion flow and the resulting physical phenomena. Moreover, various SAGD viscosity models and flaws with the current analytical and numerical models were reviewed. Different emulsification mechanisms were reviewed based on experimental and field evidence. Finally, the gaps in the research were identified. **Table** 7 shows a summary of the results concluded from this review study.

Table 7- A summary of the SAGD reservoir emulsion

Parameter	Remarks
Emulsion type	- W/O emulsion, some reports on complex emulsions
Produced fluid volume fraction	- W/O emulsion + Free water phase - High free water values reported in the literature, increasing up to 90 % in the late SAGD production stages

Emulsified water volume fraction	- It depends significantly on the wettability of the system and other factors including steam quality, reservoir, and operating conditions and geometrical effects of the steam chamber. It often decreases in the late SAGD production stages due to the steam chamber development. Various values in the range of 0.76 to 0.19 EWOR has been reported in the literature under relevant SAGD conditions.
Droplets mean size and DSD	- A wide range of sizes from 1µm-60µm reported. However, the mean size of 10 µm to 15 µm was measured for the size of the droplets. DSD often has multi peaks and follows a multimodal size distribution.
Rheology	- The viscosity of the emulsions increases significantly with the emulsion quality. - Phase inversion possibility is minimal and may exist only at the early stages of SAGD production when EWOR is somewhat higher. This phenomenon results in a drastic drop in the emulsion viscosity. This has not been captured yet in the experiments. - Richardson correlation seems to be the best one that describes the SAGD emulsion viscosity. This applies to modified versions of the Richardson equation such as Broughton and Squires correlation.
Stability	- SAGD emulsions are generally categorized as kinetically stable emulsions due to the presence of natural emulsifiers and the shearing provided by the flow through the pores. - Asphaltenes, resins, and fine solids contribute to the stability of SAGD emulsions. It appears that asphaltenes have the main role in the stability of the emulsion. - pH, Brine composition, DSD, pressure, and temperature may also have effects on the emulsion stability.
Emulsification	- SAGD emulsification is a result of steam condensation at the bitumen-steam interface and engulfment of the small droplets by the mobilized oil phase. - Direct condensation of the steam when the steam chamber is rising is associated with higher water emulsification within the continuous mobile oil phase. EWOR decreases as the stable condensate films are formed at the late stages of SAGD production (lateral expansion of the steam chamber).
Emulsion flow modelling	- Most of the analytical, mechanistic and numerical models employed Taylors' model to describe the emulsion viscosity which does not appear to be valid for high concentrations of the dispersed phase in SAGD. Additionally, the kinematic reaction of the condensation and emulsification needs to be investigated. - Emulsion flow may facilitate convective heat transfer and reduce the residual oil saturation. On the other hand, emulsion blockage by the dispersed phase droplets can reduce the permeability of the reservoir. - It seems that emulsion flow has complex effects on production. However, it may be concluded from the experiments and studies

	that W/O emulsion in early SAGD production stages reduces the production due to high viscosity resulted from high EWOR. However, in the late stage of production emulsion viscosity is reduced owing to the lower EWOR. Convective heat transfer by the emulsion results in dilution of the residual oil which leads to an increase in production.

Future work

There are several gaps in the literature regarding the characterization of SAGD emulsion flow. Some specific areas that require further research include rheological modelling of SAGD "W/O" emulsion incorporating the DSD and dispersed phase volume fraction effects; understanding the convective heat transfer mechanisms of emulsions; assessment of fines mobilization and sand production under emulsion flow; potential SAGD emulsion blockage and mechanisms; reaction kinetics of steam condensation; thermodynamics of water droplets emulsification; quantification of emulsion effect on relative permeability and residual saturation of reservoir fluids; and assessment of sand control screens facing emulsion flow, among others.

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