

**A NOVEL EXPERIMENTAL STUDY OF CRUDE OIL
DEHYDRATION USING MICROWAVE ENERGY UNDER
ELECTROSTATIC FIELD**

by

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ABSTRACT

In this study, microwave energy was introduced simultaneously with electrostatic field to investigate the efficiency of the coalescence process in crude oil emulsions as a hybridized technique for oil/water dehydration. Oil demulsification, the breaking down of crude oil emulsion into oil and water phases, is important to the industry for several reasons. The rate or speed oil/water separation takes place at, the amount of water left in the crude oil after oil/water separation, and the quality of the separated water have significant impacts on costs, time, and the environment. The novel experimental studies in this research aimed at finding a fast rate of separation, a low value of residual water, and a low value of oil in the disposal water. This unique research introduced microwave energy into the process to target oil/water separation at a molecular level, by combining two technologies. The research results showed a noticeable increase in the coalescence speed with both voltages AC (Alternating Current) and DP (Dual Polarity), while DP voltage with 20 seconds of microwave irradiation time exhibited the best coalescence rates versus the total consumed energy. These findings can contribute to future research to assist the industry in establishing specifications and practices to lessen the environmental impact oil production currently has, as well as assist the industry in providing low cost and efficient energy.

LIST OF ABBREVIATIONS USED

MW	Microwave
EST	Emulsion Stability Tester is a proprietary of Cameron, a Schlumberger Company
AC	Alternating Current
DP	Dual Polarity
CO ₂	Carbon Dioxide
API	American Petroleum Institute

GLOSSARY

MW	An apparatus that generates an electromagnetic wave, with a wavelength ranging between 0.001 m to 0.003 m.
EST	A device that generates utilized alternating current or direct current to generate an electric field.
Emulsion	The dispersion of a non-soluble immiscible liquid from one to another.
Coalesce time	The time required for the minute water droplets in the emulsion to merge with one another and the beginning of emulsion resolution.

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CHAPTER 1 INTRODUCTION

This chapter presents an introduction to the dehydration of crude oil and discusses the motivation and objectives behind this research. Based on previous hands-on experience and research since 2016, there was an opportunity to study various oil/water separation technologies in the market. Oil/water separation technologies have been advancing since the electrostatic technology implemented on large vessels in the 1960s and 70s, which has steadily progressed from implementing AC and DC individually to combining AC/DC, to use dual frequencies to enhance the commercial operations of oil/water separation. My observations were focused on electrostatic treaters to gain working knowledge of effective and efficient methods for oil/water separation. From these observations, a substantial body of knowledge was acquired. As a result, my inquiry and focus shifted to the concept of implementing two technologies; a combination of electrostatic and microwave energy, to accelerate the process while reducing commercial use of chemicals during oil/water separation. The hypothesis was that a hybridized electrostatic and microwave technology would enhance the separation retention time which is critical to the efficacy of speed during the oil/water separation process. Although this research is in its early stages, it has the potential to significantly improve oil/water separation methods and techniques, which could have major implications for environmental sustainability and economics in the petroleum industry.

1.1 Motivation

Reservoir fluids arriving at the wellhead are a mixture of hydrocarbons, water, sand and other unwanted substances, at some pressure and temperature. They do not meet any customer specification and require some treatment to safeguard the equipment. The

unwanted substances are generally removed as close as possible to the well head, to minimize the overall capacity of the production facilities. Oil treatment consists of removing water until meeting the industry specifications.

In many cases, water is co-produced with oil production and part of or all the water produced may be in the form of an emulsion with the oil phase. An emulsion is a semi-stable dispersion of one liquid (dispersed phase) in another liquid (continuous phase). Two types of emulsion can occur:

- Water in oil (W/O) emulsion (or normal emulsion)
- Oil in water (O/W) emulsion (or reverse emulsion).

Physical properties of the produced crude oil, such as API gravity, oil viscosity, chemical composition, solids, water density and water content level, determine the optimum technologies to be used for effective dehydration. Current industrial methods of crude oil/water emulsion destabilization techniques include:

- Heating the oil/water emulsion enhances its breaking or separation. Increasing the temperature has several effects on the emulsion breaking. It reduces viscosity, increases Brownian motion and increases frequency of collision).
- Chemical Demulsifiers: By far the most common method of emulsion treatment. These chemicals are designed to neutralize the effect of emulsifying agents that stabilize emulsions.
- Mechanical methods: These methods are applied on the surface facilities production system. The coalescence surface induces the collision between droplets and forces them to coalesce.

- Electrical methods: These methods are applied on the surface facilities production system. High voltage electricity supplied by electric grids is often an effective means of breaking emulsions. The electric field disturbs the interfacial rigid film by rearranging the polar molecules thereby weakening the tight film and enhancing coalescence.

1.1.1 Electrostatic Coalescence Forces:

The mechanism of coalescence of two drops in the presence of an electrostatic field involves three forces.

- Dipolar Attraction is an electrical force produced by positive and negative centers on induced dipoles of water droplets.
- Electrophoresis is an electrically induced movement of polar bodies in a uniform field toward closest electrode based on the polarity.
- Dielectrophoresis is the movement of polar bodies induced by a divergent electric field toward increasing gradient.

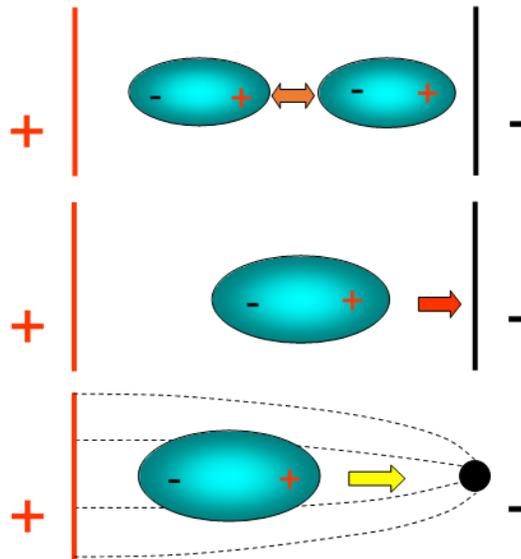


Figure 1-1: Illustration of the movement of polar bodies induced by a divergent electric field (Selman et al, 2005).

There are several mature types of electrostatic technologies in the market to enhance the oil dehydration process:

- Alternative Current (AC):

Alternating Current (AC) is crude dehydration technology, more than 100 years-old technology, and was for a long time the main technology used. It applies an alternating electric field at 50 to 60 Hz to the emulsion, causing the water droplets to deform due to the dipolar attraction force and quickening the water droplet coalescence by the attraction force between oppositely charged ends of the water droplets. The AC field treaters are quite effective for bulk water removal due to the nature of the dipolar attraction but usually the performance suffers degradation when lower water cuts are encountered, due to the dipolar attraction is weakened when the water droplets are spaced further apart.

- Direct current (DC):

It was recognized that the DC field provide superior coalescence due to its ability to utilize electrophoretic movement to enhance the water droplet collision rate.

However, DC field applied to a water rich emulsion resulted in electro-corrosion; which limited its application to a low water content (second or third stage refined products).

- Combined (AC/DC) or Dual Polarity:

Dual Polarity technology is about 40 years old, developed around 1972. In this process, the incoming crude oil emulsion is first subjected to a weaker AC field for bulk water removal followed by a stronger DC field where the remnant water droplets are removed.

This design eliminated the electro-corrosion as the DC field exists between the electrode plates only and will have a better result on the lower water cuts content.

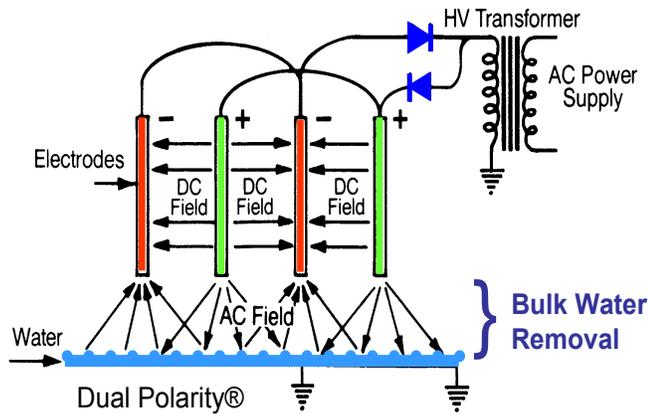


Figure 1-2: Diagram of dual polarity (Selman et al, 2005).

1.1.2 Microwave Energy

Recently, an innovative microwave heating technology has been successfully tested in field and laboratory tests for the demulsification of oil/water emulsion. Microwaves are electromagnetic (EM) energy. Microwave energy is a nonionizing radiation that causes molecular motion by migration of ions and rotation of dipoles but does not cause changes in molecular structure.

Microwaves frequencies (wavelengths) are in the range from 300 MHz ($\lambda = 1$ m) up to 300 GHz ($\lambda = 1$ mm). Following international conventions, domestic microwave ovens operate at frequencies of about 2.45 GHz, ($\lambda = 12.23$ cm).

Dipolar molecules respond to an electric field by rotating so that their positive and negative ends line up with the field. In an alternating field, this causes the molecule to rotate back and forth.

Due to its dipole moment, the water molecule attempts to align with the field of radiation. As the microwave passes by a molecule in the field range, the electric field direction changes at a frequency of 2.45×10^9 1/s (2.45 GHz). Just as a water molecule gets partially aligned with the field, the field direction reverses, and the water molecule must realign.

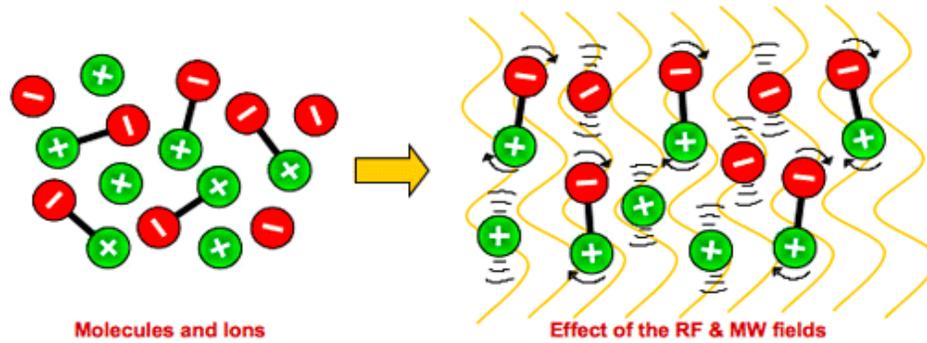


Figure 1-3: The aligning and realigning of water molecules produces heating through frictional effects (Selman et al. 2005).

When microwave radiation penetrates a material, the total energy absorbed by the material at any given power of irradiation is dependent upon the dielectric properties of the material. The dielectric constant (ϵ') and the dielectric loss factor (ϵ'') quantify the capacitive and conductive components of the dielectric response. The most important property is its loss tangent (also known as dissipation factor) which is defined as a measure of rate of loss of power. Mathematically, the loss tangent, $\tan \delta$, is a ratio of the material's dielectric loss factor, ϵ'' , to its dielectric constant ϵ' ,

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \quad (1-1)$$

where δ is the dielectric loss angle (the difference between 90° and the dielectric phase angle), and the dielectric constant is a measure of a material's ability to store the microwave energy as it passes through, while the dielectric loss factor measures the material's ability to dissipate that energy.

When microwave energy penetrates an oil water emulsion sample, the energy is observed by the sample at a rate dependent upon its dissipation factor.

The dielectric constant (ϵ') and the dielectric loss factor (ϵ'') both are affected by the

frequency of radiation, the relative permittivity changes with the wavelength (and hence frequency):

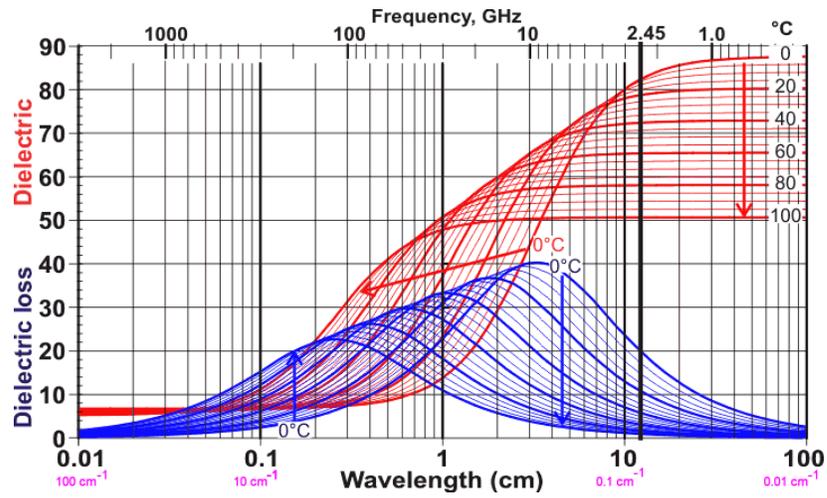


Figure 1-4: Shows the dimensionless dielectric and dielectric loss reducing with temperature at the microwave oven frequency 2.45 GHz of water (R. Buchner, 1999)

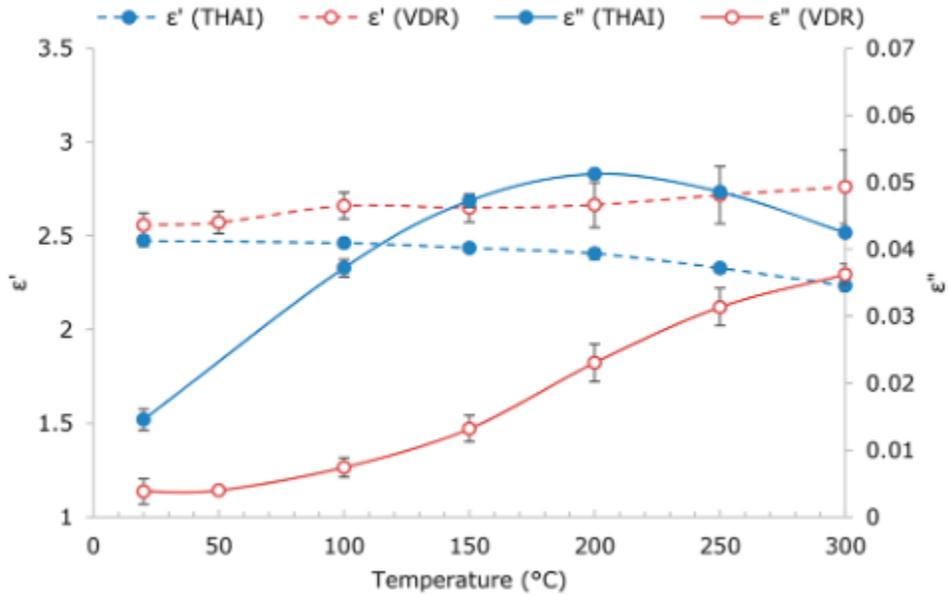


Figure 1-5: Dielectric constant (ϵ') and loss factor (ϵ'') of two heavy oils a function of temperature at 2.45GHz (Yang, 2018)

1.2 Objective

Crude oil/water separation (dehydration) using electrostatic and microwave technologies has been studied and implemented in the industry separately; no study or attempts of combining both methods were conducted in one research. The objective of this research; is to quantify experimentally the dehydration process of a crude oil/water emulsion with microwave field energy under an electrostatic field with different voltage types in order to enhance the existing oil/water dehydration process by maximizing the through put of the oil production facilities and reducing the operational cost.

Despite the heating effect of the microwave energy, exposing the emulsion to both microwave and electrostatic field is expected to enhance the coalescence process. Both energies will have a different level of effect:

- The electrostatic field will have effect at the droplet level.
- The microwave field will have effect at the molecule level.

Oscillating and polarizing the water molecules with the electromagnetic field is assumed to help the electrostatic dipolar attraction force to combine more microdroplets to create a bigger one, accelerating settlement.

In order to achieve that, a new testing apparatus was designed to combine the Cameron EST device with the domestic 700W microwave.

CHAPTER 2 LITERATURE REVIEW

The main purpose of oil production is to separate the oil and water into their original phases or separate components. There are different techniques used by oil companies to separate oil from water, but some of the most common ones include microwave and electrostatic separation of water from oil or oil from water (Xia et al., 2010). This chapter will be a detailed review of both these technologies of oil/water separation beginning with the microwave oil/water separation technique.

2.1 Crude Oil Emulsions

Water and crude oil often combine (emulsify) during the process of harvesting oil resulting in either oil-in-water or water-in-oil emulsions, depending on which component gets dispersed in the other. Usually Hydrocarbon in its initial state at the reservoir; oil, gas, and water are separated by gravity, and are in a state of high-pressure equilibrium. Once a well is drilled through the hydrocarbon bearing reservoir rock, this equilibrium is immediately disturbed. During the production stage oil and water will flow together; with the existing of the emulsifying agents (i.e. asphaltene, sand, wax etc..) a stable crude oil emulsion form. The water in oil emulsion consists of oil as the continuous phase, and for that reason, it must be treated or demulsified. The demulsification of oil in water is a key process aimed at removing water from crude oil (Evdokimov and Novikov, 2007). Cho and Yi (2010) argue that it is important to note that water is a requirement during the production of oil; this means it is present with oil, especially in the latter stages or phases of the well life when the injection of water is a requirement used to improve or enhance the production rate of oil.

Oil/water emulsions contain several contaminating materials such as metal particles, dirt, soaps, solids, emulsifiers, solvents and cleaners among other contaminants, that mainly get

formed when pressure reduction in valves used to harvest oil creating an enormous shear within the fluid. In other words, during the production of crude oil, there is significant shear such as the flow through flow lines, reservoir rock, valves and fittings among others, which are difficult to avoid (Zhang et al., 2015). By so doing, emulsions, which mainly contain more than 20% water get formed, and this must be separated before further downstream transportation and processing can begin. Emulsions are two immiscible liquids characterized by one liquid becoming a collection of droplets in another liquid phase. (Zhang et al., 2015) further argue that as the global oil production continues to come from increasingly heavy reserves of oil, such emulsions are becoming more stable, meaning they are becoming costly to separate. In some cases, gravity separation can be utilized to separate the two substances, but this process can be prohibitive when the separation of oil from water needs to be carried out either in remote locations or on offshore platforms (Zhang et al., 2015).

According to Binner et al. (2014), crude oil occurs in the natural state in the form of emulsions which have proved to be problematic during transportation, processing, and storage. Binner et al. (2014) further assert that close to 80% of exploited crude oil exists in emulsion state all over the globe with water and other components, such as silt and fine sand, being held in a number of crude oils in permanent emulsions. There have been several methods used for the process of separating crude oil emulsions with the purpose of reducing production costs while subsequently boosting the quality of crude oil emulsions (Zhang et al, 2015).

Even though there are many ways of separating oil from water, such as chemical destabilization with some form of dissolved air flotation (Zouboulis, 2000), freezing and thawing (Chang, 2007), membrane-associated method (Nakashima, 1991), electrical systems (Zhang et al., 2015), and ultrasonication (Mason, 2002) among others, there is a technique that has gained much attention from a number of researchers in many places

across the globe. Known as the microwave heating technique, this technique has proved to be effective in demulsification or the separation of oil from water. Most researchers have argued that through selective heating of water, microwave heating has proved to be a success in enhancing the separation of oil-in-water emulsions (Xia, 2010).

Bottom line, the produced oil must meet transportation media's, pipeline's and refinery's specifications. In general, most processed crude oil should not contain more than 0.2% basic sediment and water (BS&W) and 10 pounds of salt per thousand barrels of crude oil (PTB), again, PTB and BS&W standard depends on company and pipeline specifications.

2.2 Microwave Oil/Water Separation Method

As noted above, there are different methods used to separate oil from water. Microwave demulsification has, however, proved to be the most effective one with reports indicating that the microwave radiation method has proved to be a success in several fields including organic synthesis, drying processes and sample digestion (Kubrakova and Toropchenova, 2008). Xia (2010) argues that by considering aspects of fast energy transfer to irradiated medium, microwaves have been termed as successful in performing the demulsification of heavy crude oil emulsions much faster than conventional methods.

The microwave demulsification process facilitates for the destabilization of emulsions, first, by increasing the temperature and, second, by reorganizing or rearranging the electrical charge distribution of water molecules through rotating them and subsequently moving ions around the drops. By so doing, the emulsion breaks without the addition of any other chemical agent (Martínez-Palou et al., 2013). The main concept of microwave heating aimed at separating oil from water was initially used by Klaila (1983) and it showed

a positive result to the extent of being adopted by the majority of oil drilling companies in many locations across the globe. Microwave heating is a totally different method from convection heating to separate oil from water, based on the fact that microwave adopts the use of electromagnetic waves that pass through the molecule opposed to other conventional methods where heating transfer heat all the way to the surface of the material (Chan and Chen, 2002).

Through the microwave heating process, heat energy is directly made to penetrate into the water molecule and by so doing, the interfacial thin film found in between the small water droplets becomes destabilized, breaks and allows the droplets to form a bigger water droplet. After the droplets has been formed, it is then separated as water will form at the bottom with oil floating on top of the water, since the density of oil is much lower than the density of water (Jin et al., 2014).

2.3 Advantages of Using Microwave Heating

There are many advantages of using microwave heating as opposed to other conventional heating of emulsions in a process aimed at separating oil from water. However, two main advantages are that, First, microwave heating is volumetric in nature, meaning that all the dispersed water is heated in a rapid manner without the limitations of conductive and convective transfer of heat. A second advantage of this method is that the water phase of the emulsion has the capability of being heated selectively thereby reducing the overall energy requirements (Binner et al., 2014).

Table 2-1: Microwave Dielectric vs. Conventional Heating (De la Hoz,, 2007).

Microwave Dielectric Heating	Conventional Heating
Energetic coupling	Conduction/ convection
Coupling at the molecular level	Superficial Heating
Rapid	Slow
Volumetric	Superficial
Selective	Non selective
Dependent of the properties of the material	Less dependent

2.4 Effectiveness of Microwave Heating Technology

A number of scholars and researchers have made several attempts in efforts aimed at investigating the effects of salinity, water content, and pH on microwave demulsification of crude oil, and the majority of them have concluded that by increasing microwave energy input, demulsification or the separation of oil from water is enhanced at a much faster rate (Binner et al., 2014). According to a large group of researchers (Binner et al., 2014), (Chan and Chen, 2002), (Fang et al., 1995), (Nour et al., 2010) and (Kubrakova and Toropchenova, 2008), when compared with conventional heating, microwave heating is the best option. In fact, a number of experiments have been conducted with the aim of comparing microwave heating and conventional heating on the demulsification of water in oil emulsions. In all these experiments, it was evident that microwave heating yielded better results than conventional heating (Binner et al., 2014).

Previously reported coalescence of water droplets in the process of microwave heating attribute this occurrence/mechanism to the reduction of the interfacial tension of the emulsion. Chan and Chen (2002) reported that microwave heating enhances demulsification or the separation of oil from water. The scholars demonstrated a reduction in the zeta potential of an oil/water emulsion immediately after microwave treatment was

applied. For this reason, the scholars reached a conclusion that microwave-induced molecular heating is one of the most effective methods in separating water from oil (Kubrakova and Toropchenova, 2008).

Apart from the aforementioned scholars, others, such as Xia and Ferreira, studied microwave-assisted demulsification, and they too argued that through microwave heating, the separation of oil from water particles was easy and more effective (Xia et al., 2010; Ferreira et al., 2013). Microwave-heated emulsions, which get heated with the same average bulk temperature, separate faster than conventionally heated emulsions (Kubrakova and Toropchenova, 2008). To validate these findings, a research effort was undertaken as indicated below.

2.5 Non-Thermal Effects of Microwave Irradiation

The issue of non-thermal effects (also called specific microwave effects) arise from interactions between the microwave field and the material, non-thermal effects are effects that are not due to the increase of thermal energy of the material. Instead, the microwave energy itself directly couples to energy modes within the molecule due the dipolar molecule polarization and magnetization under the electromagnetic waves. Although several theories have been claimed and some predictive models have also been published about the non-thermal microwave effects, but it is still a controversial matter.

Loupy (2001) published a tentative explanation of non-thermal effects (Loupy, 2001). He studied the nature of the microwave effect considering the reaction medium, the polarity of the transition state and its position along the reaction coordinate.

The non-thermal effect was also recently address in organic synthesis by Antonio de la Hoz (2007), where he concluded that microwave effects involves thermal (e.g. hot spots,

superheating) and non-thermal (e.g. molecular mobility, field stabilization), but overall he suggested to consider the separation of thermal effects during the future studies; considering the magnetic component, the polarity and the polarizability of the transition state and the effect of the reaction medium (De la Hoz, 2007).

2.6 Materials and Methods of Research

Nour et al. (2010) carried out a research tasked with proving the effectiveness of microwave heating in the separation of water from oil. In this case, Elba microwave oven model EMO 808SS with a rated power of 900 watts and an operating frequency of 2450 MHz was used in heating samples of water-in-oil emulsions. The microwave oven consisted of materials such as data loggers, sample holder, a PC, turntable, thermocouple, microwave cavity, and microwave control panel as indicated in the Figure 2-1.

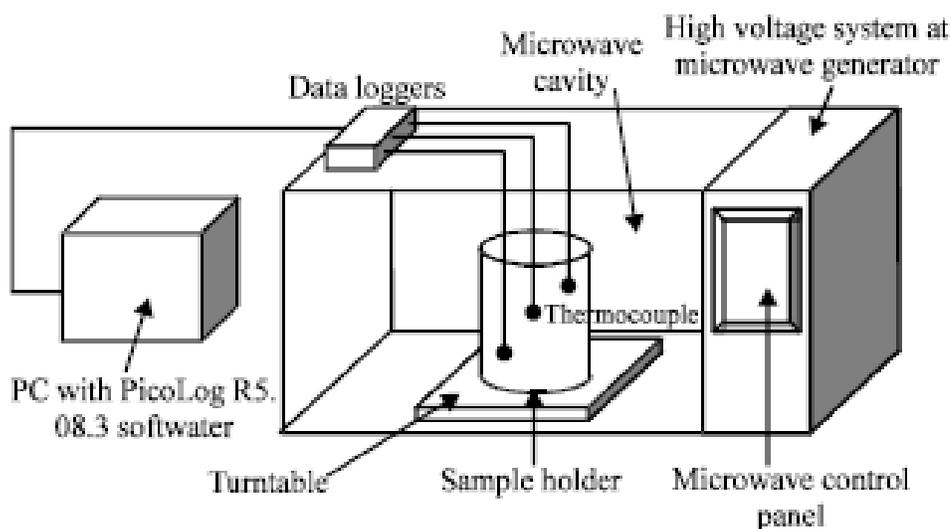


Figure 2-1: Illustration of an Elba microwave oven with the following component; data loggers, sample holder, a PC, turntable, thermocouple, microwave cavity, and microwave control panel (Nour et al., 2010).

In the research process, crude oil samples were obtained from the Petronas refinery located

at Malaka city with 50-50% and 20-80% water-in-oil emulsion prepared to test the effectiveness of microwave heating in the separation of water from oil. The experimental results indicated that microwave radiation or heating was very effective towards the separation of water-in-oil emulsions (Nour et al., 2010). Generally, the study was divided into three important parts. Phase 1 included the preparation and formulation of crude oil samples followed by phase 2 that involved the characterization of the prepared and formulated emulsion samples in terms of chemical and properties. The last phase was the actual demulsification process where the separation of oil from water was carried out via microwave heating technology (Nour et al., 2010).

The results of the study were an eye opener indicating that microwave radiation or heating is a dielectric heating technique that has the characteristics of being fast, volumetric and effective with the potential to be used as an alternative way towards the demulsification of water-in-oil emulsions. Of importance to note is that this new technology does not require the use of chemicals, in addition to being effective based on the fact that those who have used it before have argued that microwave heating or demulsification appears to be a faster means of separating oil from water or water from oil than the commonly used conventional heating method (Martínez-Palou et al., 2013).

The use of microwaves has been found to be one of the most effective, clean and chemical free methods for heating oil emulsions. Lately, the majority of oil drilling companies are experimenting on this process with the majority of them seeing the benefits of using microwave heating as opposed to conventional heating methods that demand too much energy intake among other requirements, which may turn out to be costly. A number of oil drilling companies in a number of locations across the globe are lately embracing microwave heating to separate oil from water. For instance, oil drilling companies in places such as Tamaulipas and Altamira in Mexico have been reported to be using this technology based on its proven success rate (Kubrakova and Toropchenova, 2008).

Jin et al. (2014) argue that for a long time, oil drilling companies have used sedimentation and other centrifugation techniques to separate oil from water. However, as mentioned earlier, apart from such techniques being hazardous to the environment, such conventional methods have proved to be costly or expensive to the extent of creating a demand for newer, cheaper and more effective methods of demulsification.

2.7 Electrostatic Oil/Water Separation

The problem of crude oil containing water is an issue that accompanies the petroleum industry, water and salt in the oil production system may cause number of problems such as oilfield surface qualification treatment, corrosion of the process equipment in addition to the refinery plant upgrading exercises among others. Dispersions of one fluid in another immiscible fluid can be found in a many a natural and synthetic product such as paints, food products, milk, and petroleum, among others. For this reason, the separation of the two immiscible fluids becomes a necessity in order to purify or recover the much-needed product, such as the separation of water from crude oil (Varadaraj, 2004). Since 1911, the majority of oil companies have been using electric fields in oil/water separation based on the fact that electric fields enhance coalescence of water drops found in oil, which results in more efficient separation. This is known as electro-coalescence (Aryafar and Pirouz, 2007).

As noted earlier, crude oil contains a significant amount of water which is dispersed in the form of tiny droplets. This calls for effective separation techniques aimed at separating the two products. Apart from microwave heating technology discussed above, electrostatic oil/water separation or demulsification of crude oil is another technology that has attracted a lot of attention consistently during the past few decades (Varadaraj, 2004).

Frederick Cottrell inspired the invention of an electrostatic precipitator that was able to separate water from oil in early 20th century, and since then, the use of electrostatic forces for phase separation of oil from water led to several publications, especially in the first third of the 20th century. The electrostatic technique involves the use of the electric field in phase separation of liquids, a practice commonly referred to as electro-coalescence. This technique has developed in addition to being extensively investigated based on its clean, fast and efficient coalescence capabilities (Varadaraj, 2004).

Apart from water separation from oil, Zhang argues that electro-coalescence can also be applicable in phase separation undertakings such as the extraction of solvent and dispersion as well as the process of fractionating mixed oils. In industrial usage, such as crude oil demulsification, the electric field is mainly used to assist the small water droplets to come in contact or close to one another and eventually merge into each other. The large drops of water can then be easily settled by gravitational force, resulting in a final product that comprises of water below a prescribed level. By the application of an electric field, the rate of coalescence is increased in addition to the increment of migration speed of the droplets towards the electrodes, which also facilitates phase separation of oil from water (Zhang et al., 2015).

Research into the field of electro-coalescence has given rise to many findings that have helped to make the separation of oil from water slightly faster. Additionally, several studies identifying the challenges in electro-coalescence and methods, aimed at resolving them, have been carried out (Peng et al., 2016).

2.8 The Dynamics of Electro-coalescence

2.7.1 Electrostatic Force of Attraction between Drops

The main mechanism of coalescence of two liquid drops in an electric field is made up of three distinct steps. The applied electric field works by polarizing an individual drop with each drop acting as a dipole with induced negative and positive charges at two polar ends. The dipole then aligns towards the direction of applied electric field. The initial or first step of electro-coalescence involves the interaction of two drops based on the attraction between opposite poles of polarity (Zagnoni et al., 2010). In huge or large separation limits, the opposing forces acting on a drop can be drag force, electrostatic force, and gravitational force if the drops are coarse. When two drops move close or towards each other, a small separation exists in an interstitial film of the fluid in between the leading faces of the drops. The next step of electro-coalescence involves the pressing or squeezing of fluid at the plateau border of the thin film and, as the drops come closer to each other, the thickness of the film reduces even further. The third and final step is characterized by the film becoming very thin coupled by the action of electrostatic and molecular forces breaking the film to allow the two drops to merge together (Zhang et al., 2015).

According to Zagnoni et al. (2010), in addition to bringing drops closer to each other, an electric field also enhances the thin film breakup. Previous studies of electro-coalescence have found out that for two anchored drops, the coalescence rate was proportional to the strength of the applied electric field when the electric field was small. However, when the electric field was high, the rate was found to be proportional to the square of the electric field (Zhang et al., 2015).

It is important to note that apart from the magnitude of the applied electric field, other

parameters such as inter-drop separation, size of the drops, fluid properties, including permittivity, viscosity, conductivity, and interfacial tension among others, can influence the force of attraction between the coalescing drops. Additionally, the shape of distortion is another factor that can influence the force of attraction between the coalescing drops. In order to make the electrostatic process slightly faster, subsequent studies in electro-coalescence were focused on these parameters (Hemmingsen et al., 2005).

2.7.2 Shapes of Coalescing Drops

The shape of coalescing drops is another dynamic of electro-coalescence worth noting. An immediate effect that a drop indicates upon the application of an electric field is known as shape deformation. According to Zagnoni et al. (2010), two closely placed drops in an electric field do exhibit or portray deformation when the electrocapillary number is very large. At a small electrocapillary number, deformations can only be observed at the leading poles of the coalescing drops. Such deformations are due to high charges of the electric field in between the leading edges of the two drops that creates high charge density. A drop can also display aft and fore asymmetric deformation, especially when it is near to the surface of the electrode. However, the presence of drops near the electrodes not only enhances deformation, but also protects the inner drops in the emulsion (Peng et al., 2016).

2.7.3 Damping Forces

In the event that two approaching drops are at fairly large separation distances, the drag force will oppose the motion. However, in cases where a drop motion in a viscous medium, the actual drag force experienced by the drop is lower on account of the circulations on both sides of the interface (Peng et al. 2016).

2.7.4 Breakup of the Thin Film

The breakup of the thin film is another characteristic of electro-coalescence. In this instance, the approaching drop contains a film of the medium fluid found between their leading faces. As the drops continue moving closer, the thickness of the film continuously decreases by squeezing at the plateau border, and on further reduction of the film thickness, molecular forces begin playing their roles. Zagnoni et al. (2010) assert that the attractive van der Waals force aids in reducing the thickness as the double-layer repulsion balance each other. Due to thermal or mechanical shocks in addition to the presence of impurities at the interface, instability can set in which results in the breakup of the film causing the separation of the two drops.

2.9 Coalescence and Demulsification Dynamics by High-Voltage Pulsed Electric Fields

The demulsification dehydration of oil is an exercise widely adopted in petrochemical engineering, metallurgy, equipment manufacturing, and resources recycling among other engineering technologies. Lately, it seems that the process of demulsification dehydration using a high-voltage pulsed electric field is gaining wide attention based on the advantages offered by this technique, including simple structure, low energy consumption rate, and rapid speeds of processing (Peng et al., 2016). As one of the most effective physical demulsification methods, the application of high-voltage pulsed electric field is an exercise widely adopted by oil drilling companies to dehydrate emulsified oil.

Several researchers have attempted to summarize the dynamic behavior or reaction of pulsed electric fields in promoting coalescence as oscillation and dipole coalescence, with

a number of studies being conducted in relation to these two effects (Peng et al., 2016). Some of the early dynamic studies of dipole coalescence employed the use of the spherical dipole model to study the forces found between the droplets. By considering the deformation of droplets in oil that gets subjected to an electric field, researchers have studied the action between polarized droplets found in an arbitrary space by a sphere model known as double prolate sphere droplet mechanism (Peng et al., 2016).

Apart from the above studies, the study of oscillation coalescence is another undertaking mainly concentrated on solving or coming up with effective solutions to the optimal coalescence frequency. However, by only considering the optimal demulsification frequency is insufficient. Other factors, such as the influences brought about by the intensity of pulsed electric field, physical parameters of the system, and the pulse duty ratio, must all be considered (Peng et al., 2016).

2.10 Summary

Just as microwave heating technology aimed at the separation of oil from water, electrostatic separation of oil from water or water from oil is another form of technology that is gaining much attention worldwide; with the majority of oil drilling companies arguing that just like microwave technology, electrostatic technology is another oil/water or water/oil separation technology that has proved to be effective and cheap to use in the separation of two immiscible fluids or oil from water.

CHAPTER 3 EXPERIMENTAL METHODS

3.1 Introduction

In this chapter, details of the experimental work of this project are presented. The main objective is to quantify the effects of microwave irradiation under electrostatic field on laboratory-created water/oil emulsions. The experiments will compare between two electrostatic treated cells and one of them will be exposed to microwave energy.

3.2 Experimental Apparatus and Materials

In carrying out the experiments to study the effects of microwave irradiation on defined characteristics of water/oil emulsion, an industrial lab and equipment has been utilized. However, a custom-made apparatus was designed to combine the microwave and the electrostatic treater.

3.2.1 Material

The materials utilized in this experiment are as follows:

- Dead crude oil: Southern Alberta light chemical free crude oil with a specific gravity of 0.8581 at 20 °C (33 API) was collected from the top layer of a storage tank.
- Reservoir connate water: Water was collected from the bottom of the same oil storage tank.
- Stabilizing agent: NP-9 (Nonylphenol Ethoxylate) a non-ionic Surfactant was used to create the emulsion.



Figure 3-1: Illustration of the raw materials required to conduct the experiment. The raw materials are listed from left to right as follows; reservoir connate water, stabilizing agent and dead crude oil.

Table 3-1: summarize the fluid property values which was used in the calculations:

Density of water	1100	(g/cm ³)
Density of oil	858	(g/cm ³)
Density of emulsion	904.5	(g/cm ³)
Specific heat capacity of fresh water	4184	(J/kgK)
Specific heat capacity of saline water	3850	(J/kgK)
Specific heat capacity of oil	2130	(J/gK)
Specific heat capacity of emulsion	2388	(J/kgK)
Mass of emulsion	0.09045	(kg)
Emulsion J/K	215.9946	J/K

3.2.2 EST (*Electrostatic Susceptibility Tester*):

The Emulsion Stability Tester (EST) is a device designed by Cameron to determine and compare the treatability of oil field emulsions under electrostatic field like the real life desalter/dehydrator vessels. The EST is a portable unit which fits within a 11.5”x 9”x 15” (29.2cm x 22.9cm x 38.1cm) space; it consists of an aluminium heater block, a Teflon insulating block containing the high-voltage connections, and a stainless-steel cabinet for housing the electronics. At the time of this lab work, there were only 5 EST devices available worldwide, and unfortunately none of them were labelled with a serial number.

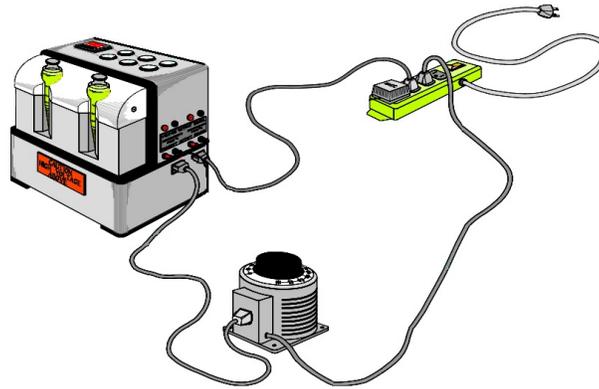


Figure 3-2: Illustration of EST apparatus from Cameron EST Operation Manual 2011.

The EST is equipped with a reversible voltage block mounted on the back of the unit. By inverting the block, the function of the EST can be changed from a DP voltage (half-wave DC) to an AC voltage. The DP wiring applies a positive and negative voltage to the electrodes. The AC wiring applies an AC voltage to one electrode and grounds the other. Additionally, it is equipped with a USB communications device; it provides a graphic representation of electrical dehydration.

- Graphically displays electrostatic coalescing process.
- Qualitatively predicts an oil’s electrostatic treatability.
- Evaluates demulsifiers using small samples.

The EST uses a custom-made sample tube (centrifuge-style), which are specifically manufactured for EST. The glass centrifuge tube has a built-in electrodes and external contacts for making connection to the high-voltage source, as well as a ground reference wire built into the bottom of the tube. The two metal electrodes on the wall side of the tubes applies high voltage ($\sim 6.5\text{K}$ Volt) to the emulsion.

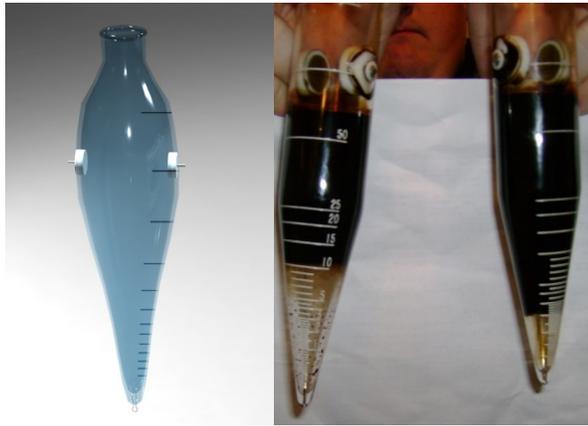


Figure 3-3: Centrifugal style tubes that contain the custom-made emulsion sample.

Once the high voltage is been applied on an emulsion, the EST will plot the electrical responses of a given emulsion verses time, which will provide an important data for processing the emulsion in the field.

As illustrated in Figure 3-3 (schematic of an EST plot), the electrical current will upsurge as soon as the high voltage is applied, which is an indicator of the existence of a conductive material in between the two electrodes; such as the water droplets.

After a while the electrical current will decline which is an indication that the emulsion has "broken" and water coalescence is occurring. Accordingly, the sooner the current declines; the faster the emulsion resolution and coalescence. Separation (water settling) is not evident in the EST plot; water separation will need additional time to separate after the electro-coalescence is completed.

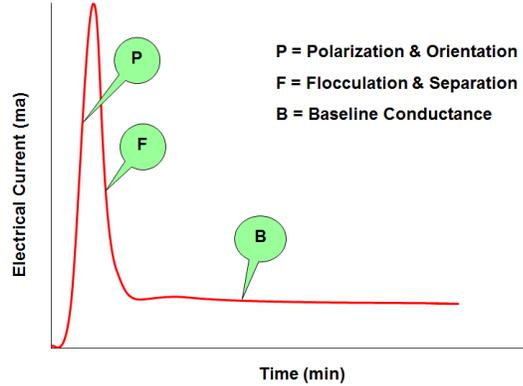


Figure 3-4: Voltage, current and time required to coalesce are recorded and displayed graphically (Selman et al, 2005).

3.2.3 Domestic microwave:

RMW733 model RCA designed domestic microwave oven with specifications which include an internal cavity of 0.7 cu ft. and 10 levels of rated power output of 700W.



Figure 3-5: Diagram of the domestic microwave utilized in experiment.

Using a 700 W domestic microwave will generate enough electromagnetic energy to propagate through the testing cell, according to (Fang et al. 1988) who used sample container with a diameter and height of 88mm and 143mm to hold 800 ml of oil/water emulsion. The continuous phase in the emulsion is oil (85% is oil and 15% is water), which

makes it is relatively transparent to microwaves due to the low dielectric constant (von Hippel 1954). The Microwaves electromagnetic waves will go through the emulsion and they should reach the other side of the cavity of the domestic microwave and reflect until radiation is discontinued.

3.2.4 Custom designed testing apparatuses:

Custom-made apparatuses were designed and built in-house specifically for this experiment to combine the EST's electrostatic field with microwave energy without jeopardizing the integrity of the EST electronics and the testing tube electrodes.

The design carefully considered the very high electrical voltage, and, also the potential of microwave energy escape through the cavity hole.

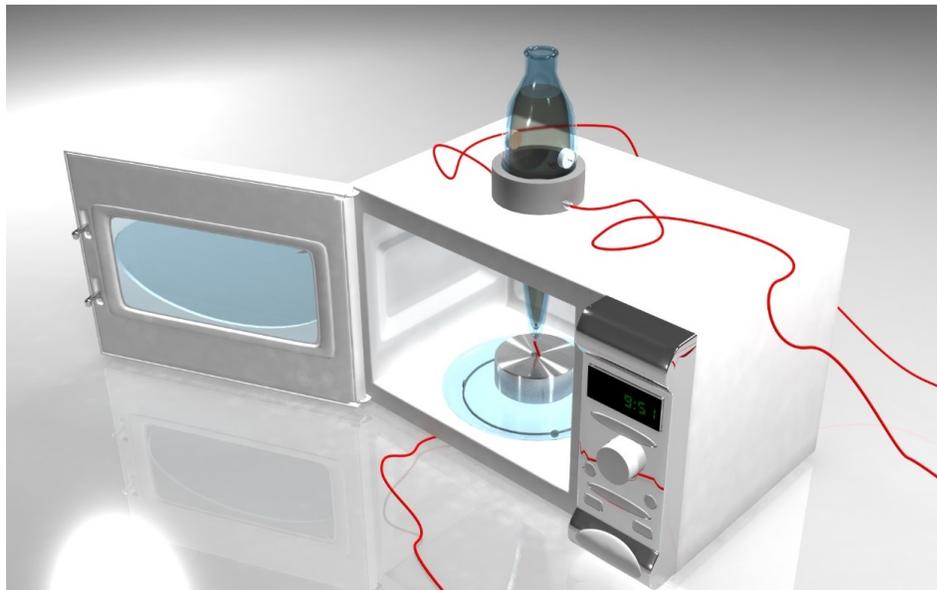


Figure 3-6: Schematic depiction of emulsion samples in the microwave oven.

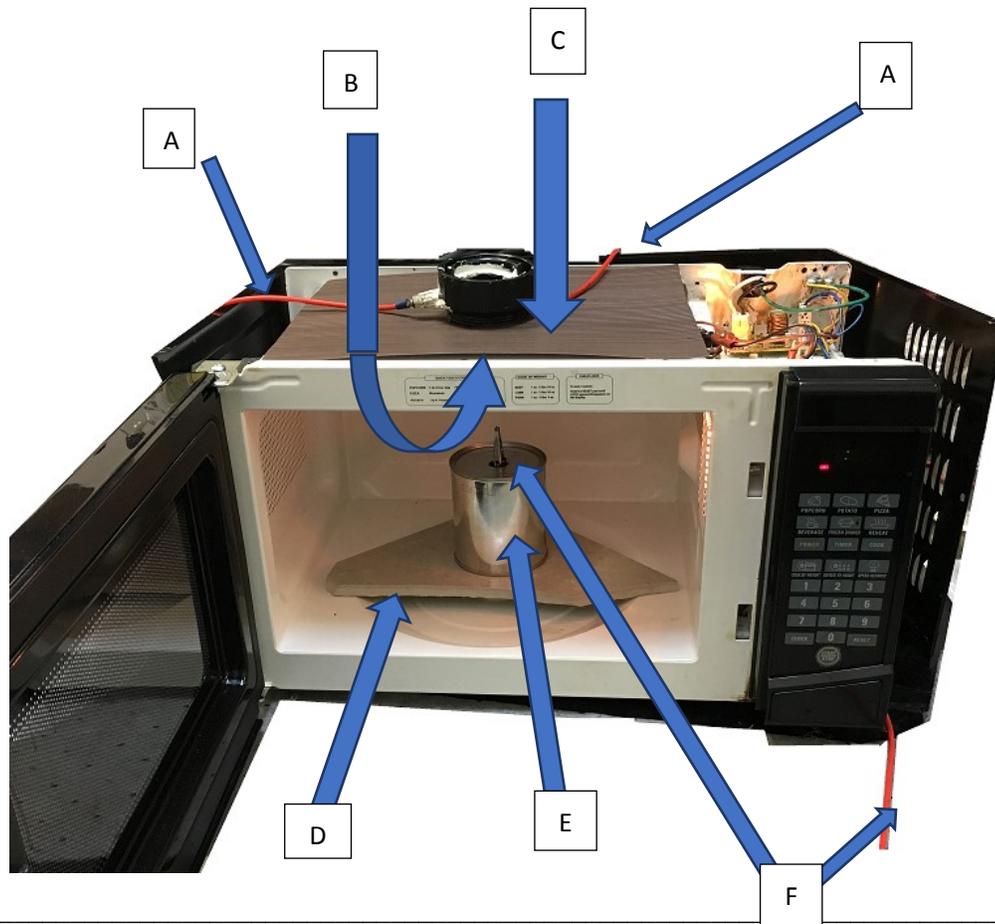


Figure 3-7: Schematic illustrates microwave modification to accommodate the test requirements.

A: EST bottle cell connector high voltage cable (rated 10k V) connects to the spring-loaded connector.

B: Microwave cavity was drilled with 2” hole.

C: PVC holder with 2 spring-loaded connectors to hold the glass bottle and connect the electrodes.

D: Ceramic plate with a hole in the middle to allow the cables to go through it.

The purpose of this plate is insulating the metal shield from the microwave’s body cavity to avoid arcing.

E: Metal shield grounded to the microwave’s body cavity. Metal shield is to protect the glass ground connector and the crocodile connector from exposure to the microwave energy.

F: EST GROUND cell connector, high voltage cable (rated 10k V) terminated with crocodile connector to be attached to the glass ground connection.

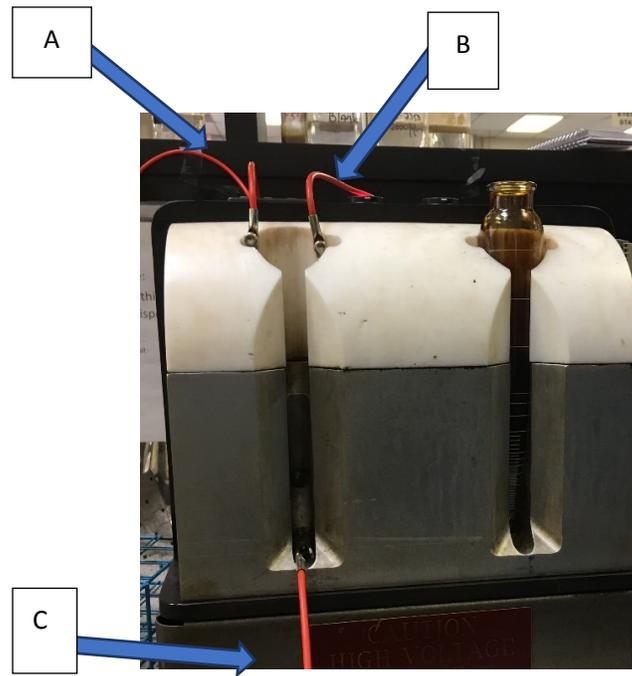


Figure 3-8: Schematic illustrates EST modification to accommodate the test requirements.

A: EST LEFT cell crocodile connector high voltage cable (rated 10k V) connects to the microwave spring-loaded connector.

B: EST RIGHT cell crocodile connector high voltage cable (rated 10k V) connects to the microwave spring-loaded connector.

C: EST GROUND cell connector high voltage cable (rated 10k V) terminated with crocodile connector to be attached to the glass ground connection.



Figure 3-9: Picture illustrating the lab setup.

3.2.5 Safety in the lab:

As with any laboratory equipment, the test operation environment will be exposed to chemicals, hot fluids, high voltages and moving parts. Every precaution must be taken to ensure this equipment does not injure the operator in the event of a malfunction.

Lab PPE (Personal Protective Equipment) must be worn all the time including:

- Safety goggles
- Lab coat
- Steel toe shoes
- H₂S gas monitor

Microwaves have significant danger associated with its electromagnetic waves. The primary danger from these invisible waves is the adverse heating of body parts by inadvertent exposure to them. For a batch system, such as a domestic oven, it is quite simple to prevent any microwave exposure due to the enclosed cavity. However, for this experiment, the only potential source of leakage during the test operation is the top cavity opening. In all tests, the top cavity was sealed with the emulsion fluid in the test bottle, which eliminates leakage from the microwave to the lab environment.

Industry has been using EST equipment for over 30 years. It is believed that equipment is free from defects. However, when operating the EST, it is important to keep in mind always that the unit operates on HIGH VOLTAGE. Although the high-voltage power supply has a limited current capability, it can still deliver a severe shock. In addition to that, the presence of combustible materials requires that the unit be operated in a well-ventilated area with adequate fire protection.

3.2.6 Sample preparation:

The objective of the mixing is to reach an emulsion mix that can break in a reasonable time while treated by EST (electrostatic treater), to ensure a reasonable visual response on the plot to be able to compare with the microwave's results.

In the field crude oils vary considerably in emulsifying tendency, some form very stable emulsions that are difficult to separate, others do not emulsify or form loose emulsions that separate quickly due to the density difference between the oil and the water. In this experiment, the lab mixed emulsion was tested with gravity separation only (without any treatment), although there was no measure of the coalescence, however volume of the separated water was measured versus time. The complete 15 ml of the mixed water in the emulsion was separated after ~8 1/2 minutes.

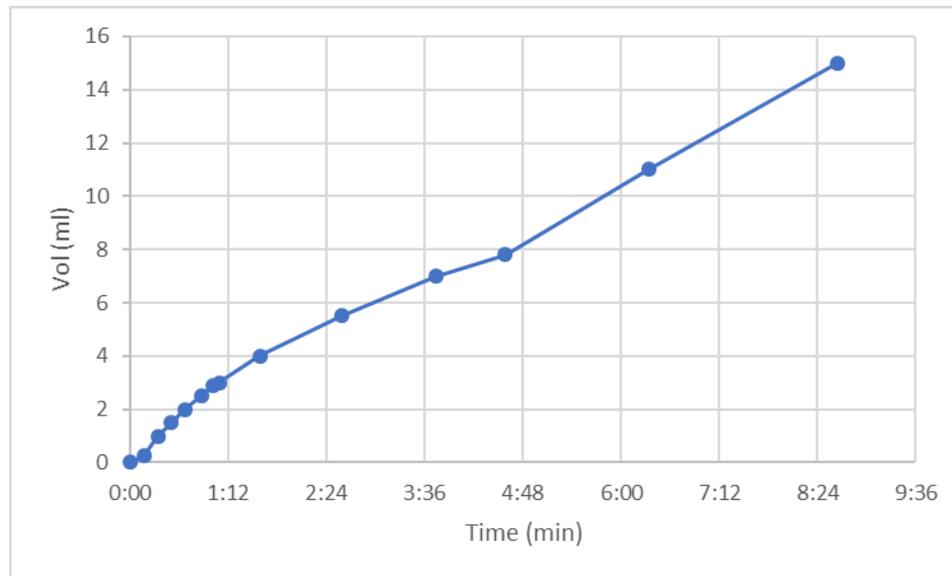


Figure 3-10 :Lab mixed emulsion (without any treatment), the 15ml of water separated in 8 1/2 minutes at ambient temperature (22° C)

Surfactant (NP-9) was mixed with the reservoir water due to its solubility in the water, and later stage crude oil was mixed with the NP9-water mix to form the emulsion.

The amount of the surfactant was the most crucial part of the formula; emulsion stability highly depends on the surfactant amount in the mix. To achieve that critical balance, the following steps were taken to reach the optimum concentration of the surfactant (NP-9):

Step 1: 1000 ml of the reservoir water mixed with 50 drops (each drop is estimated by 0.083 ml) of NP-9 (5 drops / 100ml);

Step 2: Add 15ml of the mixed water a test bottle and top it up with 85ml of crude oil;

Step 3: Mixture is agitated very well with hand shaking for at least 30 second;

Step 4: Mixture tested with EST device and record the electro-coalescence time;

Step 5: Based on the EST response adjust the water/NP-9 ratio.

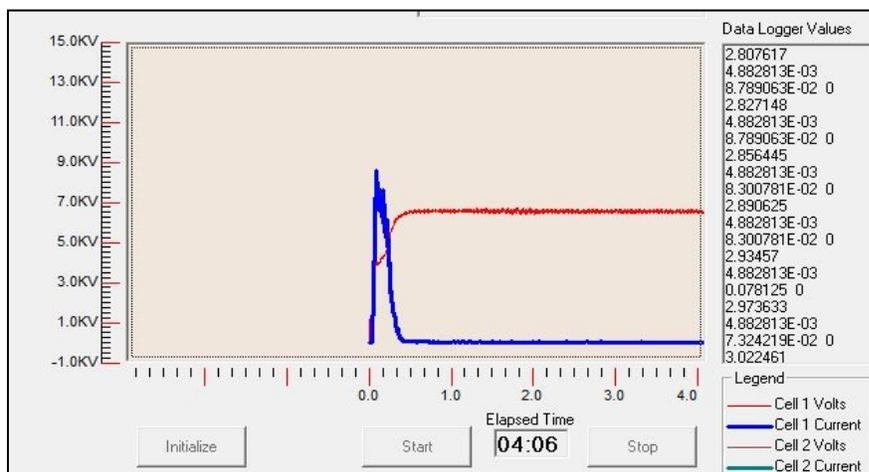


Figure 3-11: Example of a poor-quality mixture: Too little of the surfactant will create an unstable emulsion, which will break up very fast before observing the effect.

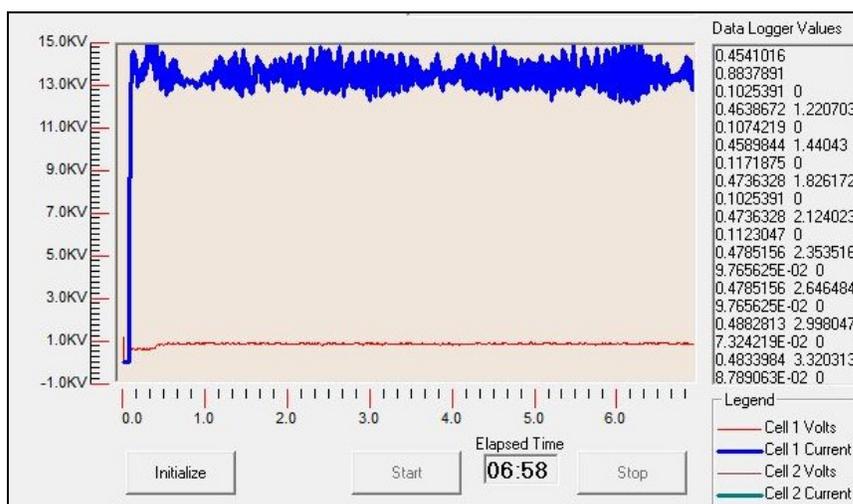


Figure 3-12: Example of a very stable mixture: Too much of the surfactant will create a very stable emulsion, which will not breakup quickly, it may need 20-30 min to breakup, that long period may overload the equipment and over heat the samples.

Once the Water-NP9 mix has been optimized, a test sample can be prepared for measurements, as shown in Figure 3-13.

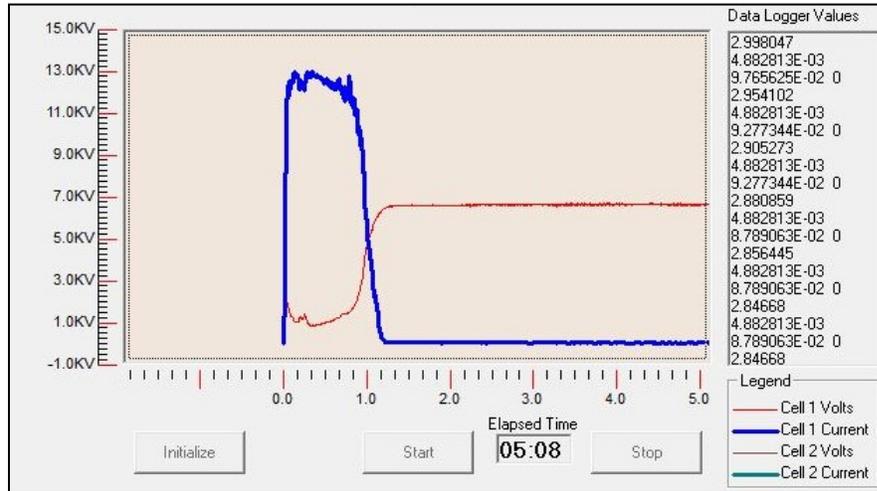


Figure 3-13: Example of a good mixture: A well-balanced mixture will result in a good EST test which shows electro-coalescence in more than 40 seconds.

Every test, two (100 ml) test bottles were prepared simultaneously with the same ingredients to eliminate any discrepancy. Although the Water/NP9 ratio was varying, from test to test, maintaining the same sample content in both test bottles was a must to eliminate any variabilities between the EST measurements, and the EST with microwave measurements. Figure 3-14 illustrates the overall process in preparing an acceptable emulsion mixture.

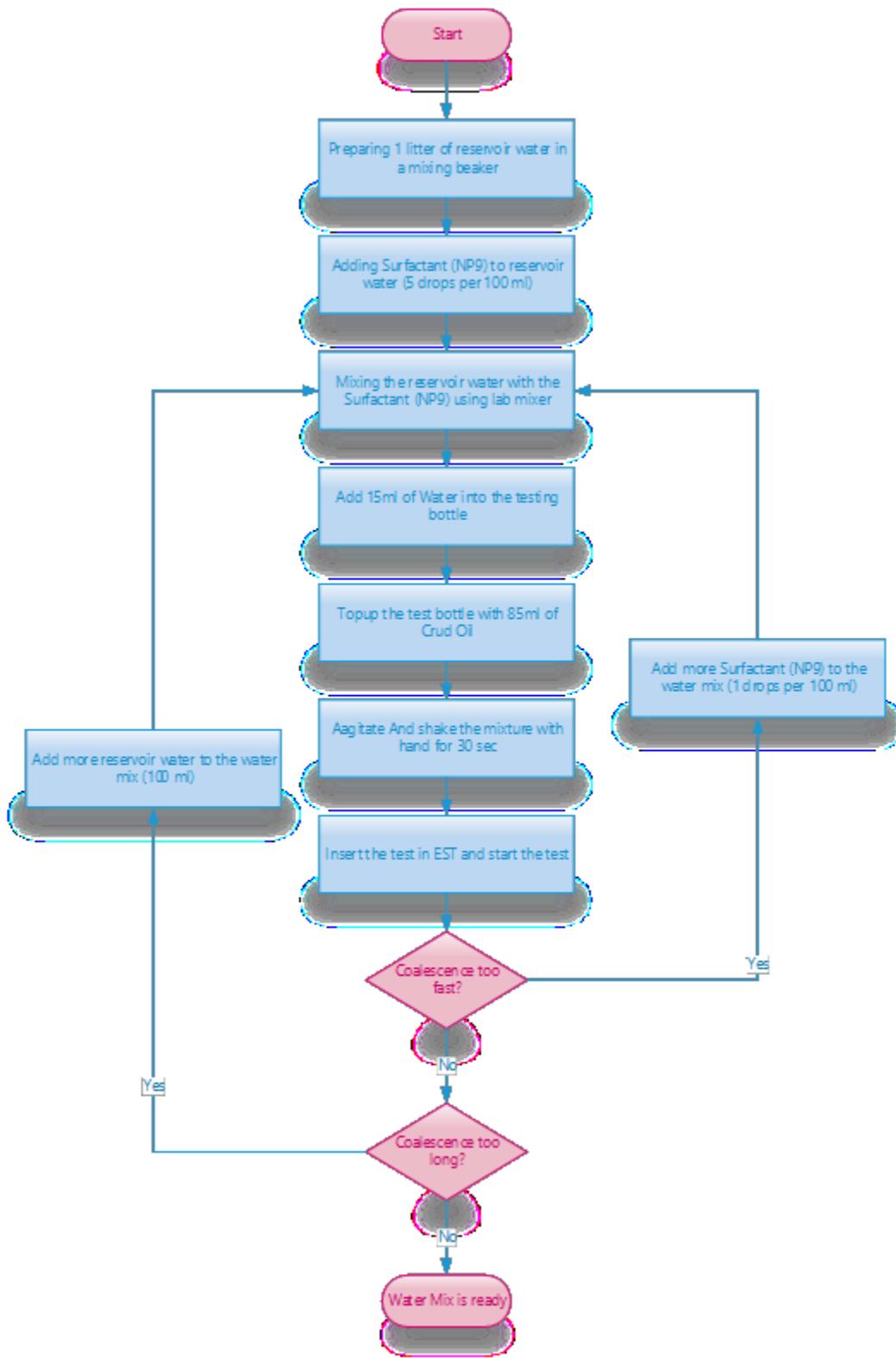


Figure 3-14: Flow chart showing the reservoir water mix process with the surfactant.

The steps below include the measurements utilized to create an acceptable oil/water mixture:

Step 1: Add 15ml of water-NP9 mix in a 100ml test bottle 1;

Step 2: Add 15ml of water-NP9 mix in a 100ml test bottle 2;

Step 3: Add 85ml of crude oil Test Bottle 1;

Step 4: Add 85ml of crude oil Test Bottle 2;

Step 5: Seal both bottles;

Step 6: Hand agitate both bottles at the same time (one with the right hand and the other with the left hand) for 30 secs;

Step 7: Unseal and measure the mix temperature of both bottles.

CHAPTER 4 EXPERIMENTAL RESULTS

The purpose of this chapter is to illustrate the results obtained by using AC and DP type voltages on two different cells one of the cells is exposed microwave irradiation and the other is cell is not, whereas both cells were exposed to electrostatic voltage from the EST. The energy consumed to achieve the purpose of the experiment was explored as well. To ensure consistency in the results and eliminate any odd measurement, all the tests were repeated three times and the results were tabulated in this chapter. This approach will increase the confidence of the measurements. The collected results based on the emulsion's resolution included:

- Electro-coalescence time from EST chart (voltage & current vs. time).
- The difference in fluid temperature before and after the test.
- Water separation percentage at 1 min, 5 min and 10 min.

4.1 Research Methodology

The experiment was designed with a set of tests which were grouped based on the EST's type of electrical voltage and the microwave irradiation time. The objectives of Groups 1 and 2 are summarized in Table 4-1, which illustrates the group number, type of voltage used and description of Cells 1 and 2. It is important to note that although the microwave irradiation was set for certain seconds, the electrostatic current was applied for the duration of the data acquiring window (~ 6 minutes).

- Group 1: To compare the results with microwave and without microwave, at 20 and 30 seconds, using AC Voltage.
- Group 2: To compare the results with microwave and without microwave, at 20 and 30 seconds, using Dual Polarity voltage.

Table 4-1: Tabulating illustrates the group number, type of voltage used and description of Cells 1 and 2.

Group	Voltage	MW Time	MW Power	Cell 1	Cell 2
1	AC	20 Sec	100%	EST & MW	EST
	AC	30 Sec	100%	EST & MW	EST
2	DP	20 Sec	100%	EST & MW	EST
	DP	30 Sec	100%	EST & MW	EST

4.1.2 Electro-Coalescence Time

To obtain the electro-coalescence time, EST device is equipped with a USB interface to connect to the computer, a custom-made software (NATCO Basic EST V1.0) which was developed by Cameron was utilized to record all the measurements digitally. The software will visually present a graphical chart of Voltage (kV) and Current (mA) of both cells vs. time, which will indicate the electro-coalescence time.

In the beginning of each experiment, the applied voltage will induce an electrical current due to the suspended water droplets in the emulsion, gradually the electrical current will start dropping and voltage will start to ramp up. The drop of the current between the two-sided electrode correlates with the existing small water droplets in the emulsion. Once the droplet settles below the electrode level, electrical current will drop to the lowest value, as close as zero.

To unify the critical point of the electro-coalescence time for all experiments, the maximum value of both the electrical current and voltage will be normalized from 0 to 1.

The half value of the normalized electrical current will be used to determine the electro-coalescence time of each cell.

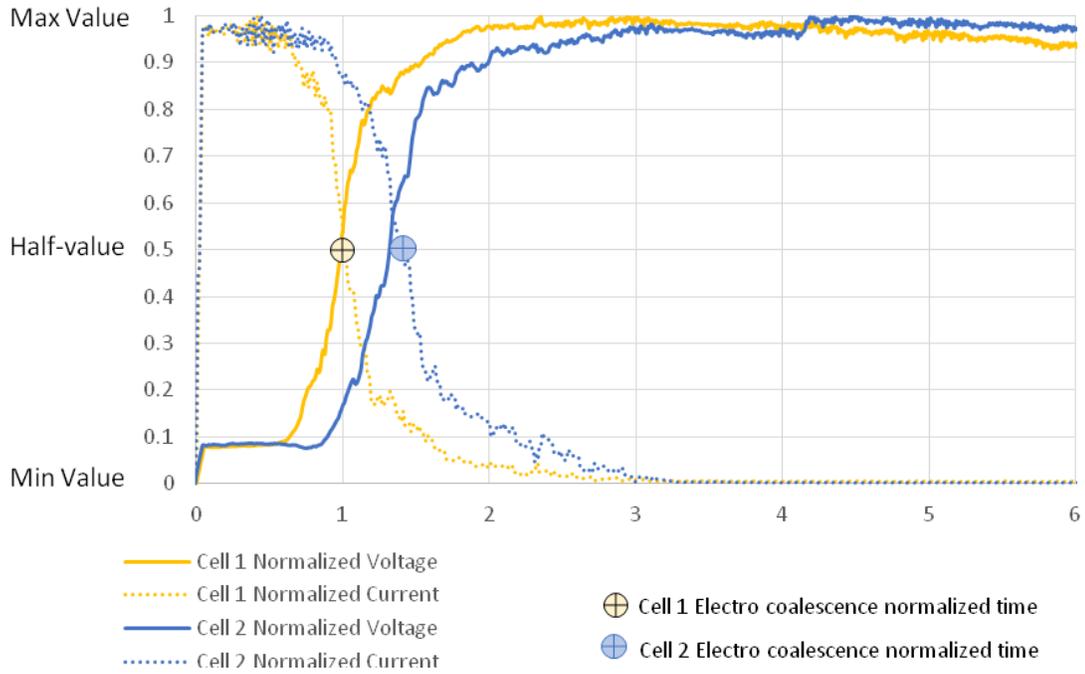


Figure 4-1: Electro-coalescence normalized time measured from halftime of the normalized current value.

For ease of understanding the color-coding representation of each curve and the bottle sticker, Table 4-2 summarizes the colors and their definitions:

Table 4-2: Summary of colors utilized for Cells 1 and 2, with their respective devices, current and volts.

Cell	Device	Current mA	Volt kV	Bottle Sticker
Cell 1	MW & EST	Dotted Orange	Solid Orange	● Yellow
Cell 2	EST	Dotted Blue	Solid Blue	● Blue

4.1.3 Relative performance:

To quantify the improvement percentage, the following relative change formula will be used, which is shown in Equation (4-1). For instance, if Cell 1 took 20 seconds to complete the coalescence and Cell 2 took 60 seconds, by utilizing Equation (4-1), this would indicate that Cell 1's coalescence time is faster by 66.6% than Cell 2.

$$\frac{|Actual\ Change|}{Reference} = \frac{|\Delta\ Time|}{Longest\ Time} = \frac{|Cell\ 2\ Time - Cell\ 1\ time|}{Cell\ 2\ time} \times 100 \quad (4-1)$$

The same equation will be utilized to calculate the relative energy consumption performance too.

4.1.4 Change in Temperature

The temperature difference will represent the driving force for this experiment. The temperature of the mixture was obtained at the beginning and the end of the experiment for Cells 1 and 2 and was recorded by a digital thermometer in degrees Celsius. The customized apparatus (microwave with EST) did not include thermocouples in the cavity to record accurate final temperatures. Hence, the temperatures obtained at the end of the experiments (T_2) were inaccurate. The inaccuracy stems from the delay that occurred until the final temperatures were recorded, meaning the final temperatures recorded by the digital thermometer were lower than expected. To remedy the problem or obtain more accurate results, the final temperatures were theoretically computed through Newton's law of cooling (UBC, 2009).

For this experiment, Newton's law would suggest that the temperature difference of the

emulsion is directly proportional to the temperature difference between the emulsion mixture and the surroundings. Equation (4-2) shows the differential equation of the change in temperature of the emulsion mixture with respect to time (UBC, 2009):

$$\frac{d\Delta T}{t} \propto (T - T_s) \quad (4-2)$$

Where ΔT is the change in temperature of the emulsion mixture in °C, T will represent the temperature at a specific time; it will be the temperature of the surroundings in °C. The final form of Equation (4-2) will be represented by Equation (4-3) below, where k is a positive constant obtained experimentally by heating the mixture and recording the heat loss for 20 minutes that governs the rate of cooling and is obtained by taking the natural logarithm of Equation (4-3) for a specific time and emulsion mixture (UBC, 2009), from the Table 4-3 (k) was found to be 0.00072.

$$T(t) = T_s + (T_0 - T_s)e^{-kt} \quad (4-3)$$

Table 4-3: Tabulating the heat loss temperature to the ambient.

Time (min)	Temp (°C)
1	42.5
2	41.7
3	40.6
4	39.4
5	38.1
6	37.2
7	36.3
8	35.6
9	34.9
10	34.2
15	31.8
20	29.9

4.1.4 Calculated Consumed Energy

The net consumed energy was computed and tabulated for all the tests of both groups; 1 and 2. The total net consumed energy was calculated from different sources of energy on both cells (gain and loss):

Cell 1:

Electrical current induced energy calculated from the summation of the electrical current multiplied by the voltage divided by the time interval.

$$Q_{electrical} = \sum_{t=0}^{t=max} \frac{I \cdot V}{dt} \quad (4-4)$$

Q is electric charge in coulombs

t is time in seconds

I is electric current in amperes

V is electric potential or voltage in volts

$$\Delta T_{electrical} = \frac{Q_{electrical}}{M_{mix} \cdot C_{mix}} \quad (4-5)$$

Q is electric charge in coulombs

M_{mix} is mass of the mixture

C_{mix} is the heat capacity of the mixture (J/K)

Heat loss to the ambient temperature during the test period (~6 minutes), calculated from Newton's law as per 4.1.4 after subtracting the electrical induced energy.

Microwave heat energy Q_{MW} , will be calculated from microwave induced temperature ΔT_{MW} which is obtained from the addition of the net heat loss to T2 and subtracting the electrical induced temperature and subtracting T1.

$$\Delta T_{MW} = \Delta T_{Cell\ 1} - \Delta T_{electrical} + T_{Heat\ Loss} \quad (4-6)$$

$$Q_{MW} = M_{mix} \cdot c_{mix} \cdot \Delta T_{MW} \quad (4-7)$$

Cell 2:

By utilizing Equations (4-4) and (4-5), electrical current induced energy was calculated from the summation of the electrical current multiplied by the voltage divided by the time interval.

Heat gain from the EST block heater (was set at 120° F, 48.8° C) Q_{Block} was calculated directly from Cell 2 ΔT with subtracting the electrical induced temperature $\Delta T_{electrical}$; this is shown in Equations (4-8) and (4-9).

$$\Delta T_{Block} = \Delta T_{Cell\ 2} - \Delta T_{electrical} \quad (4-8)$$

$$Q_{Block} = M_{mix} \cdot c_{mix} \cdot \Delta T_{Block} \quad (4-9)$$

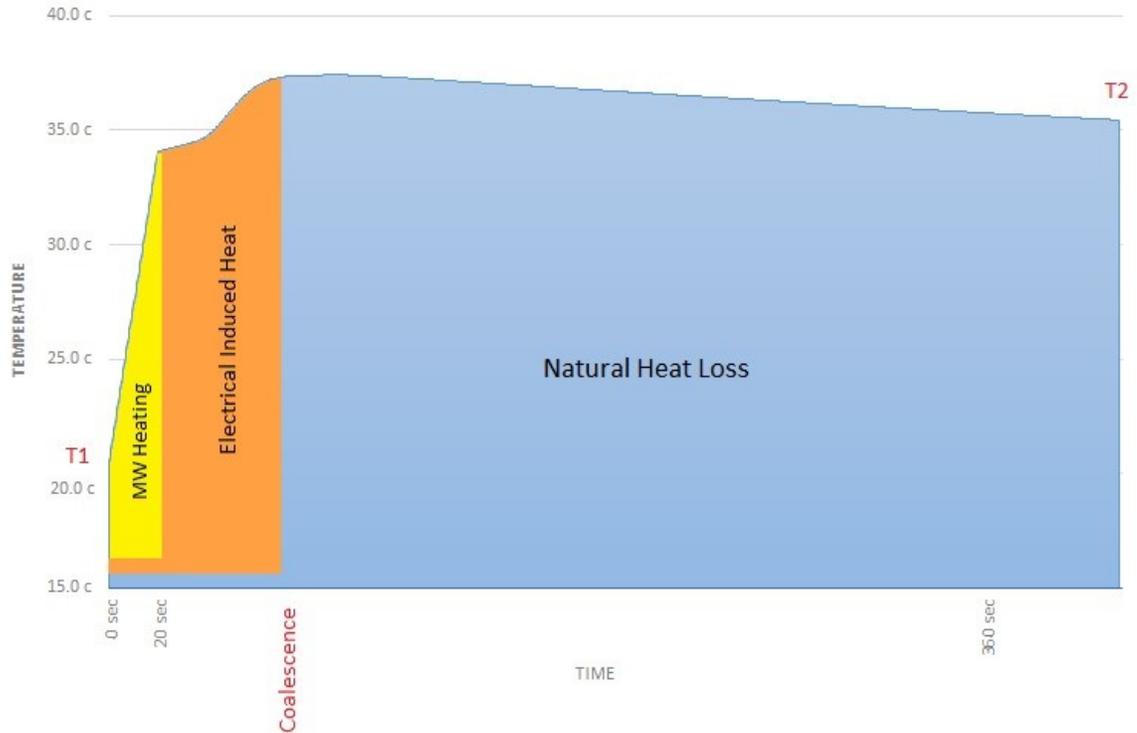


Figure 4-2: Typical temperature profile of microwave exposed cell; first 20/30 second of rapid heating due to the MW energy, electrical induced temperature increasing as long as there is a current flowing, with time heat loss will drop the temperature to ambient (calculated from Test #1).

4.1.6 Energy Efficiencies

Most conventional domestic microwave ovens perform at 60 % efficiency (Fang et al., 1988). By multiplying the efficiency and power output of the domestic microwave, the energy consumed in Watts is obtained, and thus, by considering the operational time of the microwave, the consumed energy is obtained in Joules; this is shown in Equation (4-10).

$$Energy_{MW} = \eta(Energy Output) time_{operational} \quad (4-10)$$

Assuming most industrial (liquid-liquid) heat exchanger efficiency is around 90%, such as Shell and Tube or plate exchanger. Therefore, all the observed heat energy from the EST's block heater will be divided by 0.9 to represent actual generated heat energy.

It was noticed the average absorbed MW energy varied with the type of the voltage, Group 1 (AC) had an average of 73 Watts of observed MW power, whereas Group 2 (DP) had 153 Watts. Assuming this variance is mainly related to the water droplets distribution in the emulsion, DP voltage creates larger water droplets than the droplets from the AC voltage, which is attracting more dielectric heating. To compare the energy performance among the tests, the highest recorded microwave power (170.09 Watts - Test #10) will be used as the base line of the generated microwave energy in the cavity of the domestic microwave. As mentioned earlier, the efficiency of the microwave oven is 60%, in all future calculations 283.49 Watts ($170.09 \text{ watts} \div 60\%$) will be assumed as fixed MW power for all the tests.

4.1.7 Microwave Penetration Depth:

Microwave Penetration Depth (Dp) refers to how deeply the Microwave energy can penetrate a material, which is dependent on the frequency as well as the material's properties (ϵ') and (ϵ''). Penetration is considered infinite in material that transparent to microwave energy, and is considered zero in reflective material, such as metals. If the penetration depth is much less than the thickness of the material only the surface is heated, and the rest of the sample is heated through conduction.

Since the lab formed emulsion is a mix of 15 ml of reservoir water with diluted emulsifier and 85 ml of dead oil, future calculations will consider only the waters' and oils' dielectric properties, as the emulsifier makes less than 1% of the emulsion, therefore it is negligible.

The dielectric constant (ϵ') and loss factor (ϵ'') of light petroleum oils are in the ranges of 2.0 to 2.2 and 0.001 to 0.005, respectively at 2.45GHz (Fang et al., 1995).

Whereas the relative electric permittivity of fresh water at 20° C under the effect of 2.45 GHz frequency is $\epsilon' = 78$ and $\epsilon'' = 12.48$, but the dielectric properties of salt-water solutions such as the reservoir connect water has lower electrical permittivity, it is estimated for

reservoir water to ranges between 45 to 65, at higher salt concentrations, the dielectric decrement is observed to saturate at about $\epsilon' = 45$ and $\epsilon'' = 18$ (Hasted, 1948)

To calculate the dielectric constant (ϵ') and loss factor (ϵ'') of water in oil emulsions, the best predictive equation (4-11) by Lichtenecker and Rother (U. Erle, 2000):

$$\ln \epsilon_{mix} = (\phi_2 \times \ln \epsilon_2) + ((1 - \phi_2) \times \ln \epsilon_1) \quad (4-11)$$

By mixing 85% oil and 15% water, we will result in dielectric constant (ϵ') = 3.325 and loss factor (ϵ'') = 0.554

$$Dp = \frac{\lambda}{2\pi \times \tan \delta \sqrt{\epsilon'_{mix}}} \quad (4-12)$$

for 2.45 GHz $\lambda = 12.23$ cm

$$Dp = 1.947 \times \frac{\sqrt{\epsilon'_{mix}}}{\epsilon''_{mix}} = 6.4 \text{ cm} \quad (4-13)$$

With microwave penetration depth $Dp \sim 6.4$ cm it is believed to go through the emulsion's test cell (1 inch diameter), and they should reach the other side of the cavity of the domestic microwave and reflect until radiation is discontinued.

4.2 Group 1 – Results

EST device was set to provide AC voltage across the two test tubes' electrodes, the behavior of the AC voltage was explored in this chapter.

This group will simulate widely used electrostatic technology in the oil and gas industry which have been introduced in the past 70 years. In this test, both cells 1 and 2 (test bottles)

were exposed to the same voltage, whereas Cell 1 was additionally exposed to the microwave irradiation. The EST voltage was continuously running during the test for ~6 minutes. The microwave irradiation time will be set in two different intervals, 20 and 30 seconds from the beginning of the test, both timings were presented individually. Table 4-4 below summarizes the desired results, as previously mentioned, each experiment contained 3 sets of tests. The reason for this stems from the mixing of the crude oil and the water mixture. Although the mixtures created for each test were stable, they were not identical to one another; hence the illustration of three data sets rather than the average of the three.

Table 4-4: Group 1 summarized recorded results the coalescence time, change in temperature, water separated at 1, 5 and 10 mins.

Microwave time (sec)	Test Number	Cell Number	Type of Voltage	Coalescence time (sec)	ΔT (°C)	Separated Water (mL)		
						1 min	5 min	10 min
20	1	1	AC	48.91	9.9	3	10	11
	1	2	AC	78.25	16.6	3	10	11
	2	1	AC	38.72	8.5	3	9	10
	2	2	AC	53.48	17.5	2	9	10
	3	1	AC	65.97	10.5	2	8	10
	3	2	AC	100.14	19.6	2	7	9
30	4	1	AC	67.23	15.2	1	6	8
	4	2	AC	73.20	17	2	7	7
	5	1	AC	60.00	11.6	1	7	8
	5	2	AC	72.00	14.2	1	8	8
	6	1	AC	56.03	13.3	1	8	9
	6	2	AC	62.78	15.3	1	7	9

4.2.1 Consumed Energy

The net consumed energy obtained for Group 1 for an AC voltage type, was calculated and tabulated below in Table 4-5:

Table 4-5: Net calculated energy for Group 1, for operational time of 20 and 30 seconds.

MW Time (sec)	Test Number	Cell Number	Type of Voltage	Electrical Current Energy (J)	MW Absorbed Energy (J)	Block Heater Energy (J)	Total Consumed Energy (J)	MW Absorbed Power (Watt)
20	1	1	AC	1131.81	2743.61		3875.43	82
	1	2	AC	1501.33		2315.75	3817.09	
	2	1	AC	1060.85	2080.17		3141.02	62.40
	2	2	AC	1373.05		2674.28	4047.33	
	3	1	AC	1472.59	2298.68		3771.27	68.96
	3	2	AC	1931.01		2558.31	4489.32	
30	4	1	AC	1447.20	4330.32		5777.52	86.61
	4	2	AC	1584.77		2319.04	3903.81	
	5	1	AC	1248.1	3068.8		4316.91	61.38
	5	2	AC	1851.5		1396.3	3247.81	
	6	1	AC	3854.55	1241.95		5096.50	77.09
	6	2	AC	2136.00		1369.90	3505.91	

4.2.2 Coalescence Time

The coalescence time was obtained from the EST's generated MS Excel data set; it was estimated based on the half time of the normalized electrical current values.

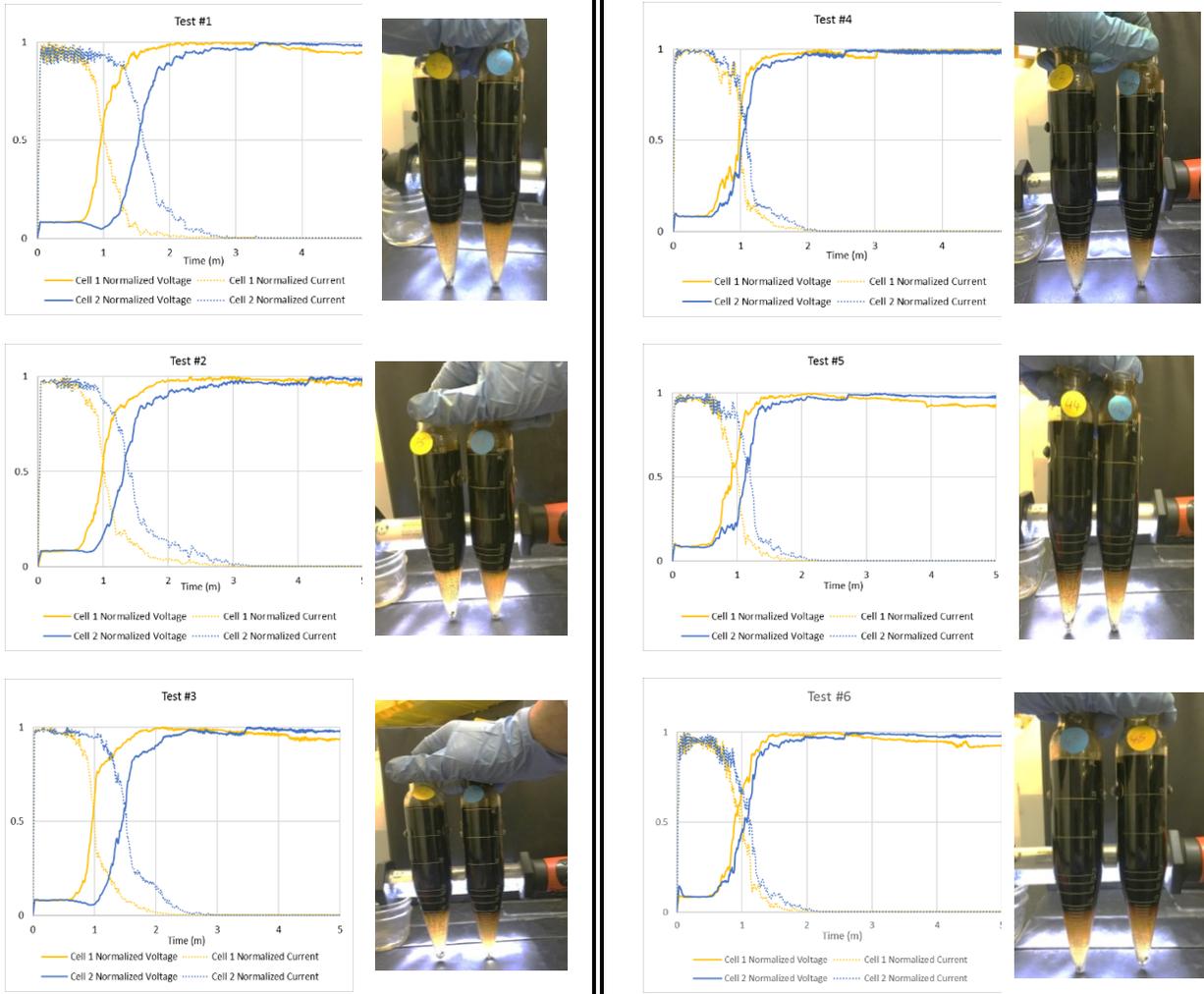


Figure 4-3: EST results plot of Test 1-6, and the picture of the test bottles after 10 min (Cell 1: Yellow tag, Cell 2: Blue tag) and linearized experimental values for cell’s half time and power under AC voltage.

Table 4-4, Table 4-5 and Figure 4-3 summarize the results of the first group (AC voltage with 20 & 30 seconds of microwave irradiation). The results showed that the microwave exposed cell 1 in test #1, #2 and #3, had faster electro-coalescence by 38%, 28% and 34% with 20 seconds of microwave irradiation exposure time, nonetheless cell consumed additional energy enhance the performance by 43.9%, 39.9% and 37.1% respectively. The visual clarity of the separated water in test #1, #2, & #3 of cell 1 looked clearer than Cell 2.

For the second part of the group, test #4, #5 & #6; cell 1 demonstrated faster electro-coalescence by 8.2%, 16.7% and 10.8% with 30 seconds of microwave irradiation exposure time with additional energy consumption of 60.8%, 66.7% and 64% respectively. The visual clarity of the separated water in test #4, #5, & #6 of cell 1 looked very similar to cell 2, other than some oil channels and droplets stick on the bottle sidewall of cell 1.

4.3 Group 2 – Results

In this test group the EST device was set to utilize DP voltage (half-wave DC) instead of the AC voltage. Using the same dependable AC power supply as a conventional electrostatic treater, the DP splits the high AC voltage with rectifiers into positive and negative components. Both test bottle electrodes were charged in opposition and exposed to the same voltage, whereas Cell 1 was exposed to microwave irradiation. The EST voltage was continuously applied during the test for ~6 minutes. Group 2 tests will follow the same experimental procedure and objectives as Group 1 tests. Table 4-6 summarizes the results:

Table 4-6: Summary of Group 2 recorded test results.

Microwave time (sec)	Test Number	Cell Number	Type of Voltage	Coalescence time (sec)	ΔT (°C)	Separated Water (mL)		
						1 min	5 min	10 min
20	7	1	DP	22.42	12.4	3	13	14
	7	2	DP	51.66	14.1	2	11	13
	8	1	DP	20.68	10.8	4	13	15
	8	2	DP	54.87	13.4	2	12	14
	9	1	DP	36.20	13.7	1	10	13
	9	2	DP	59.67	16.4	0.5	6	11

Microwave time (sec)	Test Number	Cell Number	Type of Voltage	Coalescence time (sec)	ΔT (°C)	Separated Water (mL)		
						1 min	5 min	10 min
30	10	1	DP	49.32	21.3	1	15	15
	10	2	DP	89.89	12.7	0.5	5	12
	11	1	DP	40.98	19.7	2	14	15
	11	2	DP	95.08	12.1	1	6	14
	12	1	DP	46.15	21.1	1	15	15
	12	2	DP	102.24	12.4	0.5	5	12

4.3.1 Consumed Energy

The net consumed energy obtained for Group 2 for a DP voltage type, is tabulated below:

Table 4-7: Calculated consumed energy for Group 2, for operational time of 20 and 30 seconds.

MW Time (sec)	Test Number	Cell Number	Type of Voltage	Electrical Current Energy (J)	MW Absorbed Energy (J)	Block Heater Energy (J)	Total Consumed Energy (J)	MW Absorbed Power (Watt)
20	7	1	DP	433.28	4954.61		5387.89	148.64
	7	2	DP	848.4		2438.94	3287.34	
	8	1	DP	453.9	4192.1		4646.00	125.76
	8	2	DP	798.0		2327.8	3125.82	
	9	1	DP	677.93	5047.01		5724.95	151.41
	9	2	DP	1014.33		2808.87	3823.20	
30	10	1	DP	722.67	8504.66		9227.33	170.09
	10	2	DP	1229.78		1681.50	2911.28	
	11	1	DP	670.91	7768.99		8439.90	155.38
	11	2	DP	1194.0		1577.24	2771.26	
	12	1	DP	693.3	8357.87		9051.22	167.16
	12	2	DP	1283.09		1550.27	2833.36	

4.3.2 Coalescence Time

Like Group 1, the coalescence time was obtained from the EST's generated data set.

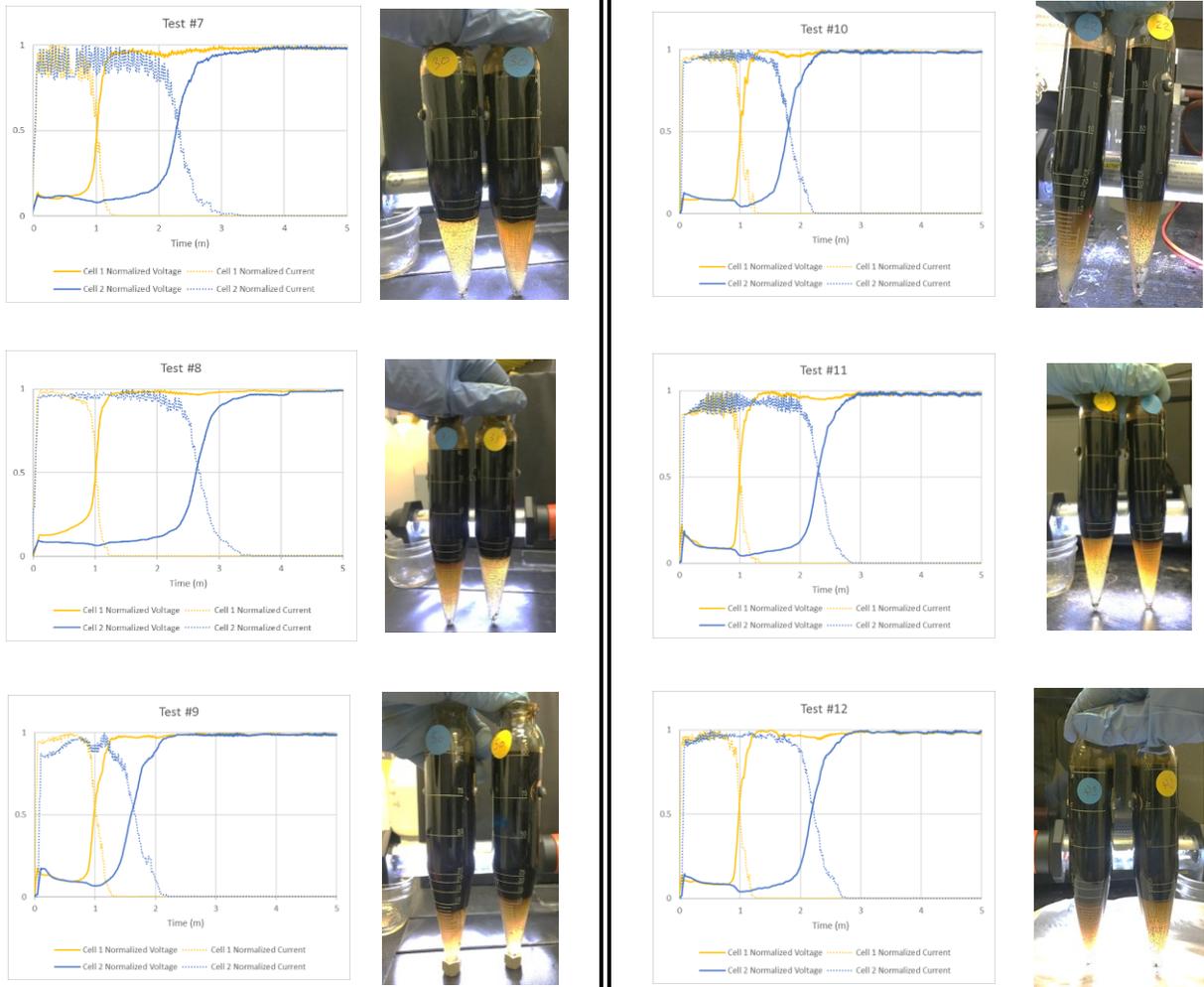


Figure 4-4: Group 2 EST results plot of Test 7-12, and the picture of the test bottles after 10 min (Cell 1: Yellow tag, Cell 2: Blue tag) and normalized experimental values for cell's half time and power under DP voltage.

Table 4-6, Table 4-7 and Figure 4-4 summarize the results of the second group (DC voltage with 20 & 30 seconds of microwave irradiation). The results showed that the microwave exposed cell 1 in test #7, #8 and #9, had faster electro-coalescence by 56.6%, 62.3% and 39.3% with 20 seconds of microwave irradiation exposure time, cell achieved that

enhancement with additional energy consumption of 46.1%, 49% and 39.8% respectively. The visual clarity of the separated water in test #7, #8, & #9 of cell 1 looked distinctly clearer than Cell 2

For the second part of group 2, test #10, #11 & #12; cell 1 demonstrated faster electro-coalescence by 45.1%, 56.9% and 54.9% with 30 seconds of microwave irradiation exposure time with additional energy consumption of 68.4%, 69.8% and 69.2% respectively. The visual clarity of the separated water in test #10, #11 & #12 of cell 1 looked slightly clearer than cell 2.

CHAPTER 5 DISCUSSION

This chapter will discuss the results from Chapter 4 and will focus on the effect of the two different types of voltage (AC or DP) on the electro coalescence time vs. the energy consumption. Data consistency was evaluated to observe any anomalies or patterns in the experimental results, followed by an examination and discussion of the non-thermal effect of microwave energy, the viability of the new technique combining two dehydration technologies, the water separation results, and the environmental footprint of the microwave heating method for oil/water separation in the oil production process.

5.1 Data Consistency

The collected data from Groups 1 and 2 have been plotted on top of each other to observe any anomalies or pattern. The curves are plotted after subtracting the difference in the coalescence time.

Although there are differences in the microwave irradiation time in each group and other experimental variables, i.e., initial temperature, surfactant NP-9 percentage in the mix, the plotted curves showed a very strong coherence. This strong coherence increases the confidence level in the measurements.

The results of the microwave heat rate of the emulsion correlate with similar work that had been conducted by Nour et al. (2010) whereas a mix of 20/80 emulsion had been heated for 20 second with 900W domestic microwave.

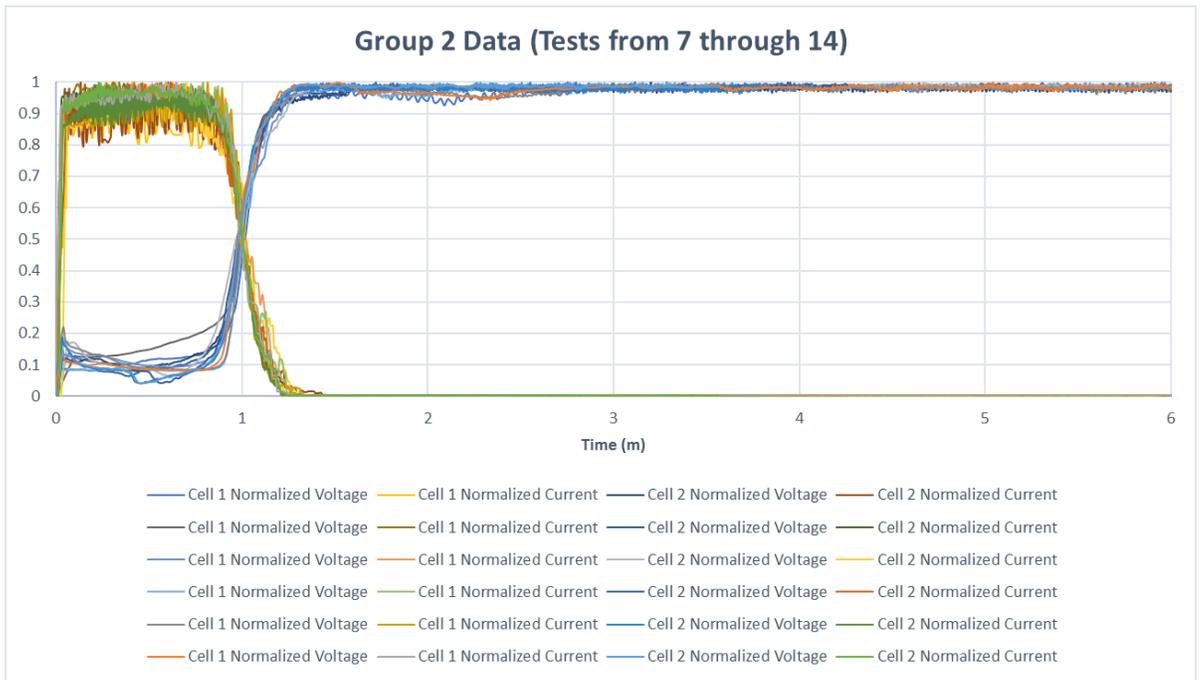
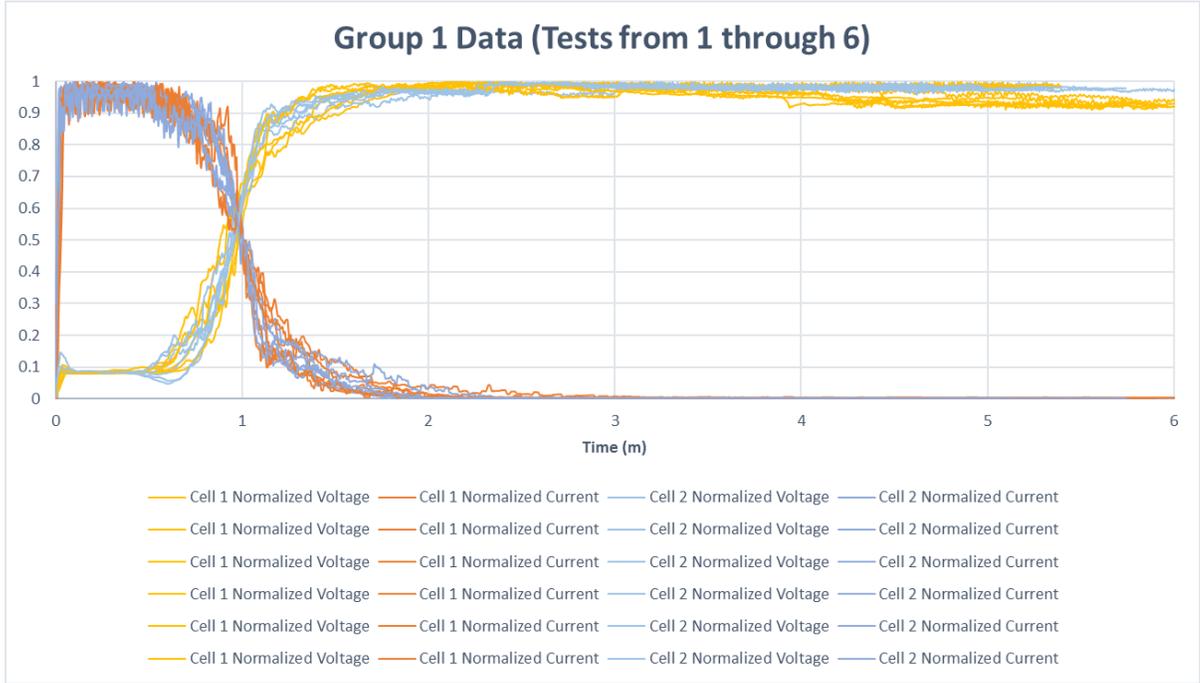


Figure 5-1: Overlay of the curves of all results from Group 1 and Group 2 increase the confidence in the collected data.

5.2 Non-thermal Effect

The microwave radiation is a dielectric heating technique which works at the molecule level, and provides fast, volumetric and selective heating that increase the performance of the electro-coalescence process. The results showed an outstanding improvement in the coalescence rate of the microwave exposed cell with electrostatic field versus the electrostatic cell only.

Figure 5-2 represents the results of the experiments conducted for two different microwave irradiation intervals (20 and 30 seconds) with two electrostatic voltages (AC and DP); undoubtedly the performance of the separation's efficiency was improved, as evident in the faster coalescence process in all experiments.

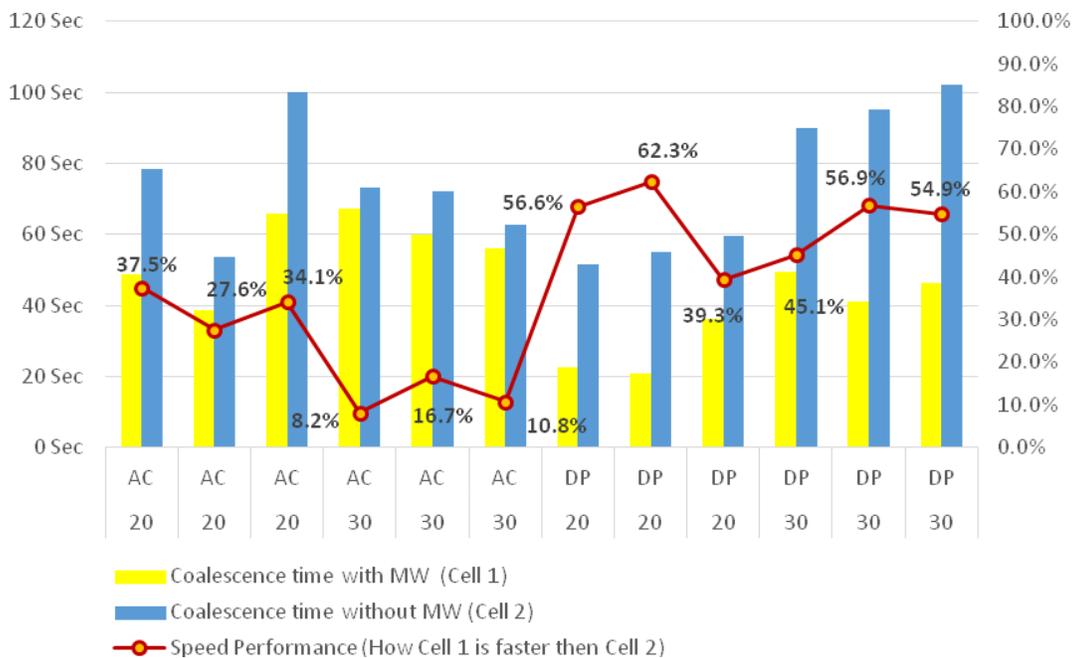


Figure 5-2: Coalescence time with and without microwave, along with the speed performance for Cell 1 and 2 under AC and DP voltages for 20 and 30 seconds.

As mentioned in 2.5 the hypothesis of non-thermal microwave effect to enhance oil/water separation process was noticeable with the Group 2 (DP) voltage. Although the existence of the non-thermal effect has not been proven to be conclusive (de la Hoz et al., 2005), evidence of it has been traced in this experiment.

It was observed from Table 5-1, that 20 seconds of microwave irradiation combined with DP voltage resulted (average) 52.7% faster coalescence time with only (average) 12.3C ΔT . Although the 30 seconds of microwave irradiation had higher ΔT , but it showed similar impact on the coalescence performance as the 20 seconds of microwave with DP voltage (average) 52.3% faster coalescence time.

This phenomenon can be referred as Specific Microwave Effect which is considered a non-thermal effect of microwave energy and associated with the selective absorption of energy by polar molecules (de la Hoz et al., 2005) (Loupy, 2001).

In this research, this phenomenon can be explained as the initial 20 seconds of the microwave irradiation penetrated the emulsion and selectively polarized and aligned the water molecules, which assisted the electrostatic field to combine as much as possible of dispersed water droplets to form larger droplets and accelerate the gravity settlement. Furthermore, the microwave energy's oscillation increased the water droplet's temperature selectively which corresponds to the droplet's shape deformation, weakening the surface tension of the droplets (Zagnoni et al., 2010).

Table 5-1: Average coalescence performance verses the ΔT ($^{\circ}\text{C}$) of group 2.

Group	Test Number	Coalescence Speed Performance	ΔT ($^{\circ}\text{C}$)
DP 20 Sec MW	7	56.6%	12.4
	8	62.3%	10.8
	9	39.3%	13.7
Average		52.7%	12.3
DP 30 Sec MW	10	45.1%	21.3
	11	56.9%	19.7
	12	54.9%	21.1
Average		52.3%	20.7

To confirm this observation, two more experiments were conducted by injecting initial thermal energy to the samples before conducting the test in order to compare the performance, the assumption; if the microwave thermal heating was responsible of the performance enhancement, by increasing the initial temperature, the expected results to be reversed.

Results were tabulated in Table 5-2. In the first experiment, a non-microwave exposed sample was pre-heated to 33.0°C , to maintain an initial ΔT between both cells 11.2°C . Results showed the non-microwave cell managed to complete the coalescence at a rate of 9.95% faster.

In the second experiment, both samples were preheated while maintaining ΔT above 10°C , and results showed the non-exposed microwave irradiation cell managed to complete the coalescence at a rate of 7.8% faster.

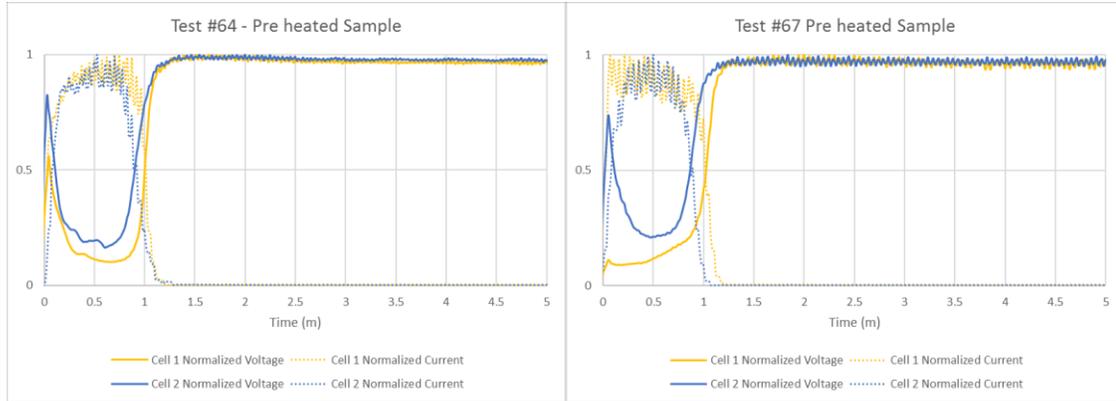


Figure 5-3: EST plot of Test 13 & 14 normalized experimental values for pre heated cell's half time and power under DP voltage.

Although the pre-heat's thermal effect was present, its influence on the coalescence was not as strong as it was with the results of Group 2. These results indicate the non-thermal effect of the microwave in enhancing the electro coalescence process.

Table 5-2: results of two experiments showing the coalescence performance for pre-heated samples.

Test Number	Cell Number	Microwave time (sec)	Type of Voltage	T1 (°C)	T2 (°C)	ΔT (°C)	Coalescence time (sec)	Coalescence time Performance
13	1	20	DP	21.8	32.4	10.6	22.11	
13	2	0	DP	33.0	41.3	8.3	19.91	9.95%
Δ				11.2	8.9		2.2	
14	1	30	DP	30.2	40.4	10.2	25.46	
14	2	0	DP	40.3	42.4	1.9	23.47	7.82%
Δ				10.1	2		1.99	

To address the non-thermal affect from different prospective, the thermal effect was quantified by calculating the terminal (Settling) velocity of the water droplets from Stoke's law and compared to the electro-coalescence results.

$$v_g = \frac{d^2(\rho_w - \rho_o)}{18\mu}g \quad (5-1)$$

Where:

V_g is terminal (settling) velocity (m/s)

d is water droplet diameter (m)

ρ_w is particle (water) density (kg/m³)

ρ_o is liquid phase (oil) density (kg/m³)

μ is liquid phase viscosity (kg/m.second)

g is gravitational acceleration (m/s³)

The terminal velocity is directly proportional to the difference of the two fluid's density ($\rho_w - \rho_o$), also it is inversely proportional to the viscosity (μ) of the continues phase, since both; density and viscosity values are susceptible to the temperature change, consequently; thermal effect can be traced through terminal velocity's calculation, given that both cells contains the same emulsion, therefore similar droplet diameters (d).

Due to the lack of the microscopic droplet diameters size, the ratio of Terminal velocity (v_g) to the power of droplet diameter (d^2) was considered as a comparing factor (v_g/d^2).

Specific gravities of oil were calculated according to the temperature change from the empirical formula:

$$SG_T = SG_{20} - (5.93 \times 10^{-4}) \times (T - 20) \quad (5-2)$$

Where:

SG_T = Specific Gravity of Crude Oil at Temperature (T °C)

SG_{20} = Specific Gravity of Crude Oil at Temperature (20°C)

Although there are several charts, empirical and semi-empirical correlations to estimate dead oil viscosity from Specific Gravity and Temperature, for the purpose of this compression, Alomair (2015) dead oil viscosity (μ_{od}) model equation (5-3) was used:

$$\ln(\mu_{od}) = \hat{a} + \frac{\hat{b}}{T^2} + \hat{c} (\rho_{od}^2) \ln \rho_{od} \quad (5-3)$$

Where:

μ_{od} is dead oil viscosity in Centipoise (cP)

T is max recorded temperature – T2 (°C)

ρ_{od} is density of oil (g/cm³) at temperature T2, calculated from equation (13)

\hat{a} is constant = 7.93

\hat{b} is constant = 309.60

\hat{c} is constant = 61.51

Table 5-3: From the equations (5-1), (5-2) & (5-3), Terminal velocity (v_g) / droplet diameter (d^2) of test #13 and #14 was calculated to compare on the settling velocity vs coalescence time enhancement.

Test	Cell	Volt.	Coalescence time	MW Time	T1	T2	Oil sg @ Avg (T1, T2)	Oil μ @ T2	Water ρ	V_g / d^2	Settlement Performance	Coalescence time Performance
			Seconds (s)	Seconds (s)	(°C)	(°C)		cP	g/cm ³			
13	1	DP	22.3	20	21.8 c	32.4 c	0.8532	3.4613	1095.6	38133.2	39.2%	10.7%
14	2	DP	19.9	0	33.0 c	41.3 c	0.8450	2.1357	1091.2	62752.0		
14	1	DP	25.5	30	30.2 c	40.4 c	0.8465	2.3041	1091.2	57812.5	24.5%	7.8%
14	2	DP	23.5	0	40.3 c	44.2 c	0.8409	1.7632	1089.0	76604.8		

Table 5-3 confirms based on the calculated viscosity and density, that thermal effect was expected to enhance the separation performance by 39.2% (test #13) and 24.5% (test #14), but with the microwave energy, it was only 10.7% (test #13) and 7.8% (test #14).

The calculated difference of (v_g / d^2) between both cells were less than the measured electrostatic coalescence difference, evidences that droplet diameter of the microwave exposed cells were larger due to the enhanced coalescence caused by the microwave's electromagnetic waves. Again; this phenomenon is probably due the dipolar molecule polarization and magnetization under the microwave electromagnetic.

Even though there was slight improvement with the Group 1 (AC) performance, the same non-thermal effect was not observed; probably the AC voltage is not effective with the small dispersed water droplet, and the microwave molecule alignment did not help much neither in the 20 seconds nor with the 30 seconds of irradiation. Likely the noticeable coalescence time improvement was due to the rapid microwave heating only.

For the sake of comprehensiveness, it is equally important to note that another salient point arising from Table 5-4; the longer the microwave irradiation interval under AC voltage, the less the performance of coalescence was observed. This observation would have been explored more experimentally, but due to the limited allocated time in the industrial lab, more experiments could not be performed.

5.3 Viability of the technique

To evaluate viability of this novel technique of combining two dehydration technologies, percentage of improvement in the coalescence was compared to percentage of added energy as it was explained in section 4.1.4.

Table 5-4 summarizes both coalescence and energy performance per each test and the average of each group. The compression of the average results of each group indicates DP

voltage with 20 seconds of microwaves irradiation time revealed the best economical results. This group achieved an average of 52.7% faster emulsion resolution, with an additional 45% of energy.

Significantly, 52% faster coalescence will reduce the retention time in the separator, which is the time emulsion is held inside the vessel for treatment, which will reduce the equipment and production cost.

This significant improvement in the coalescence time will contribute towards constructing faster, smaller and more efficient industrial oil dehydrator at the production sites.

Table 5-4: Average coalescence performance and calculated consumed energy's performance for each test and group.

Group	Test Number	Coalescence Speed Performance	Energy Consumption Performance
AC 20 Sec MW	1	37.5%	43.9%
	2	27.6%	39.9%
	3	34.1%	37.1%
Average		33.1%	40.3%
AC 30 Sec MW	4	8.2%	60.8%
	5	16.7%	66.7%
	6	10.8%	64.0%
Average		11.9%	63.8%
DP 20 Sec MW	7	56.6%	46.1%
	8	62.3%	49.0%
	9	39.3%	39.8%
Average		52.7%	45.0%
DP 30 Sec MW	10	45.1%	68.4%
	11	56.9%	69.8%
	12	54.9%	69.2%
Average		52.3%	69.1%

5.4 Water Separation

As previously discussed in sections 5.1.1 and 5.1.2, DP voltage demonstrated better results, in terms of water separation processes. The best set of data was demonstrated for Cell 1 under DP voltage for 30 seconds microwave irradiation and EST. This is due to the DP voltage creating larger water droplets, which will sediment at a faster rate than the smaller droplets from the AC voltage. Figure 5-4 illustrates the difference in sets and the previously mentioned trends.

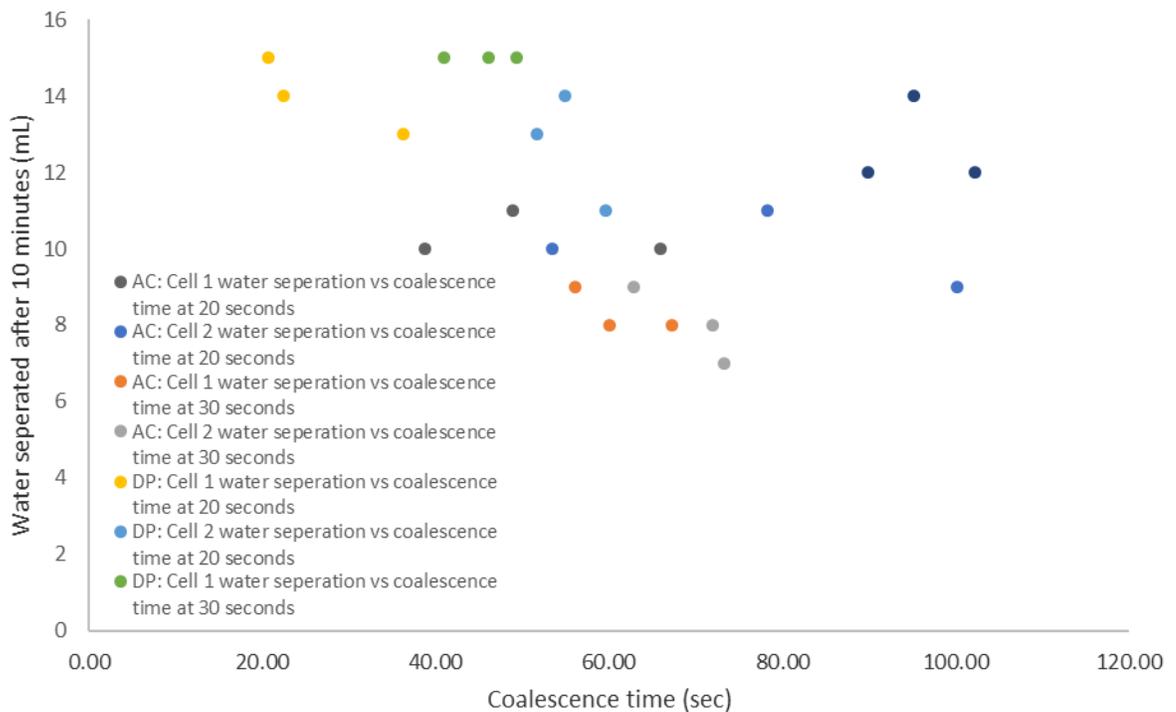


Figure 5-4: Water separated after 10 minutes with respect to the coalescence time, for Cells 1 and 2 under AC and DP voltage for 20- and 30-second irradiation time.

5.5 Environmental Footprint

Typically, the operational use of a microwave is considered as an alternative for many processes such as cracking of hydrocarbons. Microwave heating or drying is considered to have high potential for energy savings, potential to improve cost competitiveness and, potential to reduce carbon dioxide (CO₂) emissions and footprint (DOE 2015). Similarly, the electrostatic treater has the same potential except that it has low potential to improve on cost and low potential to reduce CO₂ as most electrostatic treaters require pre-heating the crude oil. Microwave is the dominant technology with regards to the operational potential; however, looking further into the life cycle analysis (LCA) of the microwave, one major problem that exists is their disposal (DOE, 2015). Microwaves became one of the highest electrical equipment of generated waste. In the EU, the total CO₂ emissions released by the microwave were almost equivalent to that released annually by cars; more focus on consumerism of microwave is implemented. It is important to note that microwaves are still being utilized on a pilot plant and laboratory scales (UOM, 2018).

A possible solution to decrease microwave CO₂ emissions and reduce its environmental footprint is the development of electric energy saving technology to be implemented in the design and structure of microwaves. Additionally, microwave disposal could be more efficient if a waste method was developed to include recycling parts for alternative use. In comparison to chemical toxins and pollutants impact on the environment, microwave energy use in oil/water separation, due to its time consumption and economic cost savings, could offset the electric energy and waste disposal issues.

CHAPTER 6 CONCLUSION

There were no dramatic findings in the field of electro-coalescence in the last decade other than Cameron's Dual Frequency. However, this research introduces a novel technique by hybridizing two demulsification techniques. This literature is focused on quantifying experimentally the dehydration process improvement of a crude oil/water emulsion, utilizing microwave energy with an electrostatic field simultaneously.

The results of this work showed that microwave radiation in combination with electrostatic field, a new technique with the unique characteristics of fast, volumetric, and selective heating, is feasible and has the potential to be used with currently existing field electrostatic treaters to enhance the demulsification process. This technique can contribute towards designing new electrostatic desalter/dehydrator with reduced retention time and improved separation efficiency.

The initial assumption was that the coalescence process will be faster by combining microwave energy with electrostatic field. The effect of microwave irradiation on a material is complex in nature and involves thermal and non-thermal (e.g. molecular mobility, field stabilization) effects. With the selective rapid microwave heating of the dispersed water, the microwave energy will polarize the water molecules, while the electrostatic field will polarize the water droplets. The improved separation times at equivalent temperatures supports the viability of this technique.

The significant findings of this research include:

- Coalescence process improvement with thermal and non-thermal effect:
Group 2 (DP voltage) with 20 seconds of microwave irradiation demonstrated significant improvement in separation relative to DP voltage alone. The initial 20

seconds of the microwave irradiation was assumed to penetrate the emulsion and selectively polarized and aligned the water molecules, assisting the coalescence process induced by the electrostatic field. Additionally, selective microwave heating of the water droplets is expected to have weakened the surface tension of the droplets and improve film drainage between adjacent droplets.

- Water separation quality

Even though the separated water quality is beyond the scope of this research, it is significant that it was observed that the visual clarity of the separated water of microwave-exposed cells looked distinctly clearer and had a faster settlement rate than Cell 2, especially with the DP voltage, which can be explained by the rapid microwave heating that enhanced the water droplet settlement by gravity.

- Viability of the technique

Granting the improvement of the coalescence time was significant, this study has questioned the viability of this approach, and a calculation of the total consumed energy, by Joules, of each group was conducted to compare the coalescence time improvement versus the total consumed energy (Fig. 29). Applying 20 seconds of microwave energy accompanied with DP voltage had the optimum coalescence time enhancement results but did require an additional 45% of energy input compared to thermal heating alone.

Final recommendation; based on the findings of this research, optimizing this hybridized technique of microwave irradiation in combination with electrostatic field needs further experimental study to examine the effect of different microwave frequencies in combination with the electrostatic field, while directing the microwave in between the two electrodes. Scaling up the experiment through pilot electrostatic test plant with microwave

energy might result in more encouraging data. Evaluating the viability of the technique with pre heating might results in different considerations. Today many of thermal microwave effects in the dehydration process have been measured and are well known, while more experiments to document and model the occurrence of the non-thermal microwave effect would be useful.

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