Using Microwave to Produce Heavy Oil Reservoirs: Experimental and Numerical Study

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Haitham A. Othman, M.Sc.

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Approved

Mohamed Y. Soliman
Chair of Committee

Waylon House

James Sheng

Mark Sheridan
Dean of the Graduate School

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ABSTRACT

This PhD dissertation presents a new technique to produce heavy oil reservoirs. This new technique may be applied to produce heavy oil reservoirs where it is difficult or insufficient to apply any of the conventional techniques. The new technique involves the use of microwave, activated carbon, and aluminum oxide. Experimental and numerical results show that this technique may significantly increase the productivity of heavy oil reservoirs. Thermal recovery is the major technique to produce heavy crude oil. Heavy oil reservoirs are heated up and as a result the oil viscosity is reduced. Consequently, it would be easier to produce oil. Currently, the major thermal recovery techniques are steam-assisted-gravity-drainage (SAGD), hot fluid injection, or in-situ combustion.

In the new technique, hydraulic fracture(s) are created in heavy oil reservoirs and filled with activated carbon. Microwave antenna(s) would be placed inside the producers or in other wells close to them. Activated carbon has significantly higher real and imaginary permittivity values than any naturally existing materials in heavy oil reservoirs, namely water, oil, and rock. Real permittivity indicates how much of the applied microwaves is absorbed by the exposed material. On the other hand, imaginary permittivity indicates the ability of the material to convert this absorbed energy into heat. As a result, activated carbon will heat up to very high temperatures when microwave irradiation is directed at it and hence it will heat up the reservoir. Numerical simulation showed that the use of activated carbon may increase the oil recovery factor between 5 and 14% when compared to the use of microwave only. Experimental results showed that activated carbon may reach a temperature of more than 800˚F in a short period of time when exposed to microwave irradiation. The time needed for water to heat up to around 200˚F is 4 times the time needed to heat the same volume of activated carbon. Also, experimental results showed that the time needed to heat activated carbon may be reduced if it is preheated by any mean then heated using microwave.

Aluminum oxide may be used to overcome the very high temperature due to the use of activated carbon. This very high temperature may affect the integrity of the well completion adjacent to the microwave antenna. The presence of aluminum oxide in the hydraulic fracture sections (as a tail-in proppant) close to the wellbore will help in lowering the temperature close to the wellbore. Aluminum oxide was selected because it has a very low imaginary permittivity. Experimental results showed that aluminum oxide has significantly lower tendency to heat up than activated carbon or water when exposed to microwave irradiation.

The new technique may be combined with fluid injection techniques to increase the recovery factor of heavy oil reservoirs. Furthermore, following certain patterns in the way wells are operated or placed may result in a further increase of the heavy oil recovered from the reservoir.

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CHAPTER I

INTRODUCTION

The number one source of energy nowadays is fossil fuel. This drives oil companies to develop and implement the best techniques to produce conventional and unconventional hydrocarbon resources. Traditional techniques may be used to produce conventional resources. On the other hand, advanced and innovative techniques should be implemented to produce unconventional ones. One of the major parts of unconventional oil resources is heavy oil. As shown in Table 1.1, according to the U.S. Geological Survey (2007) the world wide discovered original heavy oil in place is 3,366 billion barrels. That is more than double the world's estimated proven oil reserves of 1,478 billion barrels (OPEC, 2012). The major technique to produce heavy crude oil is thermal recovery. Heavy oil formations are heated up and as a result the oil viscosity is reduced. Consequently, it will be easier to be produced. Currently, the major thermal recovery techniques are steam assisted gravity drainage (SAGD), hot fluid injection, or in situ combustion.

Table 1.1 Discovered and Prospective Original Heavy Oil in Place in billion barrels (U.S. Geological Survey (2007))

Region[1]	Discovered orginal oil in place	Prospective additional	Total original oil in place
	Heavy oil		
North America.....	650	2	651
South America.....	1099	28	1127
Europe.....	75	0	75
Africa.....	83	0	83
Transcaucasia.....	52	0	52
Middle East.....	971	0	971
Russia.....	182	0	182
South Asia.....	18	0	18
East Asia.....	168	0	168
Southeast Asia and Oceania.....	68	0	68
Total.....	3366	29	3396

1.1 Steam Assisted Gravity Drainage (SAGD)

The most effective technique to produce heavy oil reservoirs is SAGD. As shown in figure 1.1, SAGD involves drilling two parallel horizontal wells in the heavy oil formation. Steam is injected through the well at the top and the injected hot steam will create a heated chamber around the injection well. As the hot steam gets in contact with the heavy oil, it reduces its viscosity and the oil drains toward the bottom horizontal well.

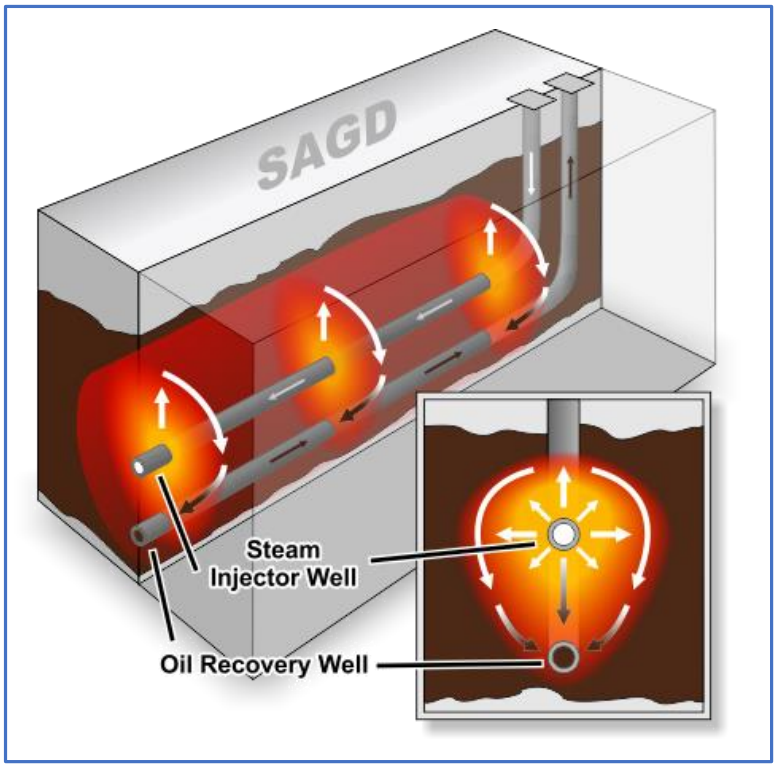


Figure 1.1 SAGD Thermal Recovery Technique

Although SAGD is an effective technique, it has some significant drawbacks. It may be an uneconomical option to produce heavy oil formations. For instances, this may happen in case limited amount of water is available to be used or in the case of offshore operations where steam generation may be very expensive. Another problem with SAGD is the low quality of injected steam into very deep formations. Due to the long distance travelled by the steam before it reaches the formation, significant

amount of the heat will be lost inside the injection well. Losing heat is also a potential problem in the case of thin-pay zones as the heat may be lost to adjacent non-producing zones. Difficulties to achieve a sufficient sweep efficiency of the hot steam may be encountered in heterogeneous or low-permeability formations. In heterogeneous formations, early injected steam breakthrough may result in a low sweep efficiency. On the other hand, it will be difficult for the steam to go deeper into formations with low permeability.

1.2 Thermal Recovery Technique using Microwave

A new technique involves the use of microwave irradiation to heat heavy oil reservoirs instead of the use of steam. An array of microwave sources that generate microwave irradiation to be lowered into the formation through a well. The word "antenna" is used in the industry to refer to microwave sources array and it will be also used in this dissertation. The microwave will heat the existing water in the formation. The heated water will heat the heavy oil by conduction and the heated oil may be produced through a production well as its viscosity is reduced. The new technique solves some of the problems encountered with SAGD. It eliminates the need of steam to be injected into the reservoir. There will be no need to inject foreign materials into the reservoir and only pure energy is introduced into the reservoir. In addition, the process will become more effective in deep formations as the microwave irradiation will be generated downhole and much less energy will be lost in the wellbore compared to SAGD. Problems related to losing heat to adjacent formations or sweep efficiency should not be of concern in the case of using microwave as the heat will be generated from within the formation. As mentioned earlier, the microwave does not heat the oil directly. Instead, microwave heats the water in the formation and consequently the heated water heats the heavy oil by conduction and convection.

- What is Microwave?

Microwave is a form of electromagnetic wave generated by a device called magnetron. Microwave irradiation has a frequency that ranges from 300 MHz to 300

GHz and a wavelength between 1 mm and 1 m. When polar material is exposed to microwave irradiation, the microwave irradiation interacts with its molecules causing them to turn back and forth at the frequency of the microwaves. This process will generate heat within the material. That is the reason why microwave heats water but not oil. Water is a polar substance as the Oxygen atom is more electronegative than the Hydrogen atoms. That causes the area close to the Oxygen atom to be more negative and the area close to the Hydrogen atoms to be more positive. However, oil molecules lack the polarity found in water and as a result it will not heat significantly when exposed to microwave irradiation.

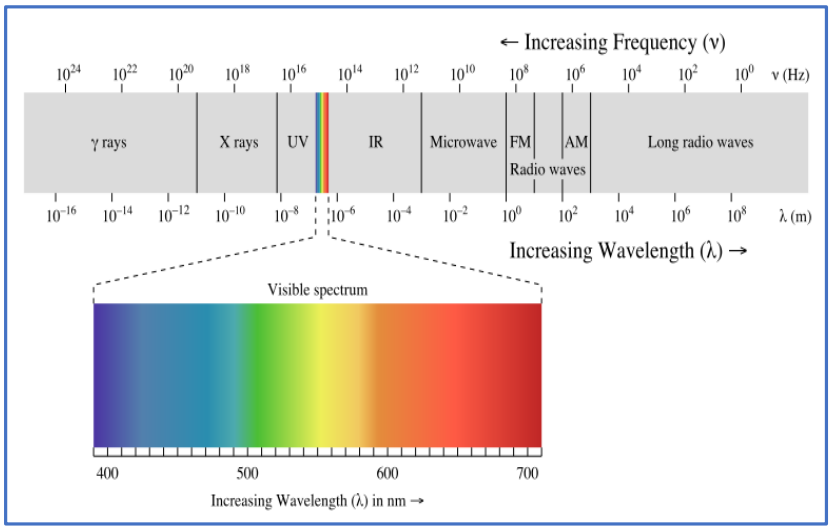


Figure 1.2 Electromagnetic Spectrum

CHAPTER II
LITERATURE REVIEW

Studies to investigate the use of microwave to heat heavy oil reservoirs as a thermal recovery technique started in the 1970's but it was not studied extensively until the beginning of the 21st century. Several experimental and numerical studies illustrated the benefits of using microwave for thermal recovery purposes. Some of these studies will be discussed briefly in the next three sections.

2.1 Experimental Studies

Cambon et al. (1978) performed their study on Canadian Tar Sand using a microwave frequency of 2450 MHz. They noticed an increase in distillable products up to 86% compared to conventional methods. In the same year, Milan (1978) conducted his experiments to find how deep the microwave irradiation may go into the formation. He used a 2450 MHz microwave and developed an empirical model. Based on that model, he reported that electromagnetic energy may go up to 15 meters into the formation.

In 2008, Hascakir et al. studied the effect of different parameters on the cumulative heavy oil produced using microwave as a thermal recovery technique. These parameters include heating time, rock initial water saturation, porosity, permeability, wettability, and water salinity. Jha et al. (2011) performed similar set experiments but using a 3000 MHz microwave frequency (2450 MHz in Hascakir et al. study). Both studies concluded that higher initial water saturation will result in more generated heat and hence more oil may be produced. Also, both studies reported that the higher the water salinity, the higher the recovery factor. Hascakir et al. related that to the fact that water with higher salinity has higher conductivity to electromagnetic waves.

Alomair et al. (2012) studied different unconventional thermal recovery techniques in a laboratory scale. Namely, they studied electrical resistant electrodes,

electromagnetic inductors, and microwaves. The results showed that utilizing microwave may increase the oil recovery up to 30% of the initial oil in place (IOIP). In addition, they concluded that microwave heating is the most economical technique compared to the other two techniques as it has the lowest power consumption per unit production.

2.2 Numerical Studies

Several people performed numerical studies to investigate the performance of the process if it is applied in the field. Warren et al. (1996) reported an improvement in the cumulative oil production when 915 MHz microwave is used to heat a heavy oil reservoir. 18% of the IOIP was produced conventionally and 27% was produced using the microwave to heat the reservoir. That is a 50% increase in the cumulative production. Similarly, Soliman (1997) developed a numerical solution to investigate the efficiency of the process. He found that the oil production was doubled by the use of a 100 kW microwave. This result was based on specific reservoir dimensions and fluid properties and more improvement may be observed if the reservoir properties is in favor of the process.

Another numerical study was performed by Sahni et al. (2000). They reported an 80% increase in the cumulative production of 10 years after the use of microwave compared to cold production. In 2002, Ovalles et al. performed their numerical study on three reservoirs with different grades of medium and heavy oil and found that microwave may accelerate the production of the oil. Furthermore, they found that the electric energy needed to heat the reservoir using microwaves is approximately one-tenth the energy that may be produced by the process.

2.3 Potential Problems of using Microwave to Heat Heavy Oil Reservoirs

Some of the significant problems with the microwave are related to the way it works. It is well-known that microwave may cause problems when directed to metals. Unfortunately, most of well completion components are made of steel. To overcome this problem, the microwave antenna may be placed in an open hole or the completion

close to the microwave should be carefully designed and built out of materials that do not interact with microwaves and meet the completion design specifications.

Heating the formation using microwave may generate fairly high temperature that may affect the integrity of the well completion adjacent to the microwave antenna. Bientinesi et al. (2013) developed an idea to solve this problem. They claim that the presence of a material with both low potential to convert microwave energy into heat and high heat conductivity would help in lowering the temperature around the wellbore. According to their study, this will also help in improving the microwave energy distribution in the formation. A numerical study performed by Okassa et al. (2010) suggested the use of aluminum oxide (Al_2O_3) for this purpose. Essentially this is Bauxite (a ceramic proppant used to fill hydraulic fractures to keep them open to flow).

Another technique involves monitoring of the temperature around the microwave antenna. The temperature should be maintained below a certain limit to maintain the wellbore integrity. As the temperature reaches that limit, the microwave antenna is turned off and the area around the wellbore is allowed to cool down.

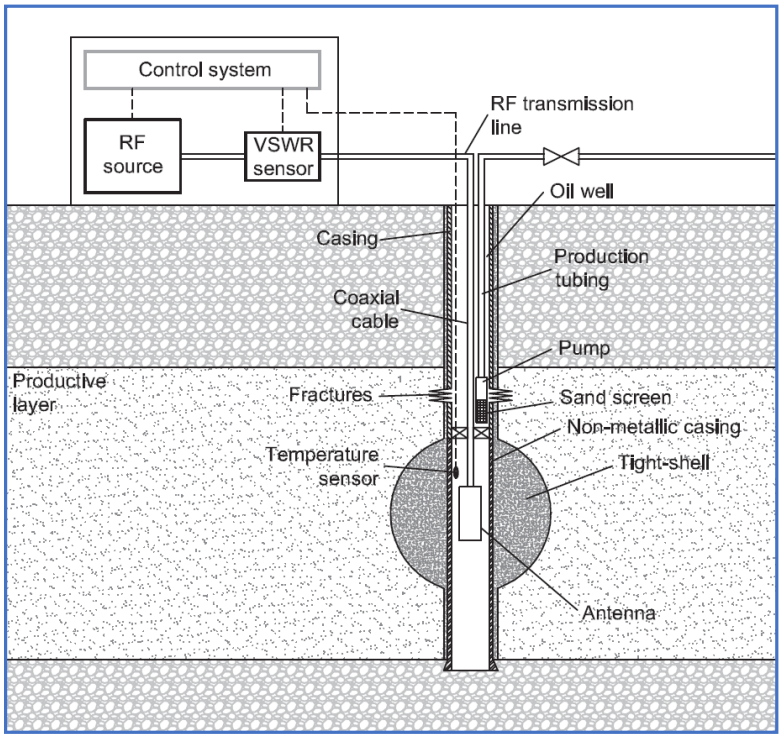


Figure 2.1 Bientinesi et al. (2013) Novel Tight-Shell Conceptual Design

Another problem of using the microwave to heat heavy oil reservoir is that microwave needs a polar substance to exist in the oil reservoir to interact with it and produce heat. Oil and rock are non-polar substance and the only polar substance that may exist naturally in the reservoir is water. This potentially could lower the efficiency of using microwave to heat formations with no or very low water saturation. Banerjee et al. (2011) suggested drilling three parallel wells. Water in the form of liquid or steam is injected through the top well. The injected water is heated downhole using a microwave antenna placed in the middle well. The heat generated by the heated water is conducted to the heavy oil and the oil may drain to the lower production well.

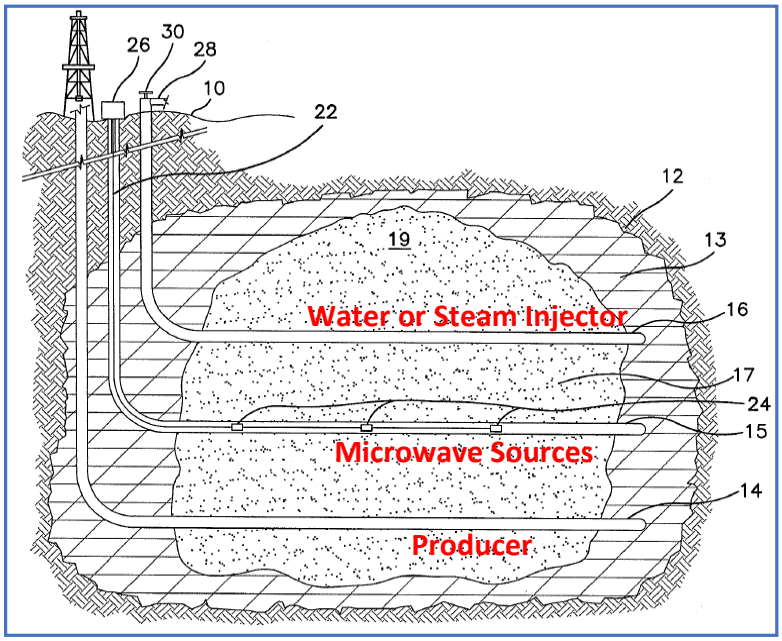


Figure 2.2 Banerjee et al. (2011) Patent

Another idea was studied numerically by Okassa et al. (2010). Their numerical simulation showed that in case a hydraulic fracture in the heavy oil formation is created and filled with silicon carbide (SiC) and aluminum oxide (Al_2O_3), the use of microwave to heat the heavy oil formation would increase the heavy oil temperature and hence lower its viscosity. The SiC was used due to its high real and imaginary permittivity compared oil and sand. Values of the permittivity of the used materials are shown in Table 2.1. Keep in mind that permittivity is function of microwave frequency and the shown data are at a frequency of 2.45 GHz. Real permittivity indicates how much of the applied microwaves is absorbed by the material. On the other hand, imaginary permittivity indicates the ability of the material to convert this absorbed energy into heat. As a result, if the fracture is filled with SiC, it will react with the microwave irradiation and will heat up creating a heated chamber around the fracture. The Al_2O_3 is to fill the portion of the fracture close to the wellbore to maintain well completion integrity as mentioned above. As can be seen in Table 2.1, Al_2O_3 has very low imaginary permittivity and thermal conductivity higher than those

for oil and sandstone. This will help in conducting the high amount of generated heat (as a result of using SiC) deep into the heavy oil formation.

Table 2.1 Properties of Substances used in Okassa et al. (2010) Numerical Study

	Real Permittivity ε' (at 2.45 GHz)	**Imaginary Permittivity ε'' (at 2.45 GHz)**	**Thermal Conductivity (W/m.K)**
Oil	2	0.002	3
Sand	3.78	0.001	1.7
SiC	6	0.45	360
Al_2O_3	8.09	0.009	30

In their numerical study, Okassa et al. (2010) assumed that a 5-m long fracture is created in an oil reservoir. They studied four different filling configurations of the fracture. They filled the whole fracture with SiC in their first run. The second run was executed assuming that the whole fracture is filled with Al_2O_3 only. Then, the fracture was divided into two equal halves and each half was filled with a different material in the third and fourth runs. They filled the half close to the wellbore with SiC in the third run and with Al_2O_3 in the fourth run. For each run, they observed the temperature distribution in the reservoir but they did not consider any fluid dynamics. The results are illustrated in the following figure. The best temperature distribution was achieved when the first half was filled with Al_2O_3 and the second half was filled with SiC.

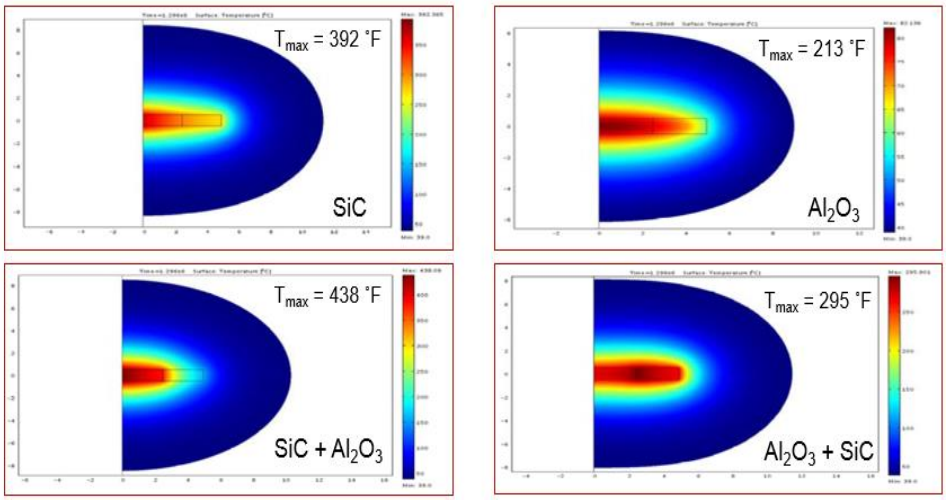


Figure 2.3 Okassa et al. (2010) Numerical Study Results

CHAPTER III
OBJECTIVES

The main objective of this PhD dissertation is to improve the technique of using microwave to produce heavy oil reservoirs. The new technique involves the use of microwave and aluminum oxide to heat heavy oil reservoirs, which will be known as the MAC technique. Activated carbon was used in a Chemical Engineering study investigating its use with microwave to upgrade heavy oil. Upgrading heavy oil is a process of changing its properties so it may be easily pumped and handled by oil refineries. Jackson (2002) reported that when heavy oil is mixed with activated carbon in the lack of water and exposed to microwave irradiations, its viscosity will decrease dramatically. The oil viscosity decreased from 11,300 cp to between 62 and 262 cp depending on the microwave frequency.

In the MAC technique, hydraulic fracture(s) are created in heavy oil reservoirs and filled with activated carbon. Microwave antenna(s) will be placed inside the producers or in other wells close to them. Activated carbon was selected due to its significantly higher real and imaginary permittivity values than any naturally existing materials in heavy oil reservoirs, namely water, oil, and rock. (Real and imaginary permittivity were previously defined in Chapter II). In general, permittivity is function of microwave frequency. Figures 3.1 to 3.7 show how real and imaginary permittivity of activated carbon, water, oil and rock change with microwave frequency. It is clear that activated carbon has very high permittivity compared to other materials.

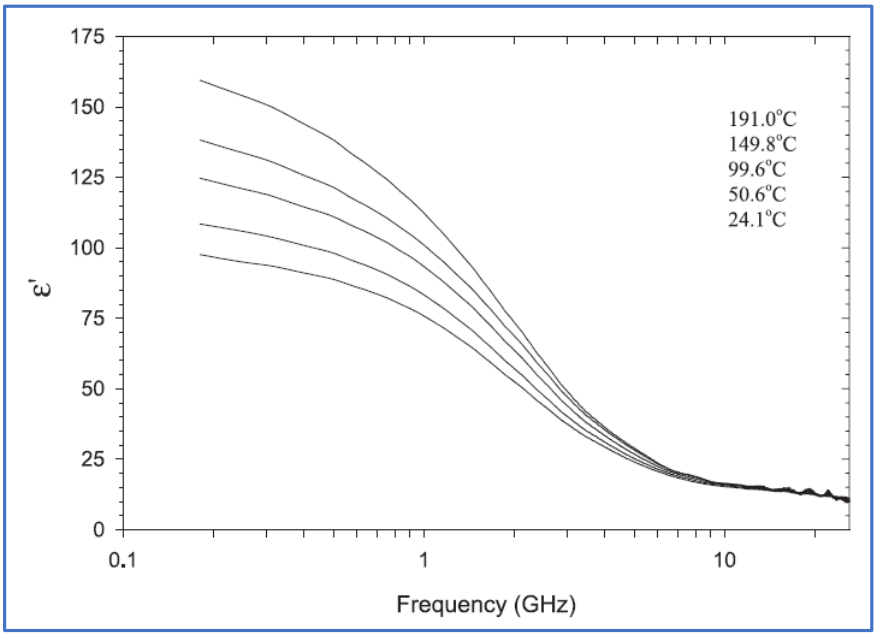


Figure 3.1 Real Permittivity of Activated Carbon (Atwater and Wheeler (2004))

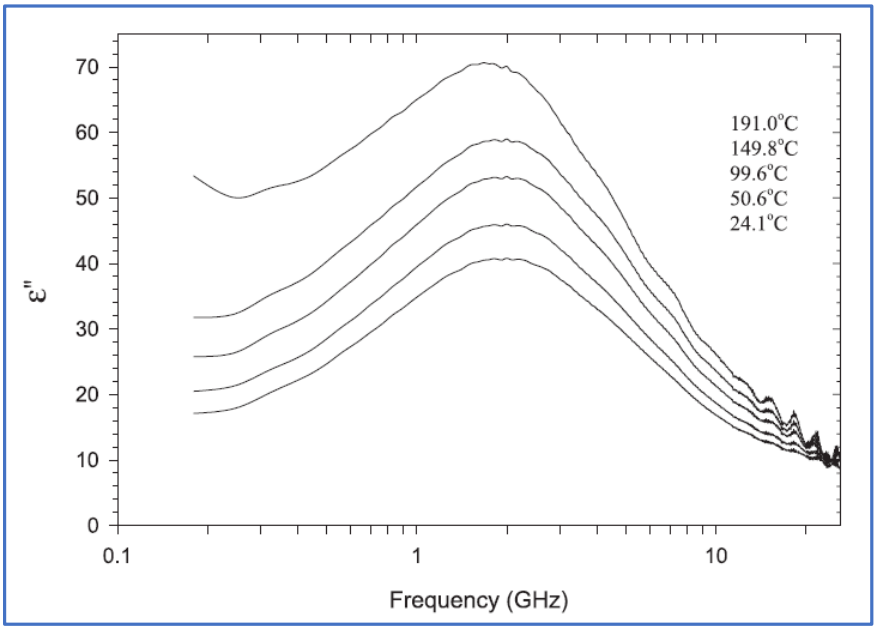


Figure 3.2 Imaginary Permittivity of Activated Carbon (Atwater and Wheeler (2004))

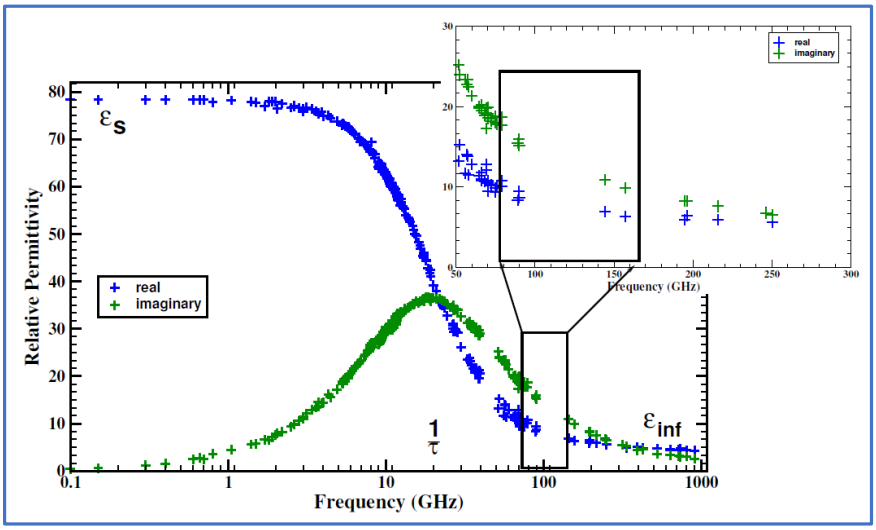


Figure 3.3 Permittivity of Water (Peacock (2014))

Peacock (2014) generated this plot using Ellison et al. (1996), Buchner et al. (1999), Kupfer (2005), Meissner and Wentz (2004), Ronne and Keiding (2002), and Kaatze (2007).

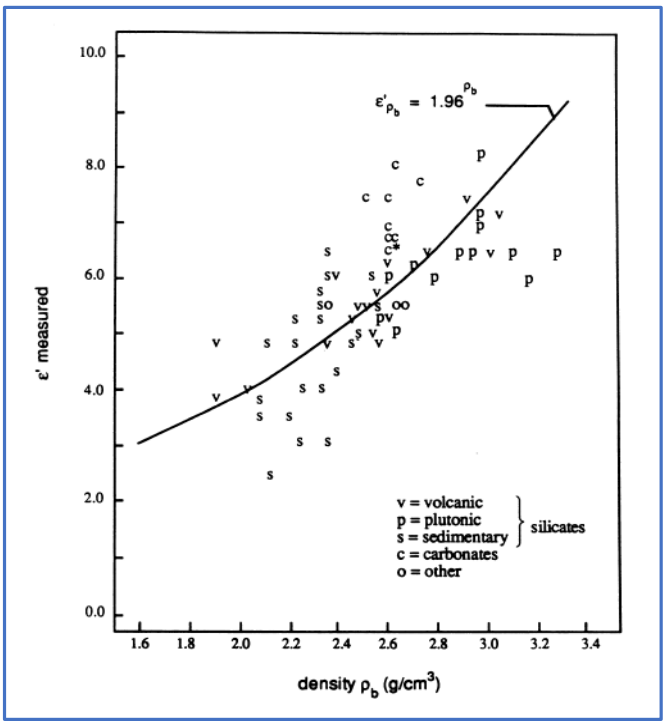


Figure 3.4 Real Permittivity of Rock (Ulaby et al. (1990))

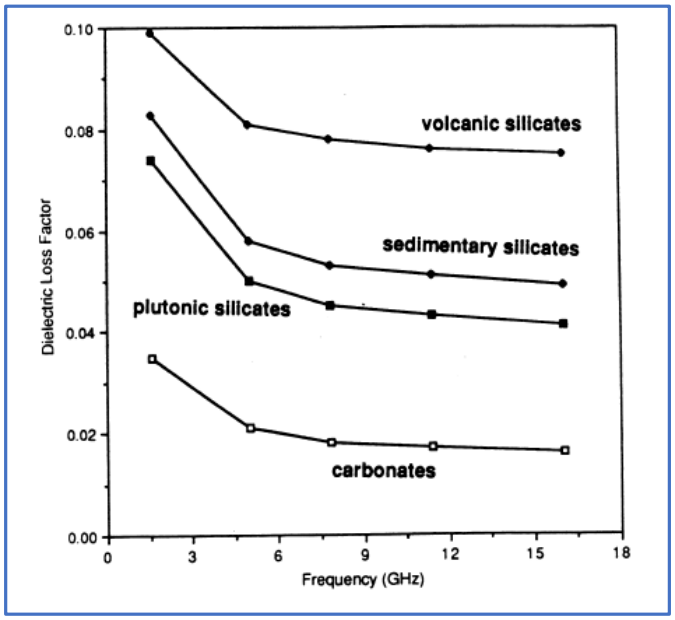


Figure 3.5 Imaginary Permittivity of Rock (Ulaby et al. (1990))

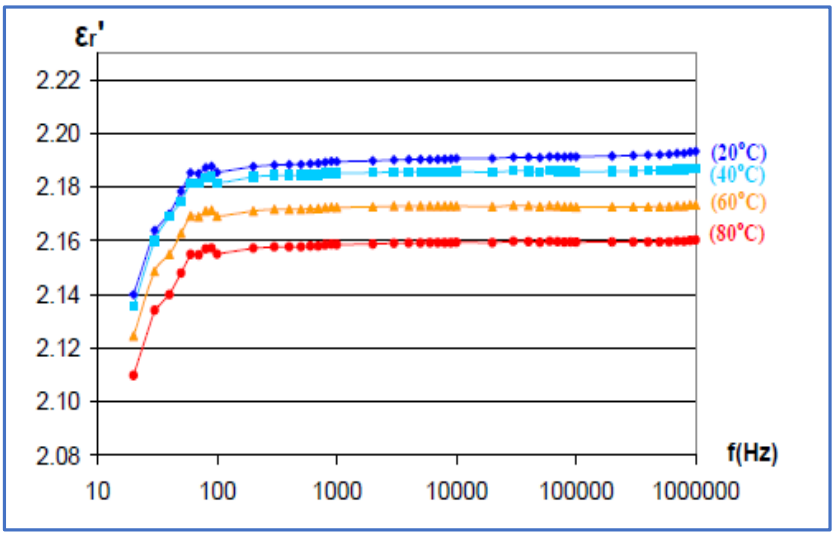


Figure 3.6 Real Permittivity of Oil (Dervos et al. (20005))

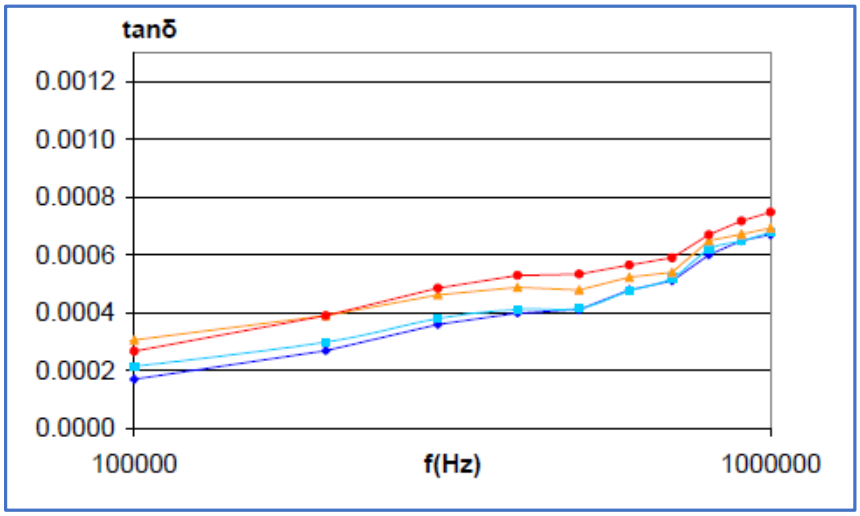


Figure 3.7 Imaginary Permittivity of Oil (Dervos et al. (2005))

The generated heat by the MAC technique may affect the integrity of the well completion adjacent to the microwave antenna. Aluminum oxide may be used to fill the parts of the hydraulic fracture close to the wellbore. It is selected because it has very low imaginary permittivity compared to activated carbon and hence less heat will be generated around the wellbore. The microwave frequency investigated in this PhD dissertation is 2.45 GHz. Table 3.1 lists the permittivity values of activated carbon, aluminum oxide, water, oil and rock at this frequency. Aluminum oxide is also selected due to its very high strength compared to activated carbon. This may help in keeping the hydraulic fracture open to oil flow.

In summary, using activated carbon and aluminum oxide in the MAC technique may significantly improve the process of heating heavy oil reservoir in terms of generated heat, uniform heat distribution, effective use of microwave power, and maintaining wellbore integrity.

Table 3.1 Permittivity of used Materials

	Real Permittivity ε' (at 2.45 GHz)	**Imaginary Permittivity ε'' (at 2.45 GHz)**
Water	79	10
Oil	2	0.002
Sand	3.78	0.001
Activated Carbon	75 - 110	37 - 70
Al_2O_3	8.09	0.009

The following will be investigated experimentally and numerically is this PhD study:

1. The use of activated carbon to improve the process of using microwave to heat heavy oil reservoirs to produce them (MAC technique).
2. The use of aluminum oxide with the activated carbon to generate the best possible temperature distribution along the heated fracture.
3. The effect of operating the microwave at different power levels on the performance of the MAC technique.
4. The effect of cyclic operation on the performance of the MAC technique. The microwave will go through cycles of on/off periods.

CHAPTER IV
STUDY APPROACHES

This PhD dissertation consists of an experimental part and a numerical part. The required equipment, procedure, and recorded data will be illustrated in the next few sections.

4.1 Experimental Approach

4.1.1 Experimental Equipment

a. Microwave oven:

A microwave oven with a technology called “Inverter Technology” is used for the experimental part. Basically this technology is taking care of one of the problems of conventional microwave ovens. Conventional microwave ovens may operate on one power level only. So when the microwave oven is needed to work on a 50% power level for example, it will go through on/off cycles of 100% power level. This causes hot and cold spots in the heated object. The inverter technology allows the microwave to transmit continuous level of energy. This allows uniform energy distribution. The microwave oven has 10 different power level (max of 1250 watt). It operates at a frequency of 2.45 GHz and has a capacity of 2.2 ft^3.

b. Fluids:

Light and heavy oil are used in the experimental part. The light oil is used to proof the concept investigated in this dissertation. It has a specific gravity of 0.86 (33 ˚API) at 25 ˚C. The heavy oil used for the experimental part has a viscosity of 415 cp and a specific gravity of 0.91 (24 ˚API) at 40 ˚C. Experiments were conducted on samples of water as well. It has a specific gravity of 1.0.

c. Activated Carbon:

As mentioned in the literature review part, activated carbon is used to generate heat inside the fracture when applying microwave irradiation.

d. Aluminum Oxide:

Aluminum oxide (Al_2O_3) has a specific gravity of 4.0 and is insoluble in water. It has low imaginary permittivity and high thermal conductivity which will help in conducting the heat inside the fracture deep into the formation.

e. Synthetic Rock:

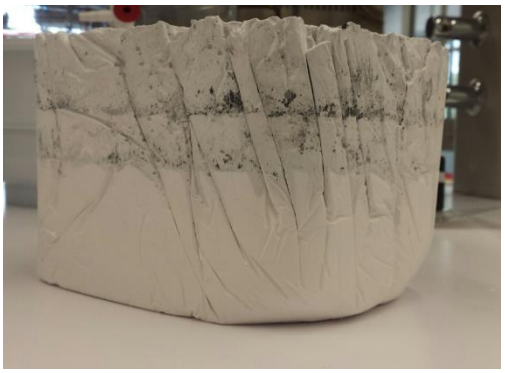
Synthetic rock samples made of plaster are made in the lab. They are divided into three categories. Sample with no additives to imitate a porous rock, fractured samples with activated carbon and aluminum oxide filling the fracture, and samples mixed with activated carbon. In the later the activated carbon is mixed with the plaster to imitate a rock sample with some of the pores filled with activated carbon. Figure 4.2 illustrates the difference between the three samples. Plaster is selected because it is easy to create a core of plaster and to imitate a fracture in it and fill the fracture with activated carbon.

f. Infrared Thermometer:

An infrared thermometer is used to monitor the temperature of the fluid and core samples when it is inside the microwave oven. It is simply a gun that uses laser to aim at an object to measure its temperature (figure 4.3). It may read temperatures as high as 800˚F and has an accuracy of ± 0.95˚F.

Figure 4.1 Activated Carbon and Aluminum Oxide

Category # 1
(no additives)



Category # 2
(top half: mixed with activated carbon
bottom half: no additives)

Category # 3
(fracture filled with
activated carbon)

Figure 4.2 Synthetic Core Sample Categories

Figure 4.3 Infrared Thermometer

4.1.2 Experimental Plan

a. The temperature change of water, oil, activated carbon, and aluminum oxide samples will be monitored as they are heated using microwave. Different microwave power levels and different samples volumes will be investigated. The infrared thermometer will be used to measure the temperature of the samples.

b. Part (a) will be repeated on samples of oil and water mixed with activated carbon at different concentrations.

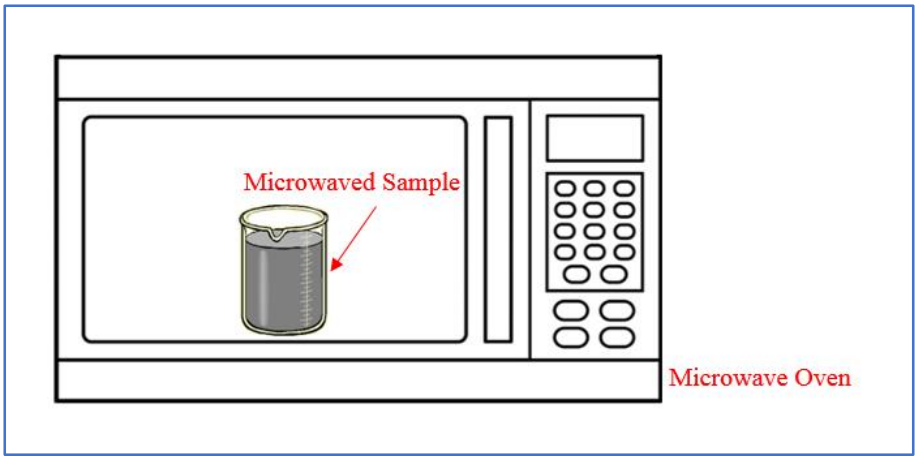
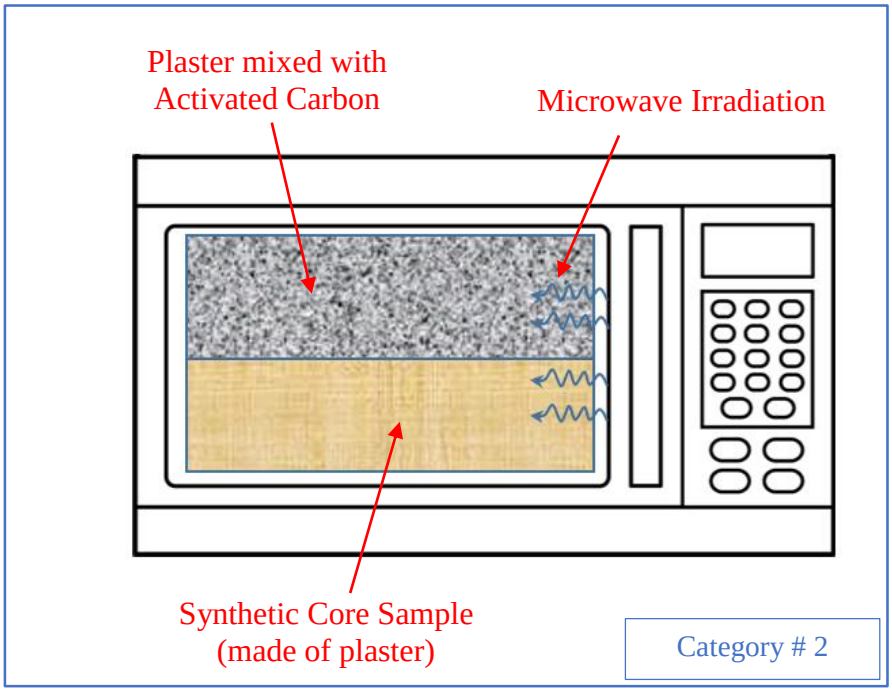


Figure 4.4 Schematic of the Experimental Lab Setup (parts a and b)

c. The 3 categories of synthetic core samples shown in Figure 4.2 will be heated using microwave. Temperature along a vertical axis along the core samples will be measured at different microwaving times.
d. The effect of reheating the samples described in parts (a to c) above will be studied. Different cool-down times are investigated.
e. The final set of experiments will be conducted to investigate the effect of cyclic on/off microwave operation. The temperature of the samples described in parts (a to c) will be recorded after each cycle.



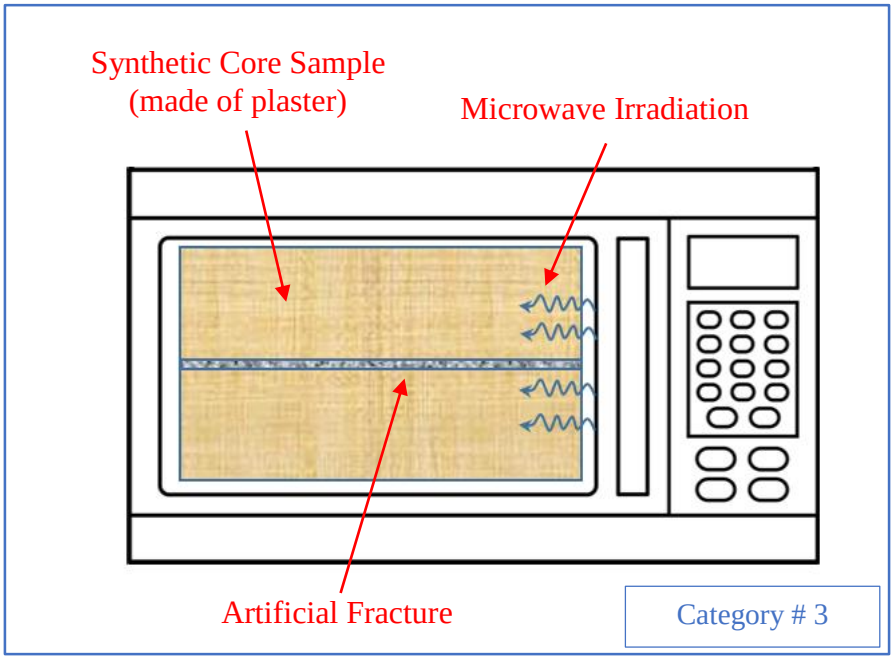


Figure 4.5 Schematic of the Experimental Lab Setup (part c)

4.2 Numerical Approach

4.2.1 Thermal Reservoir Simulator

A thermal reservoir simulator called TRS-THERM is used for the modeling part of this dissertation. It was developed by TAURUS Reservoir Solution Ltd and it has been used and validated on several studies. According to TAURUS user guide (2013), the code was written in standard FORTRAN 77/90. The simulator has the capability of modeling single-phase, two-phase, or multiphase thermal flow in hydrocarbon reservoirs. The model is a black oil model that allows treating hydrocarbon as a 3-phase component in addition to water using pressure and temperature dependent K values. The hydrocarbon components are heavy, light and non-condensable.

Since it is a thermal simulator, it can simulate heating formations using microwave or any thermal recovery process (except in-situ combustion or other processes that involves reactions). The microwave source is considered to be a point source that may be placed in any grids of the simulated reservoir. Microwave antennas are represented by a linear arrays of these point sources. The simulator has a dynamic implicit formulation allowing a full range of implicitness from IMPES to fully implicit. The well model is always fully implicit. Vertical and horizontal wells may be modeled using this simulator.

The simulator obtains the distribution of the microwave energy by solving the antenna equation analytically. Each microwave source (point source) in the kth point will generate a power of P_o^k. The energy absorbed per unit volume per unit of time P_i^k by the ith grid with coordinates (r, θ, z) away from the point source may be calculated using the following (TAURUS user guide, 2013),

$$P_i^k = \frac{1.1\, P_o^k \bar{\alpha}^3}{\pi} \cdot \frac{\left(1 - cos(\theta)\right)^{0.1}}{2} \cdot e^{-\overline{2\alpha r}} \qquad [4.1]$$

where

$$\overline{\alpha r} = \sqrt{\left(\sum_{i=obs}^{i=target} \propto_i d_i\right)^2 + \left(\sum_{j=obs}^{j=target} \propto_j d_j\right)^2 + \left(\sum_{k=obs}^{k=target} \propto_k d_k\right)^2} \qquad [4.2]$$

$\propto_i$ attenuation in the *i*'th block

$\boldsymbol{d_i}$ length of the *i*'th block

For the grid containing the microwave source, the absorbed energy is,

$$P_i^k = \frac{2\, P_o^k \alpha^2}{V} \cdot \left(\frac{1}{2\alpha^2} - \left(r^2 + \frac{r}{\alpha} + \frac{1}{2\alpha^2}\right) \cdot e^{-2\alpha r}\right) \qquad [4.3]$$

where α is the attenuation of the ith block, $\bar{\alpha}$ is the average attenuation between the kth microwave source and the ith block, $\overline{\alpha r}$ is the average of the product of the attenuation and the distance between the microwave source and the ith block, V is the volume of the grid block, and r is the equivalent radius of the grid block. That is the radius of a sphere that has the same volume of the grid block. The total amount of heat transformed to the formation has to equal the total power generated by the microwave antenna. Sometimes this is not the case because the model uses a technique that does not allow the energy transfer to be exact. A multiplier has been added to the model to correct the microwave source term to maintain the energy balance. The software calculates this multiplying constant internally. Keep in mind that the modelled reservoir should be large enough to absorb all the generated power.

Since the model is a dynamic model, where fluid saturations in any block may change with time, nonlinear attenuation should be accounted for. Due to the difficulty of doing this rigorously, the simulator uses a simplified averaging method to take the change of fluid saturations into consideration.

The attenuation parameter of the microwave ($\propto$) is function of the frequency and the complex permittivity of the microwaved material. As a result it will change around the reservoir due to the change of fluid saturations, reservoir

composition, or by adding foreign materials into the reservoir such as activated carbon. Since this is a dynamic model, attenuation parameter varies with time as the saturation changes (nonlinear attenuation) (TAURUS user guide, 2015).

$$\propto = \propto (f, \epsilon, \mu') = 2\pi f \sqrt{\frac{\epsilon'\mu'}{2}\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}-1\right)} \qquad [4.4]$$

where

f frequency of microwave source (s^{-1})

ϵ complex permittivity of the medium ($Farad.m^{-1}$)

ϵ' real part of the permittivity

ϵ'' imaginary part of the permittivity

μ' real part of the magnetic permeability ($Henry.m^{-1}$ or $s^2.(m\ Farad)^{-1}$)

In dielectric materials, ε'' is small and μ' can be considered equal to 1. Nonlinear attenuation is accounted for in the model using the following approximation for the complex permittivity:

$$\epsilon = \left(\varphi S_w \sqrt{\epsilon_w} + \varphi\left(1 - S_w - S_g\right)\sqrt{\epsilon_o} + (1-\varphi)\sqrt{\epsilon_s}\right)^2 \qquad [4.5]$$

where

ϵ_w complex permittivity of water

ϵ_o complex permittivity of oil

ϵ_s complex permittivity of rock

According to TAURUS user guide (2015), the complex permittivity of water is function of the frequency and temperature (Kaatze et al, 1989). It is calculated internally in the model using the following correlation.

$$\epsilon_w(f) = \epsilon(\infty) + \frac{\epsilon(0) - \epsilon(\infty)}{1 + \omega\tau} \qquad [4.6]$$

$$\epsilon(0) = 10^{1.94404 - 0.001991(T_K - T_R)} \qquad [4.7]$$

$$\epsilon(\infty) = 5.77 - 0.0274(T_K - T_R) \qquad [4.8]$$

$$\tau = 3.745 \times 10^{-15} \times (1 + 7 \times 10^{-5}(T_K - 300.65)^2) e^{\frac{2295.7}{T_K}} \qquad [4.9]$$

$$\epsilon_w{}' = \epsilon(\infty) + \frac{\epsilon(0) - \epsilon(\infty)}{1 + \omega^2\tau^2} \qquad [4.10]$$

$$\epsilon_w{}'' = \omega\tau \frac{\epsilon(0) - \epsilon(\infty)}{1 + \omega^2\tau^2} \qquad [4.11]$$

where

f frequency of microwave source (s^{-1})

ϵ_w complex permittivity of water ($Farad.m^{-1}$)

$\epsilon(\infty)$ high frequency limit of the permittivity of water

$\epsilon(0)$ low frequency limit of the permittivity of water

ω $2\pi f$

$\epsilon_w{}'$ real part of the permittivity of water

$\epsilon_w{}''$ imaginary part of the permittivity of water

T_K temperature (˚K)

T_R 273.15 ˚K

On the other hand, the model assumes default values for the complex permittivities of oil and rock. The user may change these values in any section of the reservoir. The default values are shown in the following table.

Table 4.1 Permittivity Default Values

	Real Permittivity **ε'**	**Imaginary Permittivity** **ε''**
Oil (at 0.915 GHz)	9.8	0.1965
Oil (at 2.45 GHz)	9.8	0.0734
Rock	4.7	0.0

As mentioned earlier, using microwave may overheat the reservoir that leads into fairly high temperature. These high temperatures may affect the integrity of the wellbore around the microwave antenna. The model allows the user to specify a maximum temperature at which the microwave antenna is turned off. The microwave antenna will be turned on when the temperature decreased to a certain temperature (specified by the user).

The output data files of the TRS-THERM simulator will be displayed graphically using TERAPRO post-processing model. The input and output data may be displayed in colored 2D or 3D visualizations of the reservoir, summary tables, or XY plots.

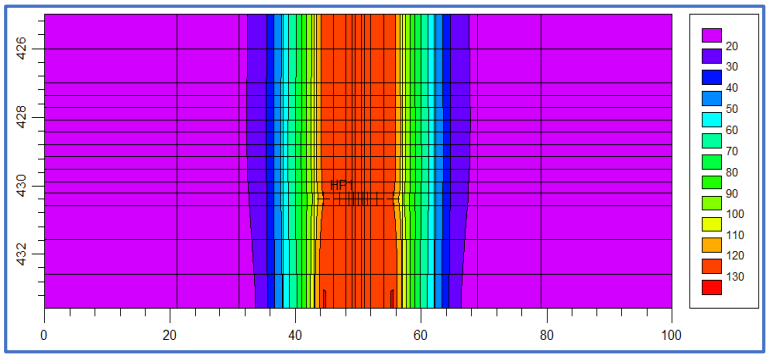


Figure 4.6 Example of Reservoir Temperature Map after using Microwave (TAURUS User Guide (2015))

4.2.2 Planned Work

Horizontal and vertical wells with hydraulic fracture(s) that are filled with activated carbon and/or aluminum oxide will be simulated. Microwave antenna(s) will be placed inside the producers or in other wells close to them. Then, the flow rate, pressure, and temperature will be monitored for a specific period of time. The base case will be executed without any microwave antennas and the cold production will be observed. Then, several parameters will be changed in different scenarios to observe their effect on the whole process.

- Adding microwave antenna(s).
- Creating hydraulic fracture(s) and filling them with activated carbon
- Initial water saturation.
- Microwave frequency.
- Microwave power.
- Radius of investigation
- Combining microwave heating with water injection.
- Cyclic on/off operations of the microwave antenna.
- Microwaving/Producing wells pattern similar to the ones in water flooding.

CHAPTER V
EXPERIMENTAL RESULTS AND ANALYSIS

The conducted experiments for this PhD dissertation are dived into different categories. The collected experimental data for each one of them is shown and analyzed in the following sections.

5.1 Single Samples

The first set of experiments was conducted to investigate the effect of microwave on water, oil, activated carbon and aluminum oxide. The following plot shows how the temperature increases with time for each one of them. The microwave oven was set at full power of 1250 watts. All the samples has a volume of 20 ml.

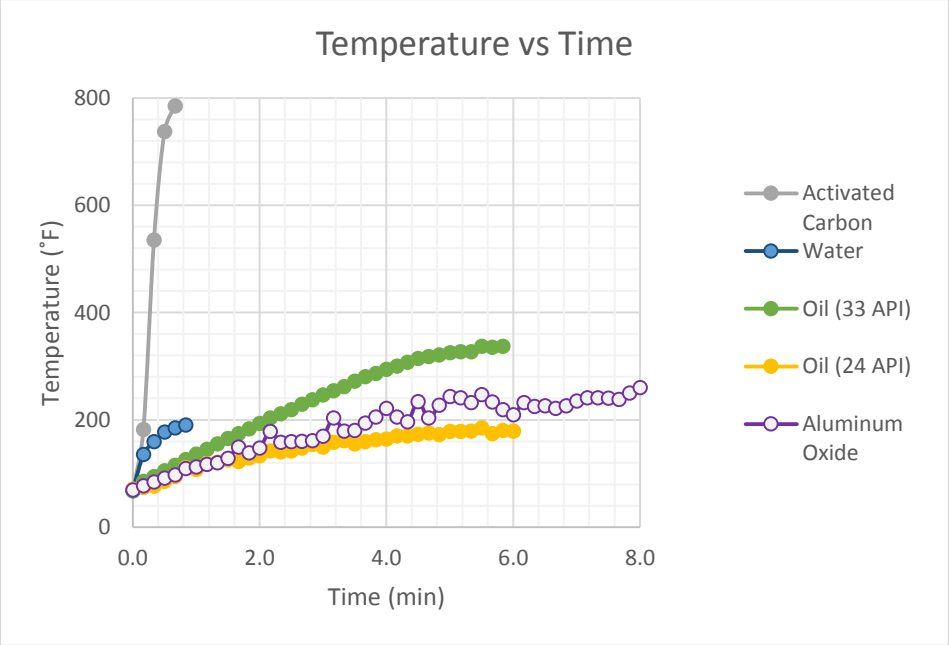


Figure 5.1 Temperature vs Time for different Materials Heated by Microwave

The plot shows that 20 ml of water heats up to a boiling temperature in about a minute. However, the same volume of activated carbon reaches 800˚F in 40 seconds. That supports the idea of MAC technique. This high temperature would generate

significant amount of heat to reduce the heavy oil viscosity. When it comes to oil, experimental results showed that microwave heats oil but not to the degree of water or activated carbon. Actually, the heavier the oil the more time it needs to heat up. The heavier oil sample used for this study took 6 minutes to reach a temperature of 190˚F. Comparing aluminum oxide to other substances, it is clear that aluminum oxide does not heat up as fast as water or activated carbon. This support the idea of using aluminum oxide to fill the fracture sections close to the wellbore to maintain the wellbore integrity.

5.2 Microwave Power Level

In this category, the effect of microwave power level on different substances is studied. The samples include water, oil (33 ˚API), and activated carbon. The plots shown in this section illustrate the temperature change of 20 ml samples of these substances with heating time at different power levels.

Figure 5.3 shows that the change of temperature of activated carbon with time follows a semi-log trend. Decreasing the power level increases the time needed to reach a certain temperature. The increase in time is relative to the decrease in power level. For example, it is expected that the time needed to reach a temperature of 500˚F using a 100% power level is around 20 seconds. Reducing the power level to 80% would increase the needed time by 100/80 which is 1.25. As a result, the expected time should be around 25 seconds. That is close to the value obtained in the experiment. Experimentally, it took the same sample 28 seconds to reach a temperature of 500˚F using 80% power level. This relativity is valid between the 100% and 80% power levels with a maximum error of 12%. However when it comes to the other power levels (60 to 20%), the experimental results are not relative to the power levels. This is may be because the microwave oven used in this study is much larger than the activated carbon samples. Lower power levels produce less microwave irradiations that increases the possibility some of the irradiations may be scattered and may not hit the activated carbon sample.

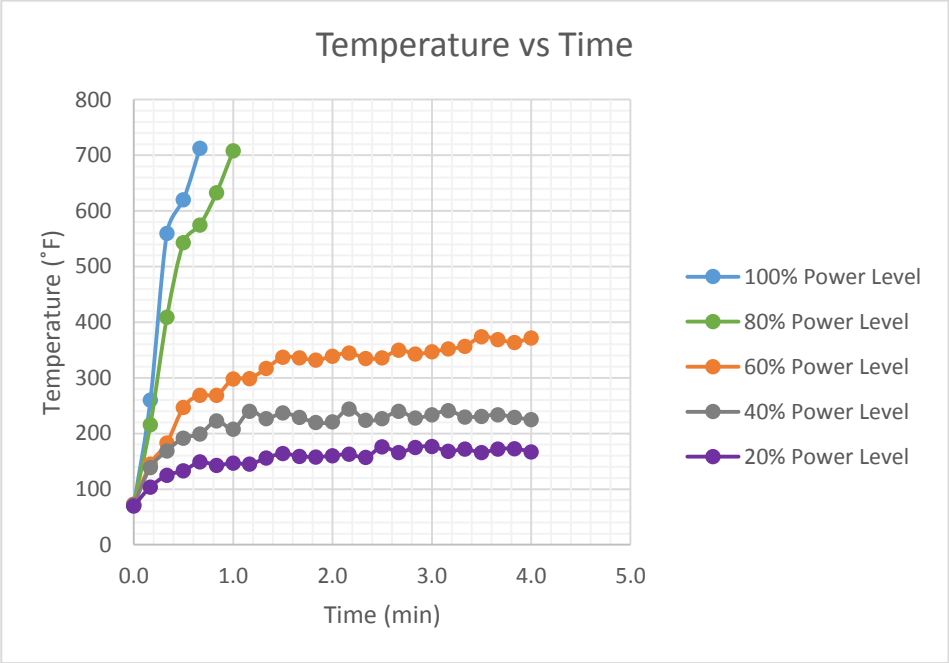


Figure 5.2 Microwave Power Level Effect on Activated Carbon

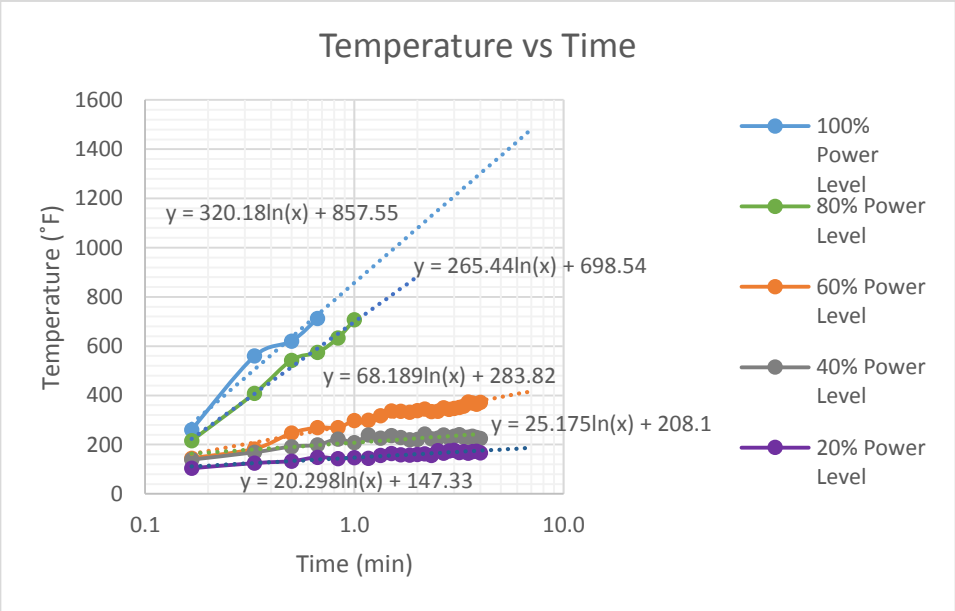


Figure 5.3 Microwave Power Level Effect on Activated Carbon (semi-log)

In the case of heating water, decreasing the power level means that the time needed to reach a plateau (around the boiling temperature) would be more. Similarly, increasing the power level would decrease the time to heat oil.

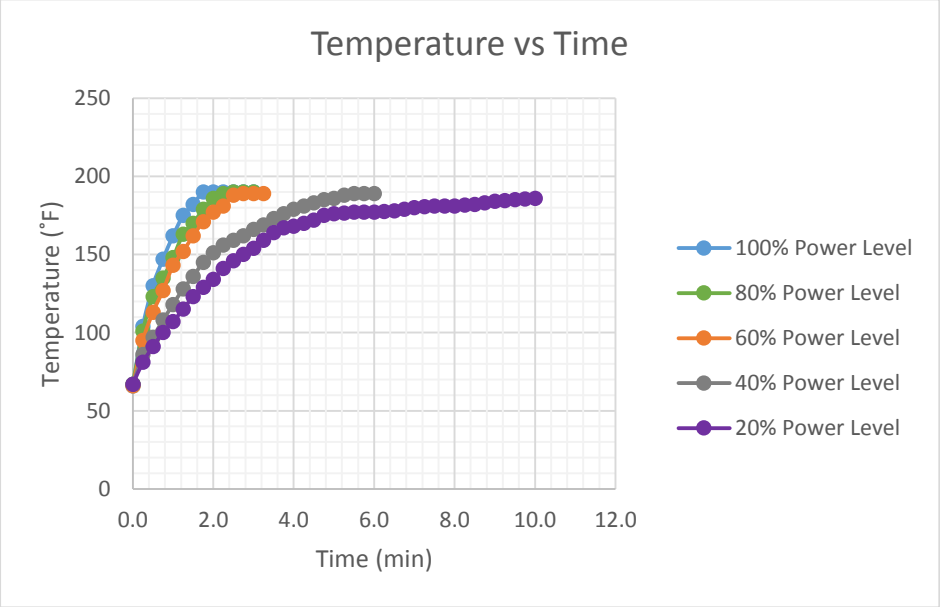


Figure 5.4 Microwave Power Level Effect on Water

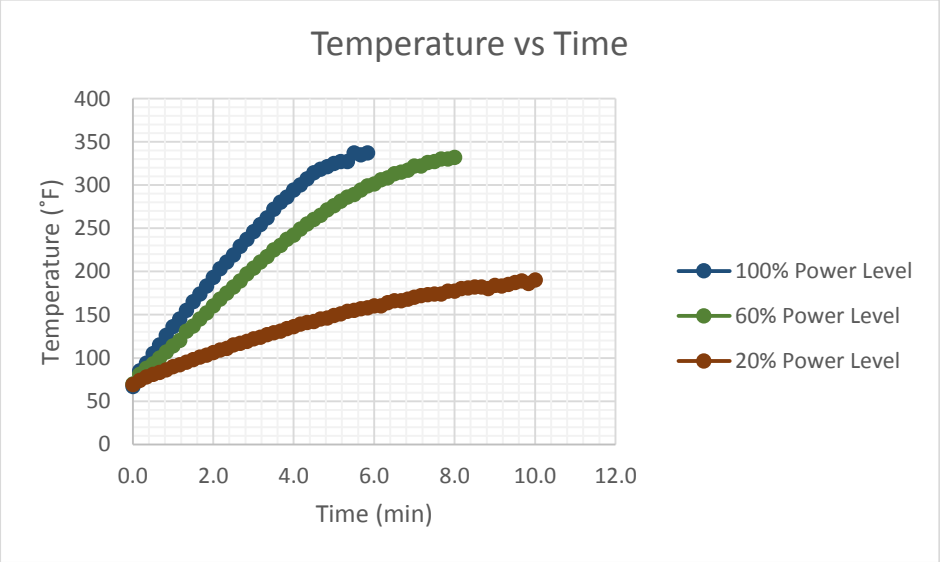


Figure 5.5 Microwave Power Level Effect on Oil

5.3 Mixtures

Mixtures of the materials used in this study are investigated in this section. The first mixture is activated carbon and water. When heating such a mixture, it takes some time for the water to evaporate then it will act as if activated carbon is heated only. Before the evaporation of most of the water in the mixture, the mixture will act as it is only water (figure 5.6). That makes sense since the water is covering the surface of the activated carbon and getting into the pores preventing the activated carbon from interacting with the microwave irradiations. This was observed visually in the lab. If activated carbon is heated alone, flashes are observed at its surface. If the mixture is heated, no flashes are observed until most of the water evaporates. The moment flashes are observed, the temperature of the mixture increase beyond the boiling temperature of water. Then, the temperature increases as if activated carbon is heated alone.

Increasing the amount of water shows that the mixture needs more time for the water to evaporate and hence the temperature of the mixture will stay around the boiling temperature of water for a longer period of time. As soon as most of the water evaporates, the activated carbon dominates and it heats up to very high temperatures quickly. Figure 5.7 shows a comparison between the mixture of activated carbon and water with the other single substances.

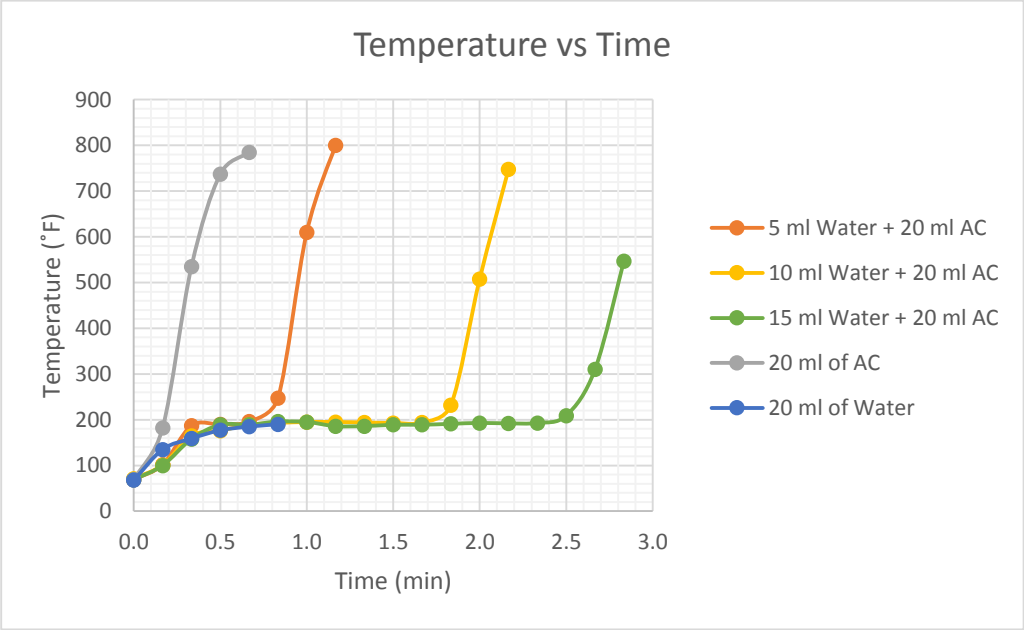


Figure 5.6 Dry and Wet Activated Carbon

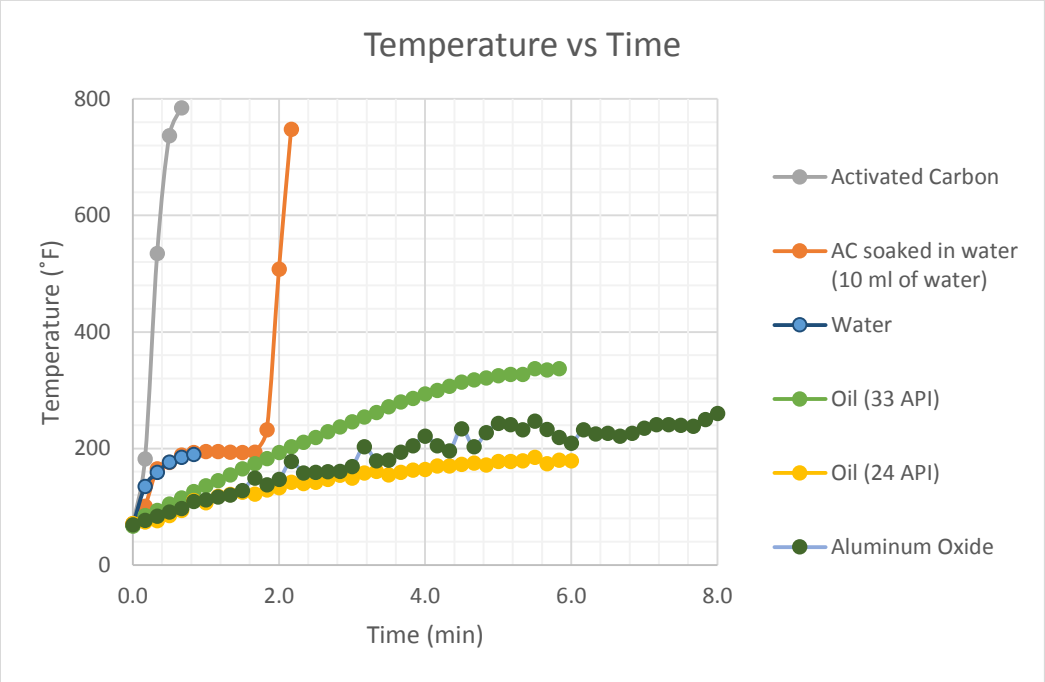


Figure 5.7 Temperature vs Time for different Materials Heated by Microwave

5.4 Reheating

Reheating activated carbon showed improvement of the performance of the whole process. The time required to heat a preheated sample may be reduced significantly. It may be decreased further if the activated carbon is preheated for several times. It also may be reduced if the sample is soaked in water before heating it for the first time. Table 5.1 shows the temperature increase with time of heated activated carbon using microwave. The dry samples are 20 ml (7 grams) of activated carbon and the wet samples are 20 ml of activated carbon soaked with 10 ml of water. Temperatures listed as 800+ means that the temperature is over 800 ˚F which is the maximum limit of the infrared thermometer used to measure the temperature in this study.

Let's start with the dry sample. It is clear that the first time the activated carbon is heated, it needs 10 seconds for its temperature to reach 277 ˚F. Then it is left to cools down for a whole day to 70 ˚F. After that it is heated for the second time. Microwaving it for 10 seconds increased its temperature to 455 ˚F. Reheating it for few consecutive days showed that the observed temperature after 10 seconds increased generally. For example, at the day 16 the temperature of the sample reached 611 ˚F after only 10 seconds. This temperature was not reached the first day the sample was heated even after 20 seconds. This decrease in the time needed to reheat activated carbon may be a huge advantage when larger amount of activated carbon needs to be heated. The energy needed to heat activated carbon to a certain temperature may be reduced significantly as less time is needed to reheat the activated carbon.

Soaking activated carbon may improve the results even more. A dry sample of activated carbon is soaked in water. As mentioned in section C, the mixture needs longer time because the water needs to evaporate. The first day, the wet sample is heated to 800+ ˚F. Then it is left to cool down to room temperature over a day. Reheating it similar to the dry samples for consecutive days showed an improvement on its performance. After 16 days, the temperature of the sample reached 745 ˚F in only 10 seconds. Comparison between the dry and wet activated carbon samples is

illustrated in figure 5.8. It shows the temperature of the samples after 10 seconds of heating using microwave. It is clear that soaking activated carbon in water before heating it for the first time may help in reducing the used energy.

Table 5.1 Temperature in ˚F of Preheated Activated Carbon with Time

Day	Dry AC			Soaked AC in Water		
	0 sec.	10 sec.	20 sec.	0 sec.	10 sec.	20 sec.
1	71	277	543	71	101	171
2	67	455	800+	67	389	755
5	68	447	800+	67	397	757
6	69	430	800+	69	545	800+
7	68	445	800+	69	615	800+
8	74	504	800+	70	702	800+
10	69	433	800+	69	690	800+
12	69	522	800+	70	692	800+
13	68	432	800+	68	649	800+
14	68	548	800+	68	691	800+
15	71	564	800+	71	768	800+
16	67	611	800+	67	745	800+
22	71	467	800+	70	641	800+
29	71	483	800+	72	547	800+

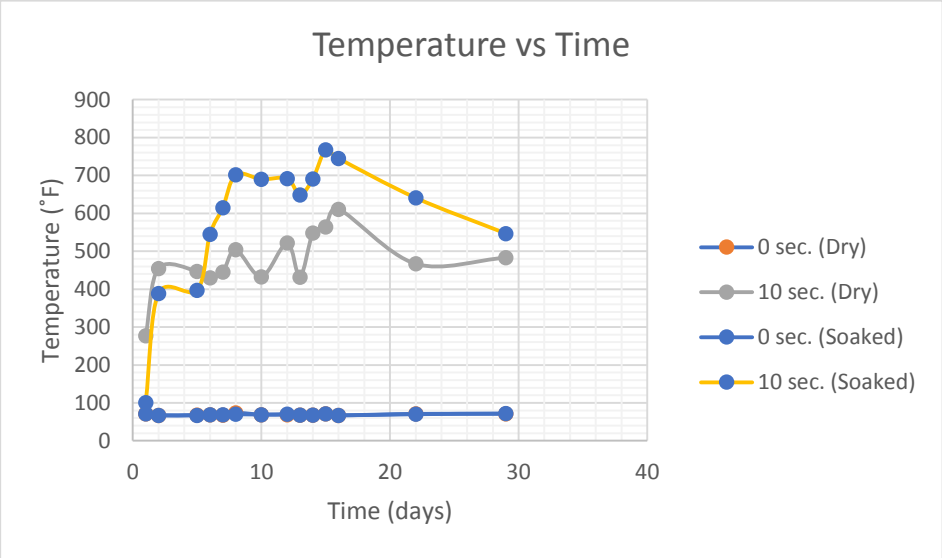


Figure 5.8 Comparison between Heating Dry and Wet Activated Carbon

Another set of experiments was conducted to investigate the effect of cool down time. 4 samples (2 dry and 2 wet) were heated in the first day. Then they were left to cool down for a week or 2 weeks. The measured temperatures are listed in Tables 5.2 and 5.3. It shows that waiting on the sample to cool down for period of times more than a day did not change the observed behavior. Reheating it may reduce the time needed to reach a certain temperature.

Table 5.2 Temperature in ˚F of Preheated Activated Carbon with Time (Heated Weekly)

Day	Dry AC			Soaked AC in Water		
	0 sec.	10 sec.	20 sec.	0 sec.	10 sec.	20 sec.
1	72	382	785	72	97	169
8	70	537	800+	69	645	800+
15	69	672	800+	70	615	800+
22	69	721	800+	70	601	800+
29	74	689	800+	70	621	800+

Table 5.3 Temperature in ˚F of Preheated Activated Carbon with Time (Heated Biweekly)

Day	Dry AC			Soaked AC in Water		
	0 sec.	10 sec.	20 sec.	0 sec.	10 sec.	20 sec.
1	72	286	706	71	101	167
15	69	538	800+	70	495	800+
29	70	523	800+	70	593	800+

The temperature of the activated carbon samples measured after 10 seconds shown in Tables 5.2 to 5.3 are presented in the following two figures. Figure 5.9 is for the dry activated carbon and figure 5.10 is for the wet one. Notice that the general trend is similar. Heating the activated carbon changes its permittivity for at least one month. Reheating it several times may maintain or improve its performance but it is not as significant as the first time it is heated.

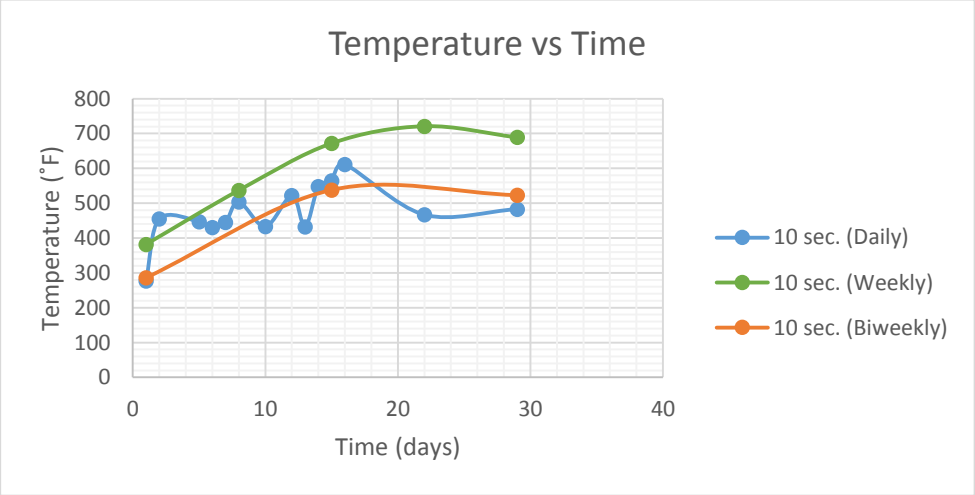


Figure 5.9 Effect of Reheating on Activated Carbon (Dry)

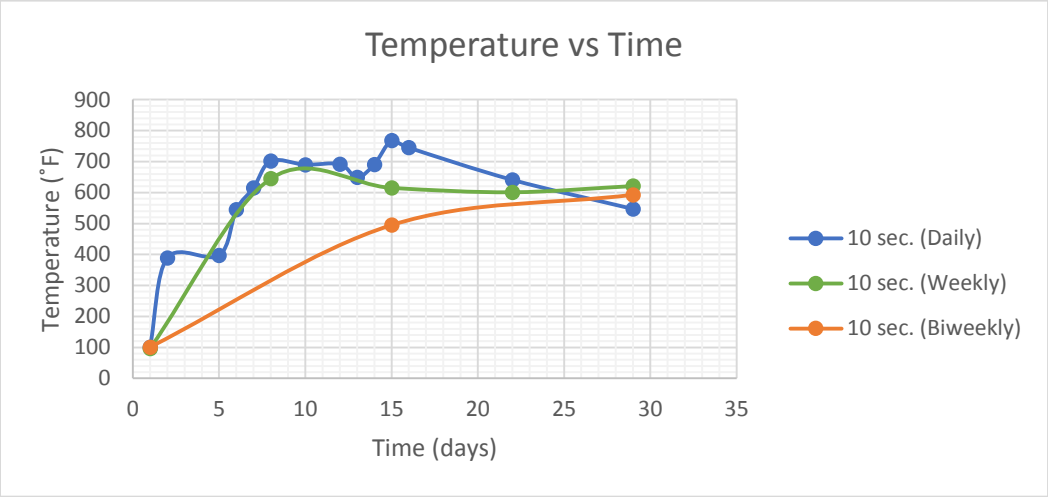


Figure 5.10 Effect of Reheating on Activated Carbon (Wet)

Further experiments were conducted to investigate reason behind the increase in temperature of preheated activated carbon. Three assumptions were tested. The first one is that activated carbon interacts or soak the vapor in the air and hence its permittivity changes. The second one is that microwave irradiations change the permittivity of the activated carbon. The last one is that the heat changes the way activated carbon reacts to microwave irradiations. To test the first one, two samples were left in the atmosphere for a whole week. The results (Table 5.4) shows that if activated carbon is not preheated, it heats up as if is taken from its container a heated immediately. This eliminate the first assumption.

Table 5.4 Temperature in ˚F of Activated Carbon with Time

Day	Dry AC			Soaked AC in Water		
	0 sec.	10 sec.	20 sec.	0 sec.	10 sec.	20 sec.
1	70	70	70	70	70	70
8	69	298	718	70	202	255
15	70	380	742	70	301	732
29	70	519	800+	71	462	765

Another two samples were heated for the first time using a stove top to over 800 ˚F. Table 5.5 shows that preheating the activated carbon by any mean changes the way it react to microwave. The preheated dry sample using stove top needed only 10 seconds to reach 507 ˚F. This is half the time needed for an unheated sample.

Table 5.5 Temperature in ˚F of Preheated Activated Carbon (Stove Top vs. MW)

	Day	Dry AC			Soaked AC in Water		
		0 sec.	10 sec.	20 sec.	0 sec.	10 sec.	20 sec.
Stove Top	**1**	Heated to 800+			Heated to 800+		
MW	**2**	71	507	800+	70	407	662
MW	**1**	71	277	543	71	101	171
	2	67	455	800+	67	389	755

Reheating aluminum oxide is investigated as well. 20 ml of aluminum oxide was heated using microwave and let cool down for a whole day. Reheating it did not change its behavior as shown in the following plot.

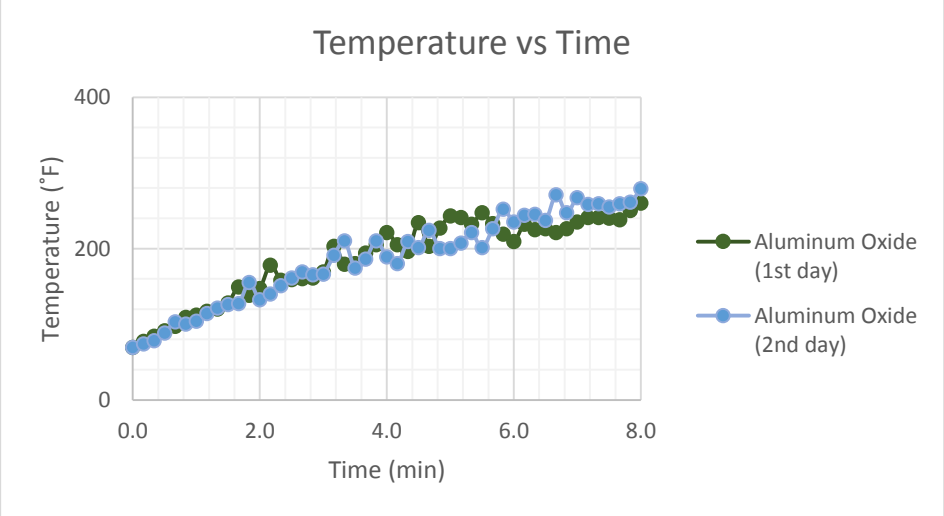


Figure 5.11 Effect of Reheating on Aluminum Oxide

The following plot shows the effect of reheating 20 ml of oil at different power levels. The samples were heated for the first time then reheated on the 2nd and 3rd days. The lighter components of oil evaporate as it is heated. As a result, the oil becomes heavier and hence more time and power is needed to heat it up.

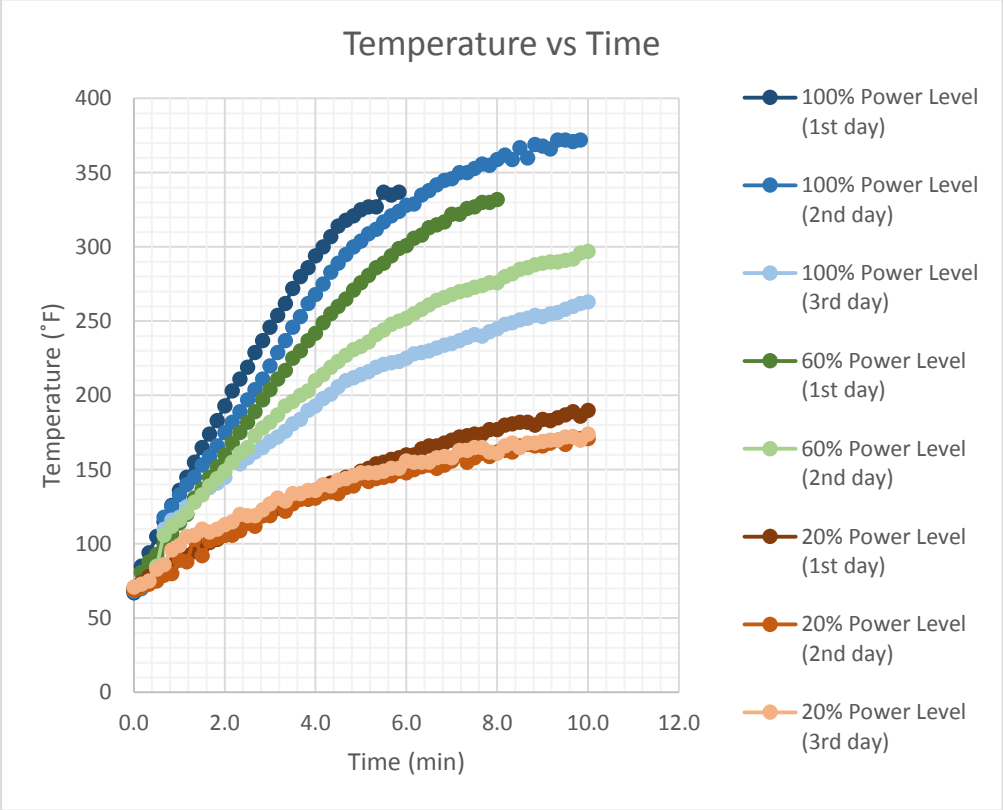


Figure 5.12 Effect of Reheating and Microwave Power Level on Oil

5.5 Activated Carbon Bath

If a mixture of activated carbon and oil is heated using microwave, an oil combustion will occur. The way oil is heated using the MAC technique in this study is to create an activated carbon bath. A small beaker filled with 20 ml of oil with a gravity of 24˚API. Then the beaker is placed inside another beaker filled 240 ml (84 grams) of activated carbon (figure 5.13). Everything is heated using the microwave and the temperatures of oil and activated carbon are monitored over time. The temperature of each substance is shown in figure 5.14. The figure also presents a comparison between the temperature of oil and activated carbon if heated in the bath or heated alone. Please keep in mind that the activated carbon used in the path was preheated using microwave.

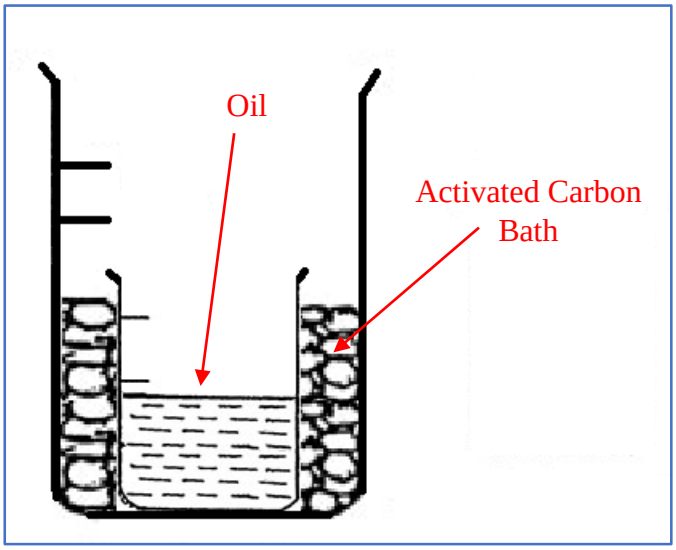


Figure 5.13 Longitudinal Section of Beakers Arrangement

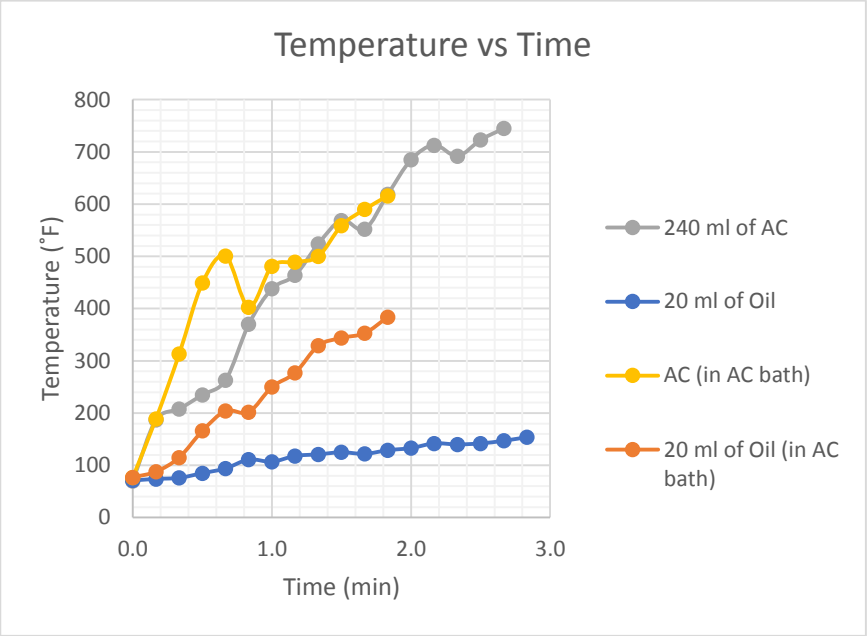


Figure 5.14 Activated Carbon Bath

The gray curve shows how the temperature of the activated carbon increases with time as it is preheated alone. After cooling down to a temperature of 70˚F the activated carbon bath was created. The oil sample was placed in the bath as shown in Figure 5.13. The yellow and orange curves shown in the figure above represent the temperature change with time of activated carbon and oil as they are heated using microwave. Notice that oil temperature increased to around 400˚F in less than 2 minutes due to the heat generated by microwaving the activated carbon. Since the activated carbon is preheated, it is expected that the rate its temperature increases be more than the first time it was heated. That is clear from the above figure but its temperature decreased after a while as some of generated heat transferred by conduction to the oil and increased its temperature.

5.6 Core Samples

Three core samples made of plaster are heated using microwave. The temperature along a vertical axis is measured over time. As mentioned earlier, the first one is just a core made of plaster. The second core is divided into two sections. The top one imitates a core sample with activated carbon filling some of its pore space. The bottom half is only a porous medium made of plaster. The last core imitates a hydraulically fractured core with activated carbon and aluminum oxide filling the fracture. The first figure below shows how the temperature of the core increases with time. Each curve represents a time step. The y-axis is the distance along a vertical plane starting at the base of the core sample. Notice that the temperature of the whole core increases slightly over time. This increase in the temperature is due to the water content of the core. Basically the core is made of plaster powder and water. Less temperature increase is expected if a real core sample is used.

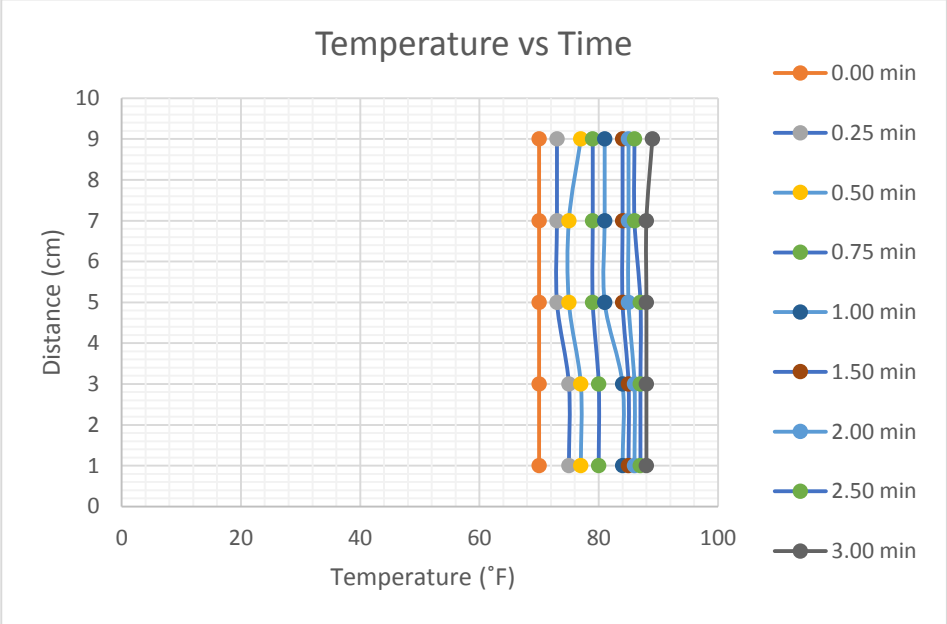


Figure 5.15 Temperature along a Vertical Axis on the 1st Core Sample

Figure 5.16 shows the temperature increase over time for the second core sample. Since the bottom half does not contain any activated carbon, the same behavior shown in the previous plot is expected. Closer to the top half (which is filled with activated carbon), the temperature increases with distance and time. Remember that the top half is not purely activated carbon. It is made of plaster and activated carbon.

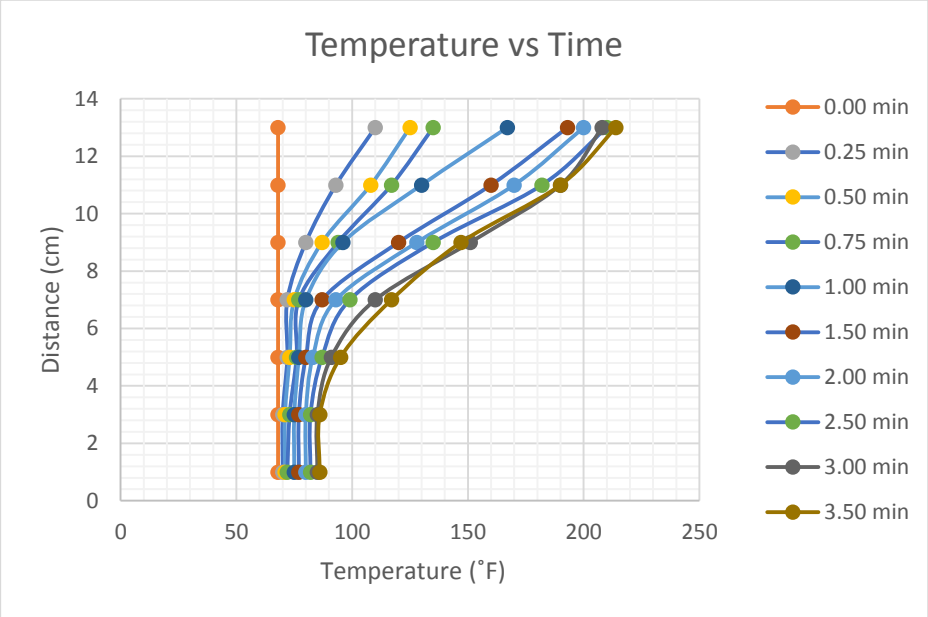


Figure 5.16 Temperature along a Vertical Axis on the 2nd Core Sample

The third core has a fracture that is filled with activated carbon. The temperature along a vertical axis over time is shown in Figure 5.17. The maximum temperature is measured at the middle of the core where the activated carbon is placed. As we move away from the middle of the core, the temperature declines. The temperature away of the fracture increases with time due to the heat generated by the activated carbon in the fracture and transferred to the core by conduction.

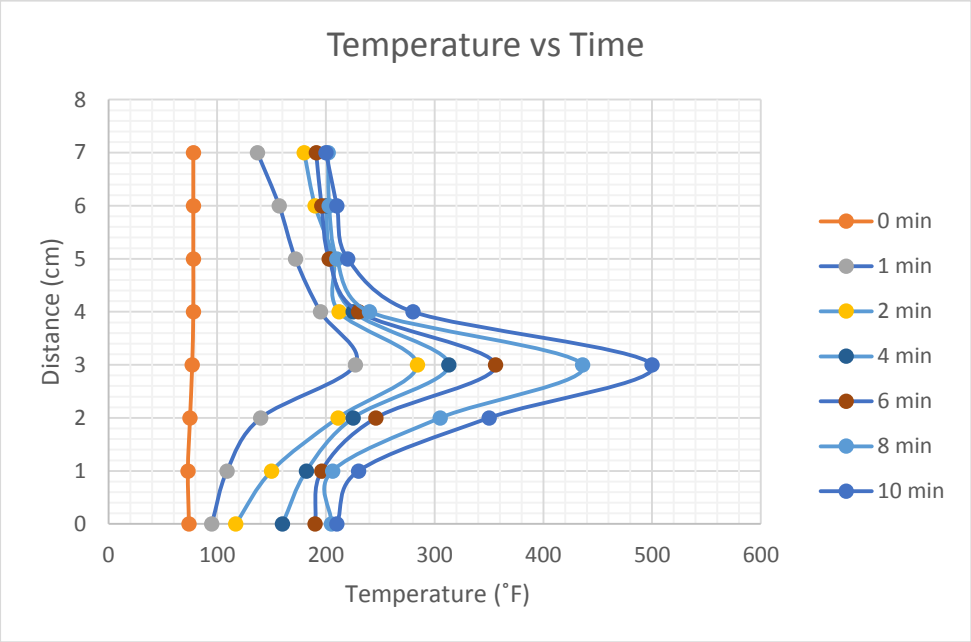


Figure 5.17 Temperature along a Vertical Axis on the 3rd Core Sample

5.7 Other Application of MAC Technique

MAC technique may be used to create micro-fractures in shale formations. Shale formations has very low permeability that makes it difficult to be produced. They require the creation of fractures to maximize the contact area with the reservoir. The new technique may allow the creation of micro-fractures that may increase the contact area around an existing hydraulic or natural fractures. It involves the use of microwave and activated carbon. It was tested experimentally and showed promising results.

In the new technique, hydraulic fracture(s) are created in shale formations and filled with activated carbon. Microwave antenna(s) will be placed inside the well. As mentioned earlier, activated carbon has significantly higher real and imaginary permittivity values than any naturally existing materials in oil reservoirs, namely water, oil, and rock and hence may heat to very high temperatures using microwave. Several micro-fractures may be created around the main hydraulic fracture due to the generated heat (figure 5.18). This will allow communication between the main fracture and any other natural fractures that does not intersect with the main hydraulic fracture. Consequently, this may increase the contact area with the reservoir. Similarly, natural fractures that intersect the hydraulic fracture may be filled with activated carbon and heated. That may allow the creation of other branches of micro-fractures around them and hence more area of the reservoir may be covered. Experiments were conducted on core samples made of plaster that are filled with activated carbon or a fracture is created in them and filled with activated carbon. The samples were heated using microwave. The heat generated because of the presence of activated carbon created fractures on these core samples (figure 5.19).

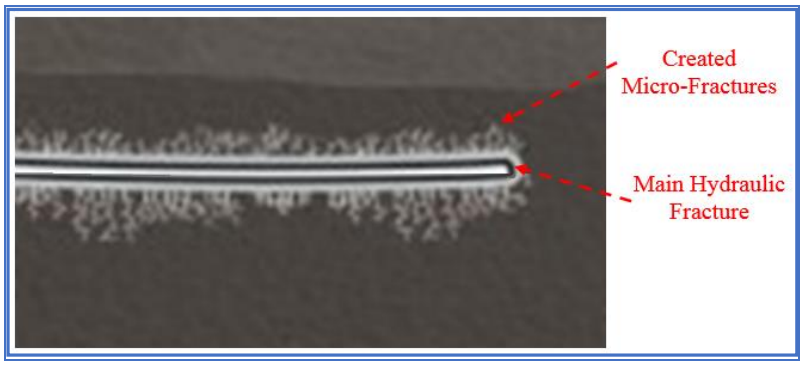


Figure 5.18 MAC Created Micro-Fractures

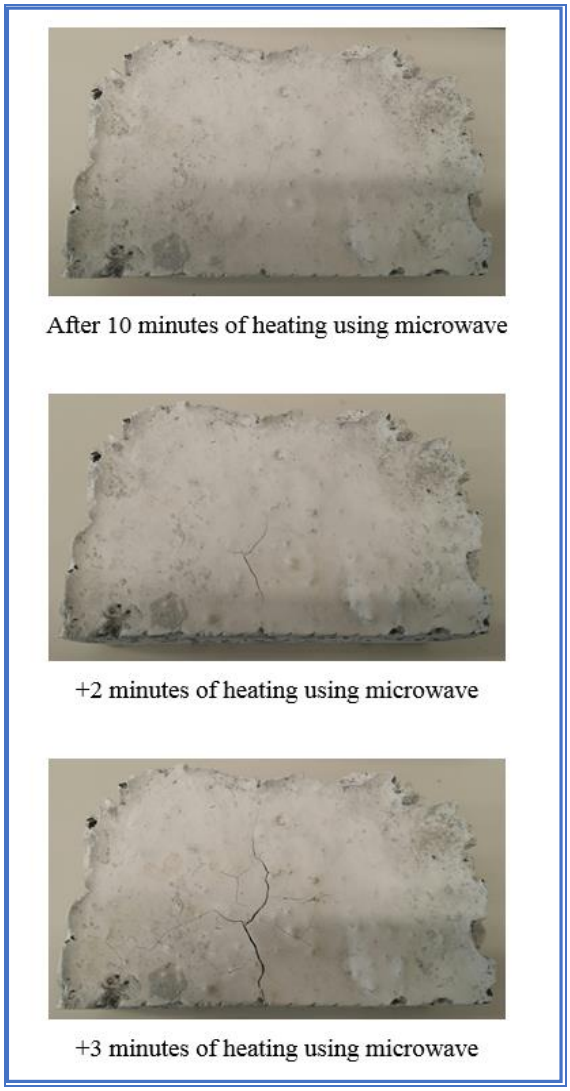


Figure 5.19 Microwave Heated Core Sample with Time

CHAPTER VI

MODELING

A thermal reservoir simulator developed by TAURUS Reservoir Solution Ltd is used for the modeling part of this dissertation. The modeled reservoir is a heavy oil reservoir is a homogenous reservoir that is approximately 6 meters thick. It covers a surface area of 5248 m^2 (82 x 64 m). The reservoir is divided into 6 layers (1 m thick each). The following table lists the reservoir properties.

Table 6.1 Reservoir Characteristics

Length (m)	82
Width (m)	64
Thickness (m)	6
Porosity (-)	0.175
Horizontal Permeability (Darcy)	2.20
Vertical Permeability (Darcy)	1.10
Initial Water Saturation (-)	0.20
Temperature (˚C)	13.0

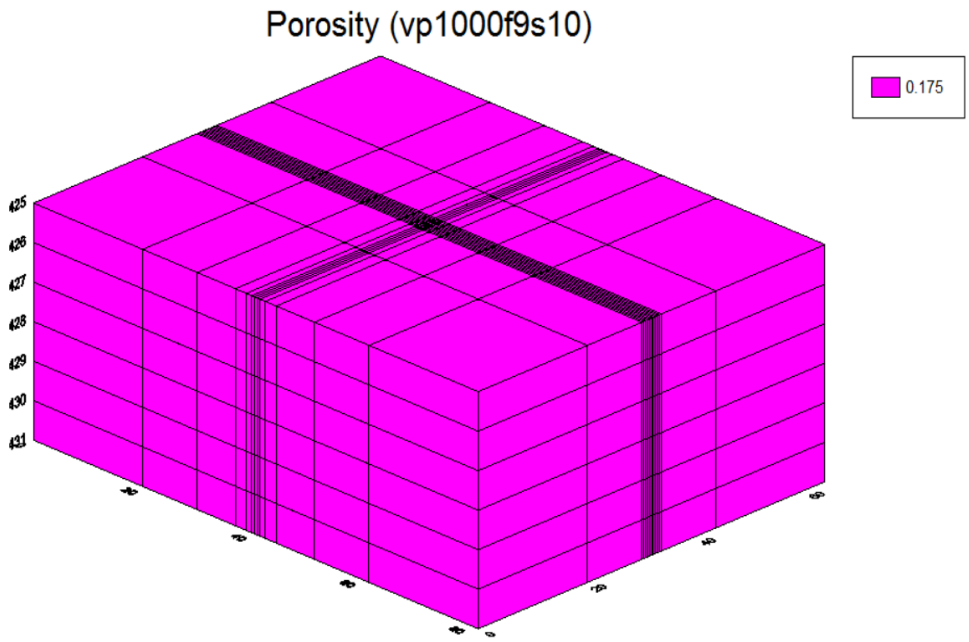


Figure 6.1 3D Model of the Reservoir

The oil viscosity as function of temperature is shown in the figure 6.2. Water viscosity is calculated internally using standard correlations. Figure 6.3 shows the relative permeability curves.

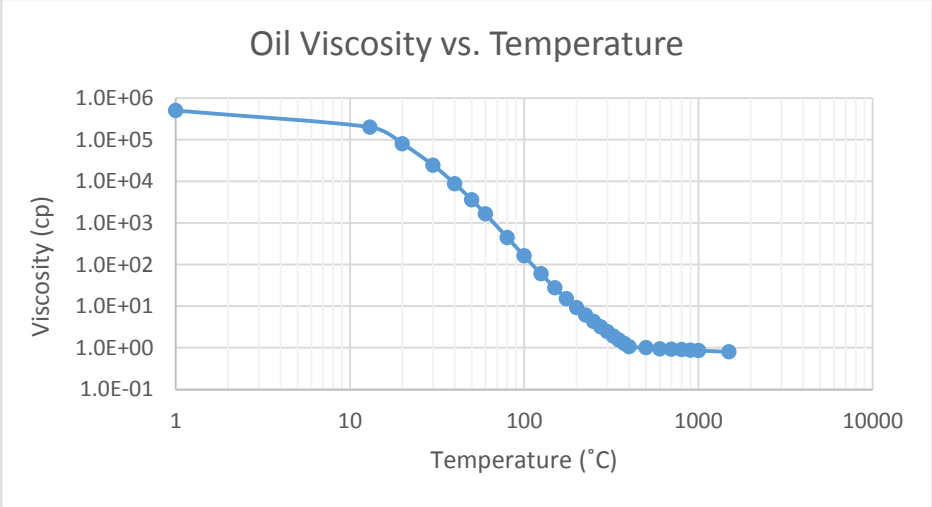


Figure 6.2 Oil Viscosity vs. Temperature

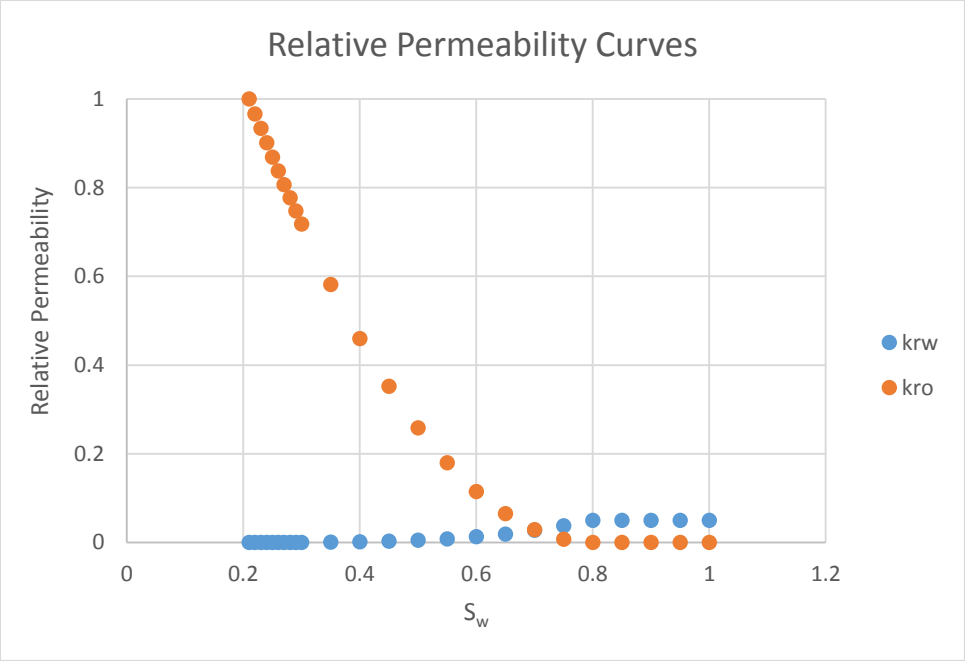


Figure 6.3 Relative Permeability Curves

In this dissertation, several ideas to improve the process of heating heavy oil reservoirs are tested and significant improvement is observed. The ideas may be as simple as the use of microwave or as complicated as combining several techniques to produce the reservoir.

6.1 Radius of Investigation

In this section, how deep into the reservoir may microwave irradiations go is investigated. Although this depends on many factors, in this study, microwave frequency, power level and initial water saturation are investigated.

6.1.1 Microwave Frequency

The simulator may handle two microwave frequencies (0.915 and 2.45 GHz). It is known that higher frequencies are stronger but goes for shorter distances. The

simulation results reaches the same conclusion. When the microwave antenna has a 2.45 GHz, higher temperatures are recorded close to the antenna but the microwave irradiation does not go deep into the formation. On the other hand, 0.915 GHz frequency results in less temperature but much deeper effect. Figures 6.4 (a, b, c) show a comparison between the two cases after heating a reservoir for a whole month. In both cases, the antenna is 3.5 m long horizontal antenna and is located in layer # 5. Although the 2.45 GHz frequency level results in more heat generation, it is not always the best option to produce heavy oil reservoirs. Sometimes, raising the temperature a little bit may reduce the oil viscosity to a degree where it is easy to be produced and that may be reached using a 0.915 GHz microwave frequency. This way more area may be covered and hence more oil may be produced.

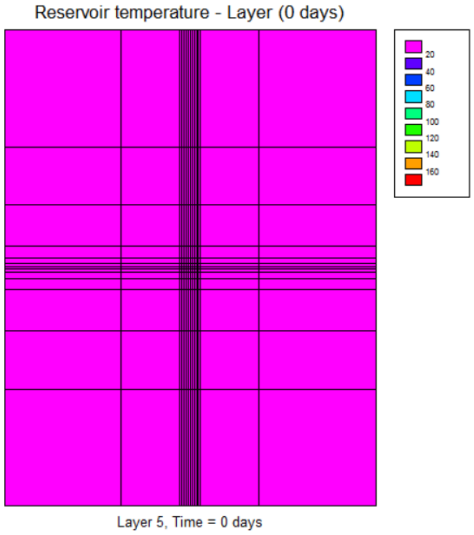


Figure 6.4 (a) Temperature Contour Map (Layer 5 – Time = 0 days)

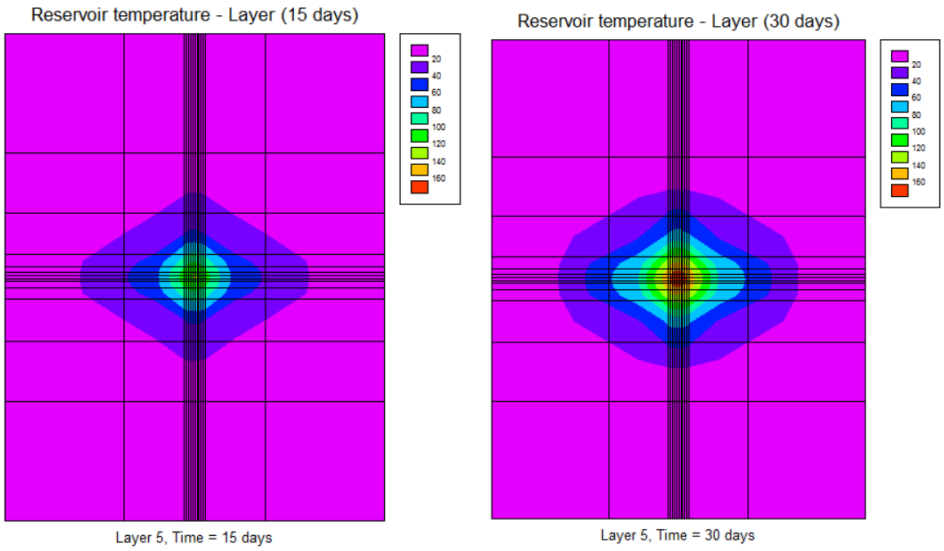


Figure 6.4 (b) Temperature Contour Map (Layer 5 – Frequency = 0.915 GHz)

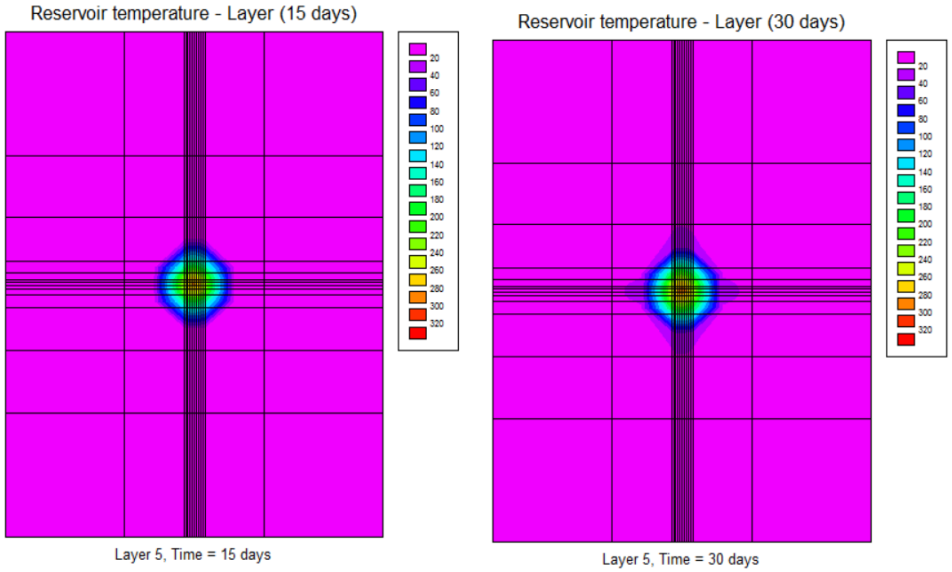


Figure 6.4 (c) Temperature Contour Map (Layer 5 – Frequency = 2.45 GHz)

6.1.2 Microwave Power Level

Higher power levels generates more heat in less time. Figure 6.5 show a comparison between three cases after 30 days of heating. The power levels are 50, 100, and 200 kW. In the case of 200 kW, the highest temperature is around 280˚C, however in the 50 kW power level, it is around 110˚C. Furthermore, microwave antennas with more power levels may go deeper into the reservoir.

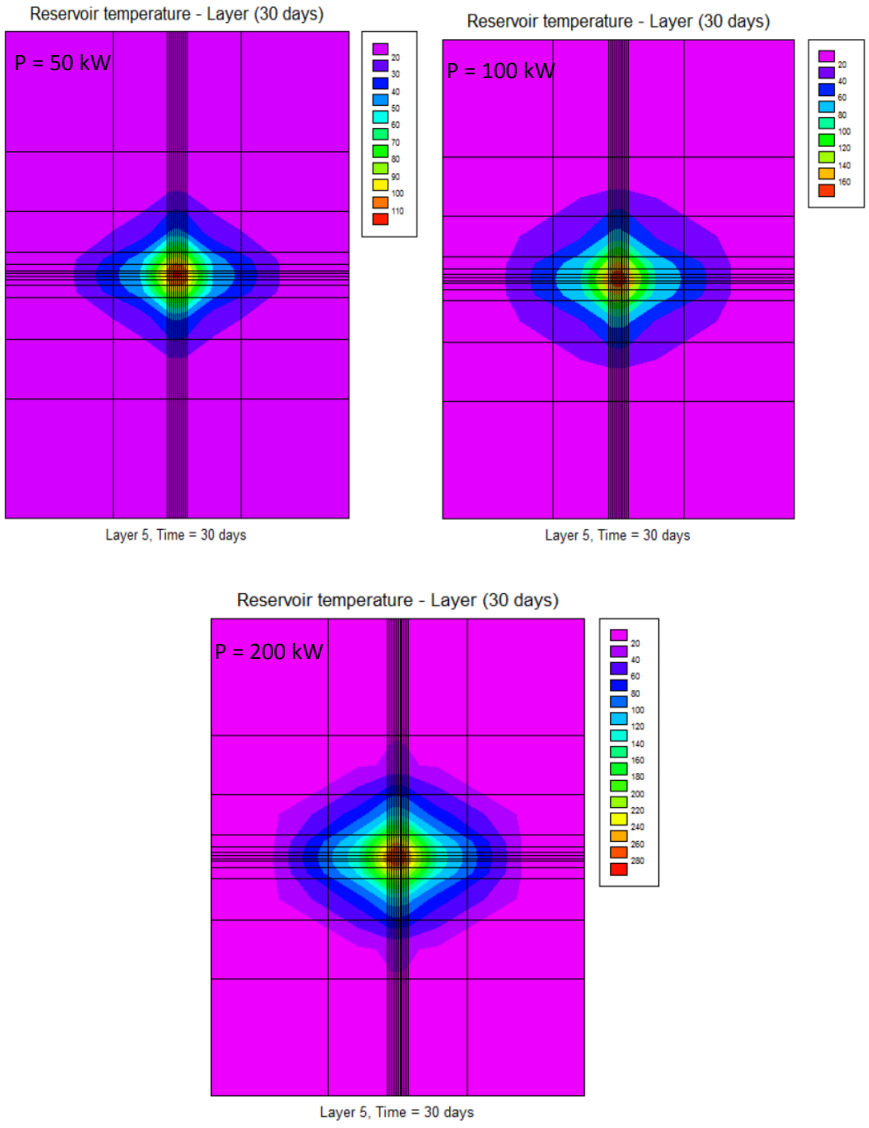


Figure 6.5 Temperature Contour Map for Different Power Levels (Frequency = 0.915 GHz)

6.1.3 Initial Water Saturation

Initial water saturation plays a role of how much heat is generated using microwave. The following plot illustrate the difference between two cases with initial water saturation of 20 and 40%. The higher the water saturation, the more generated heat. In the case of 20% water saturation, the maximum observed temperature after 30 days is around 160˚C. On the other hand, it reaches a 280˚C when the initial water saturation doubles. The depth where microwave irradiation may go into the reservoir does not depend on the water saturation.

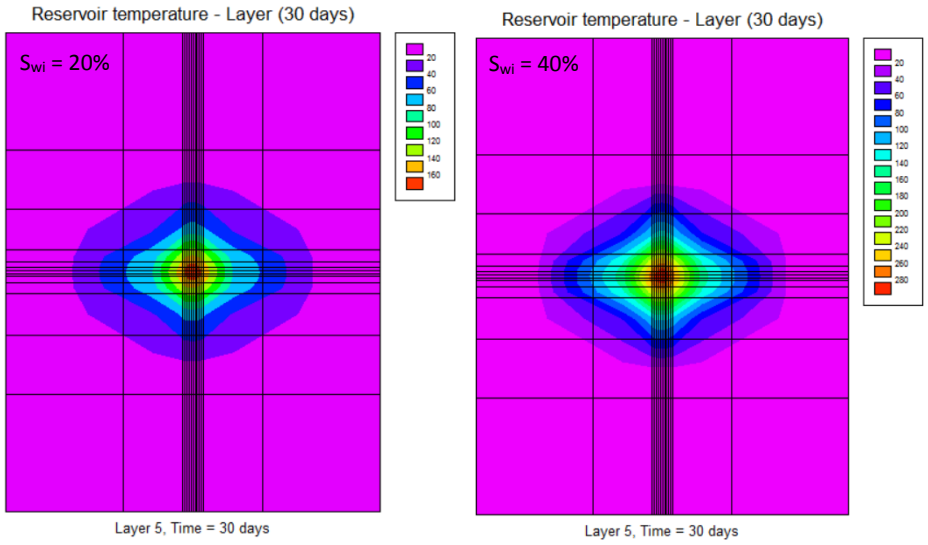


Figure 6.6 Temperature Contour Map for Different S_{wi} (Frequency = 0.915 GHz)

After a month of applying microwave at 0.915 GHz frequency, its affect can be observed between 15 and 20 meters into the reservoir. That covers an area of around 1000 m^2. Heating for longer period of time results in more covered area and higher temperatures.

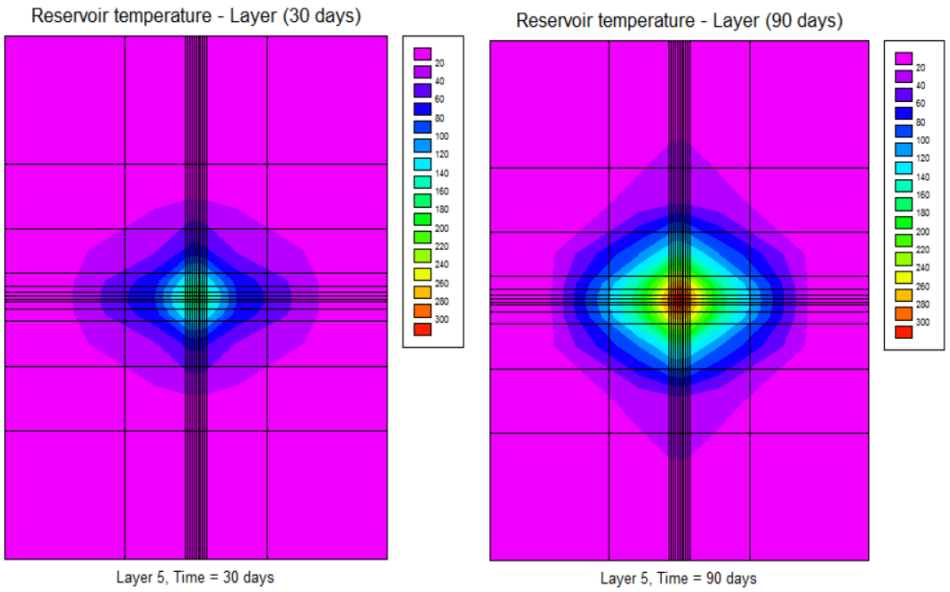


Figure 6.7 Temperature Contour Map for Different Heating Times (Frequency = 0.915 GHz)

It is obvious that the depth of investigation strongly depends on the microwave frequency level and the time microwave irradiation is applied. Increasing the power level or the water saturation may increase the covered area slightly but their significant effect is on the amount of generated heat.

6.2 Base Case

The studied reservoir in this dissertation cannot be produced without the application of any thermal recovery technique. In the base case, the reservoir is heated using a 3.5 m horizontal microwave for 15 days. The microwave has a frequency of 0.915 GHz and a power level of 100 kW. After 15 days, a horizontal well that is 1 m below the microwave well starts to produce oil. The horizontal producer is a short one that has the same length as the microwave antenna of 3.5 m. The microwave does not stop working until the end. The following plot presents the production rate and cumulative production for 90 days. The cumulative production is around 73 m^3 produced over a period of 75 days. That is around 1.7% of the IOIP. Figure 6.9 presents a contour map of the reservoir temperature over time.

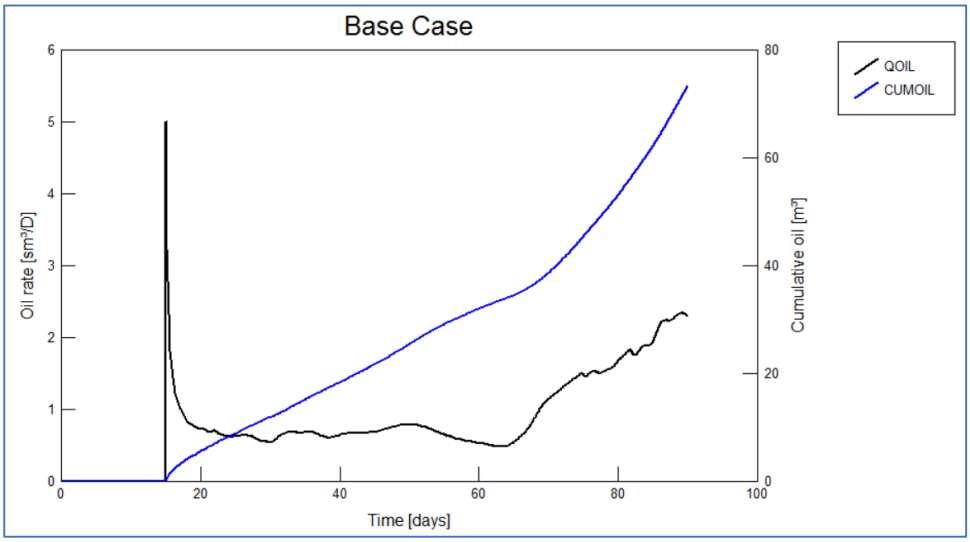


Figure 6.8 Oil Production Rate and Cumulative Production (Base Case)

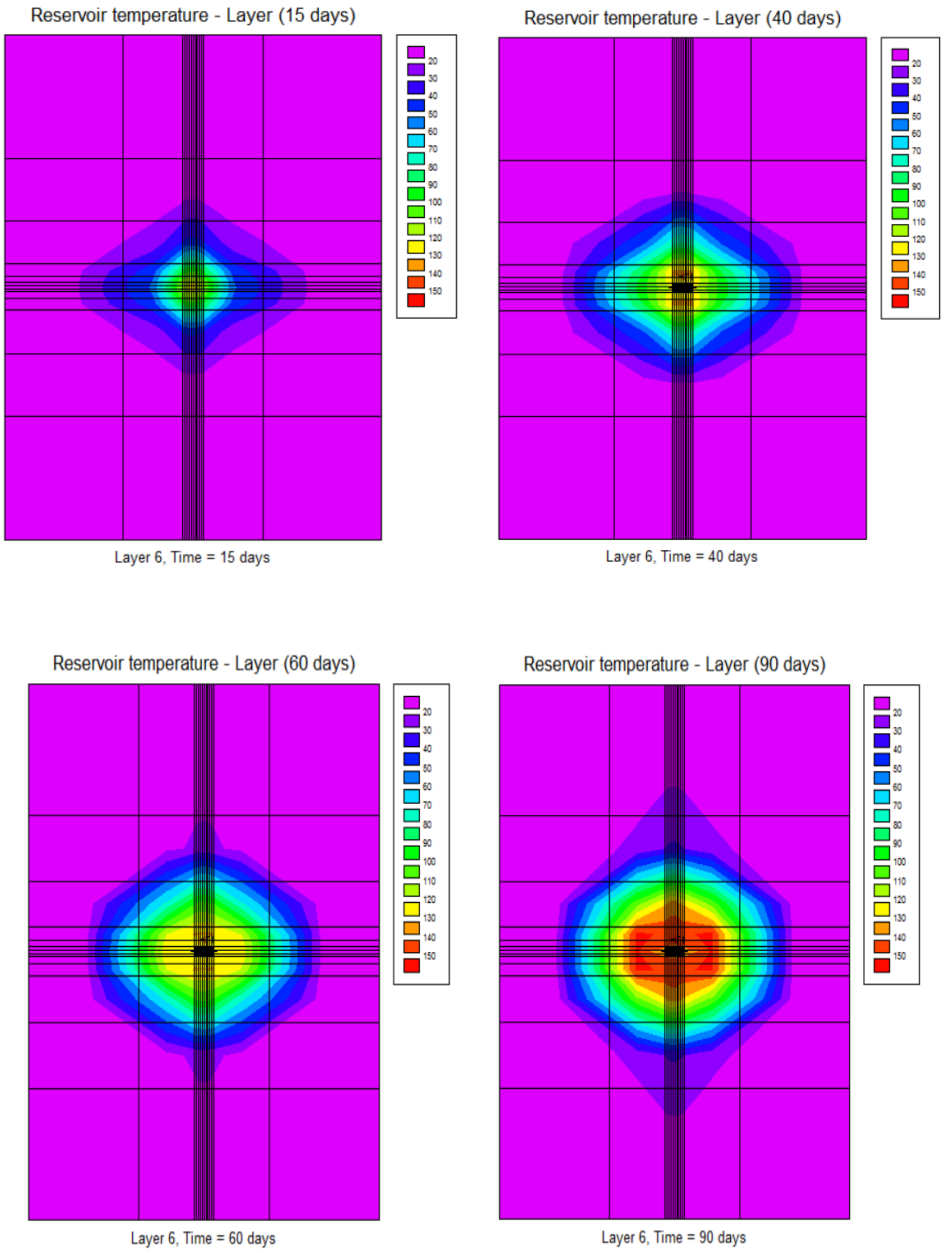


Figure 6.9 Temperature Contour Map at Different Times (Base Case)

6.2.1 Microwave Power Level

The first factor to be investigated is the microwave power level. Increasing the power level would increase the recovery factor. The cumulative oil production increased from 73 m^3 to around 250 m^3 by increasing the power level from 100 kW to 500 kW. Doubling the power level to 1000 kW added around 9 m^3 to the cumulative production. Figures 6.10, 6.11, 6.13 and 6.14 presents the production and pressure forecast for the 500 and 1000 kW cases. Notice that the reservoir pressure increases as the microwave heats up the reservoir for the first 15 days. That is due to the expansion of the liquids and steam generation resulted from heating the reservoir. Also, the pore space reduces as a result of the expansion of the grains.

The microwave antenna is automatically set up to run until the temperature reaches around 300˚C. That restriction is applied to maintain the wellbore integrity. As soon as the temperature reaches that limit, the microwave antenna shuts down allowing the reservoir to cool down to a minimum limit (set up to 260˚C) at which the microwave turns on again. Figure 6.15 shows the temperature of a grid as function of time. It is clear from the plot that the microwave works within a temperature window. Figures 6.12, 6.16, and 6.17 present contour maps of temperature and oil saturation over time. The temperature around the wellbore changes over time due to cycles of operation of the microwave antenna.

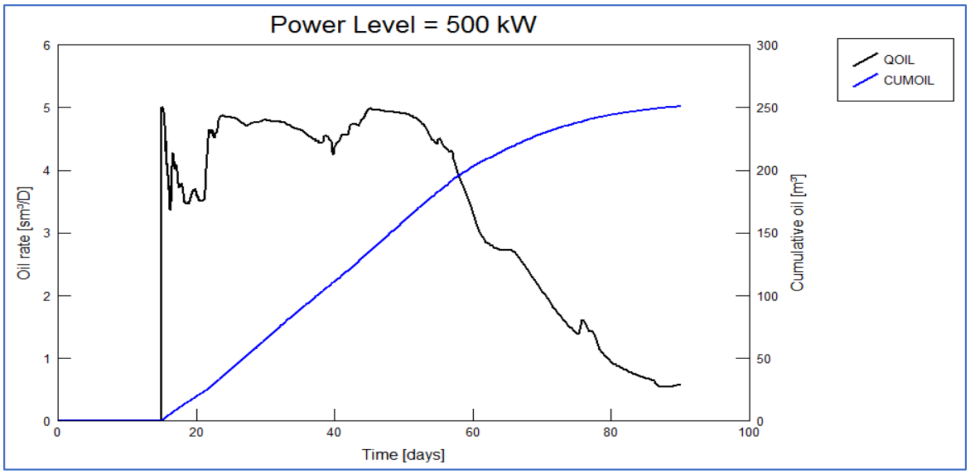


Figure 6.10 Oil Production Rate and Cumulative Production (Base Case)

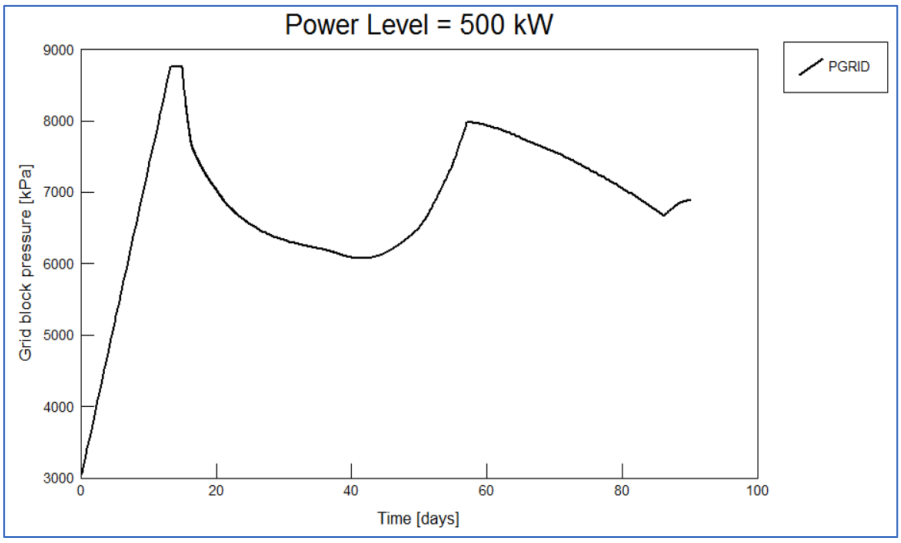


Figure 6.11 Grid Block Pressure (Base Case)

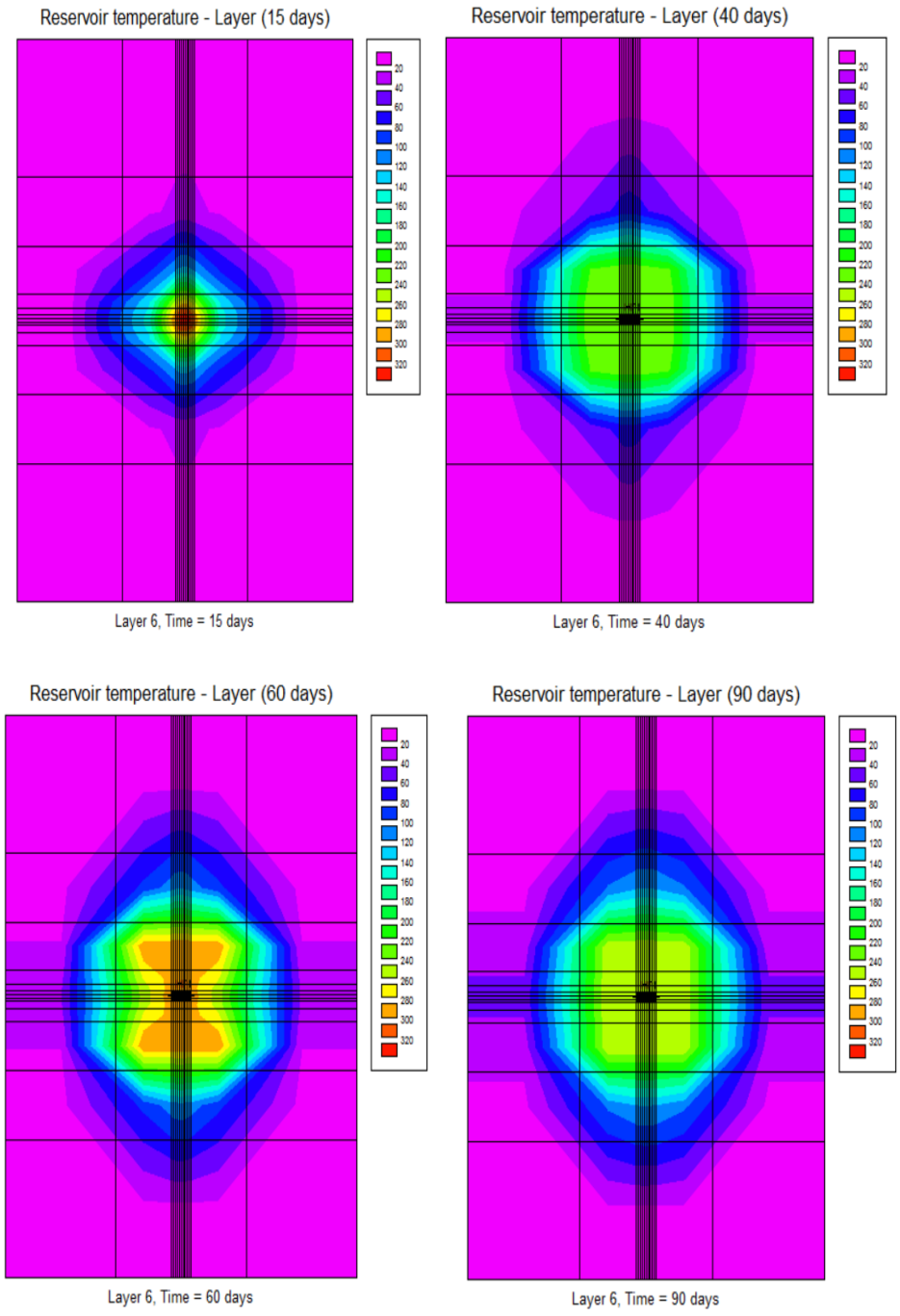


Figure 6.12 Temperature Contour Map at Different Times (Power Level = 500 kW)

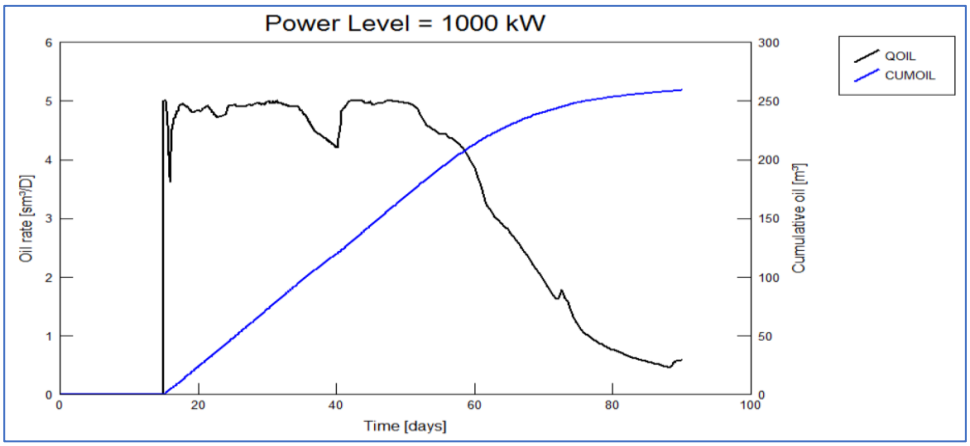


Figure 6.13 Oil Production Rate and Cumulative Production (P = 1000 kW)

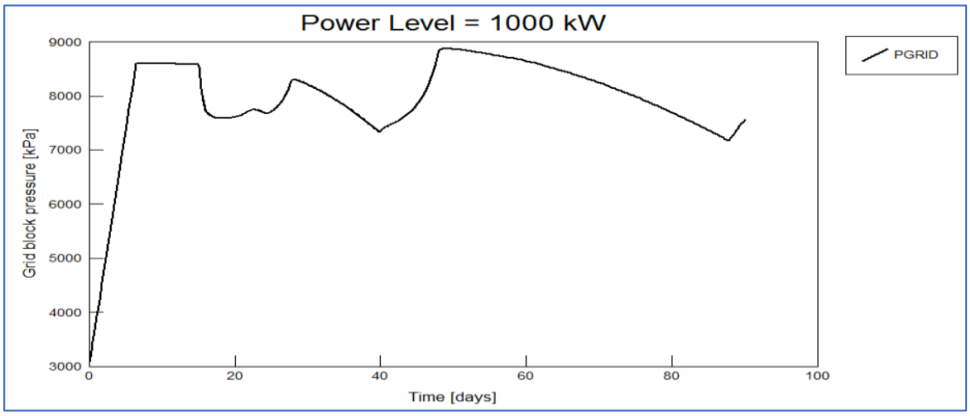


Figure 6.14 Grid Block Pressure (P = 1000 kW)

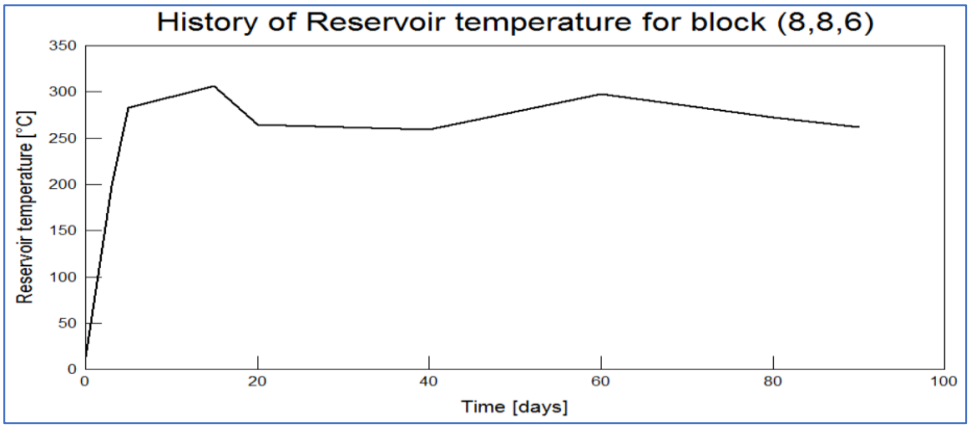


Figure 6.15 Grid Block Temperature (P = 1000 kW)

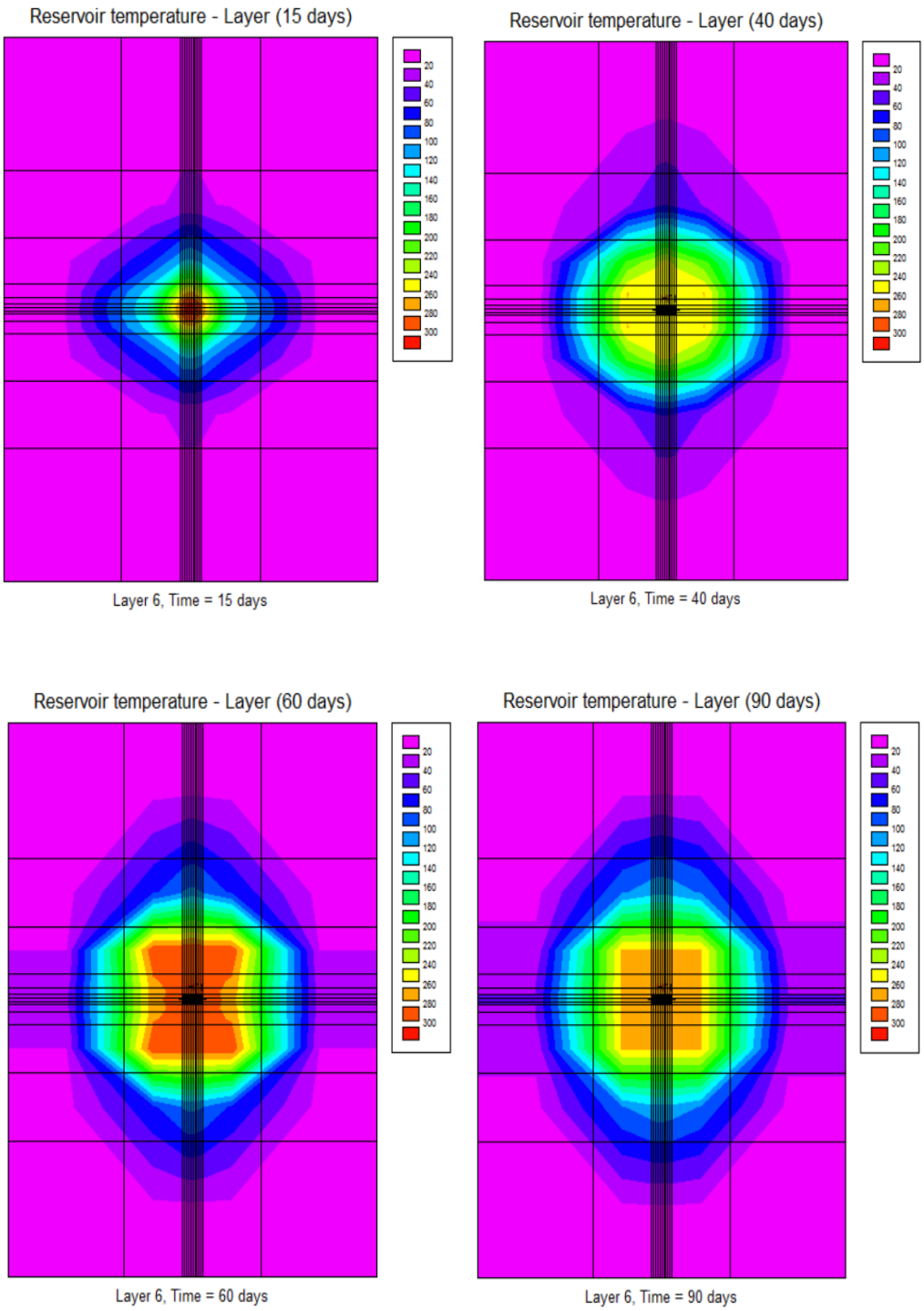


Figure 6.16 Temperature Contour Map at Different Times (Power Level = 1000 kW)

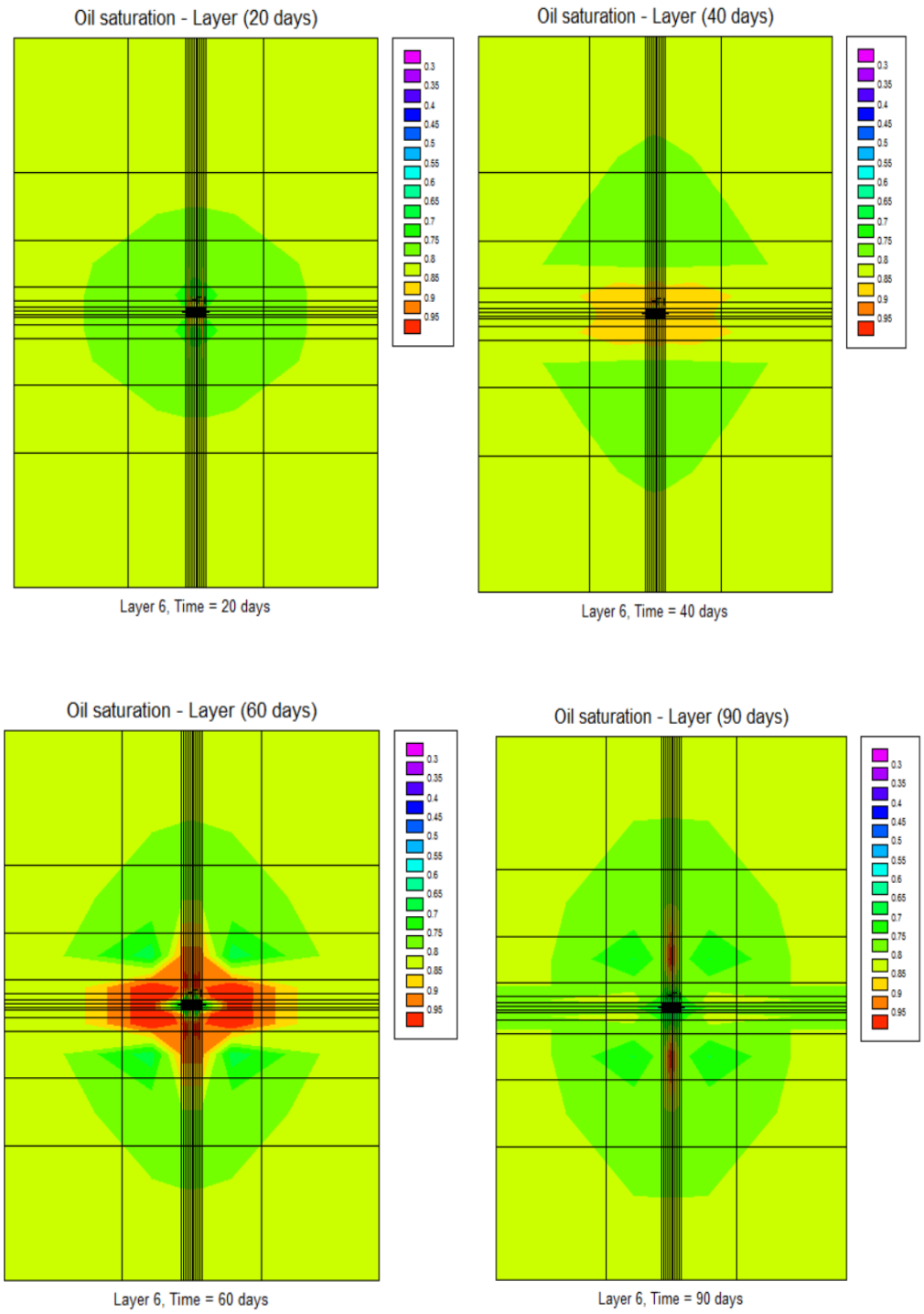


Figure 6.17 Oil Saturation Contour Map at Different Times (Power Level = 1000 kW)

Table 6.2 presents a comparison between all the cases. It is clear that increasing the power would increase the cumulative oil production. However, that increases the required energy per cubic meter of produced oil. An economic analysis is required to find the optimum power level to produce heavy oil reservoir using microwave.

Table 6.2 Comparison between Different Microwave Power Levels

Power Level	**MW Time (Days)**	**Total Time (Days)**	**Production (m^3)**	**% of IOIP**	**Incr. %**	**Water (m^3)**	**Energy (kJ)**	**kJ / m^3**
100 kW	15	90	73.4	1.69		5.5	3.1E+07	4.2E+05
500 kW	15	90	251.2	5.77	342%	122.9	2.5E+09	9.9E+06
1000 kW	15	90	259.4	5.96	353%	115.3	2.5E+09	9.5E+06

6.2.2 Initial Water Saturation

As stated earlier, the initial water saturation does not play a significant role of how deep the microwave irradiation would go into the reservoir. As a result, the less the initial water saturation, the more the available oil to be produced. Although more water means more generated heat due to the high permittivity of water, but the generated heat out of 10% water saturation is significant to reduce the viscosity of the heavy oil to be produced. This is clear in table 6.3, where in the cases of lower initial water saturation, more percentage of the initial oil in place is produced. The less the oil saturation means more water and less oil is available for production.

Table 6.3 Comparison between Different Reservoir S_{wi}

S_{wi}	MW Time (Days)	Total Time (Days)	Production (m^3)	% of IOIP	Water (m^3)	Energy (kJ)	kJ / m^3
0.10	15	90	313.9	6.41	62.1	2.8E+09	9.0E+06
0.20	15	90	259.4	5.96	115.3	2.5E+09	9.5E+06
0.30	15	90	213.1	5.60	162.0	2.8E+09	1.3E+07
0.40	15	90	152.2	4.66	222.3	2.7E+09	1.7E+07

6.3 Techniques to Increase Recovery Factor

The recovery factor may be increased by applying other techniques with the microwave. The following techniques are investigated in this study:

1. Create a network of producers and microwaving wells.
2. Cyclic operation of the microwave (huff and puff).
3. Add water or steam injection.
4. Use of activated carbon.

These techniques are illustrated and discussed in the following sections. Another reservoir is created to conduct this study. It is a bigger reservoir to accommodate more wells but its characteristics and fluid properties remain as the one mentioned earlier. Furthermore, in the new scenarios, the reservoir is heated for 50 day then the production starts. The length of the microwave antenna and the horizontal producer is 3.5 m. The microwave antenna has a frequency of 0.915 GHz because it may go deeper into the reservoir than 2.45 GHz.

6.3.1 Producers/Microwave Network

In the new reservoir, creating one producer and one microwaving well results in a cumulative production of 43 m^3. Instead of having a producer and a microwaving well, a network of producers and injectors are drilled in the reservoir and the results are analyzed. The way wells are arranged plays an important role of how much may be recovered. Following some pattern similar to the ones in water flooding may increase the recovery factor.

Different wells configurations are studied in this dissertation. Tables 6.4 and 6.5 present these well arrangements and the expected cumulative oil production. The producers are arranged to be in the same layer and similarly the microwaving wells. The distance between any two wells in the same layer is around 20 m. The distance between the producers and the microwaving wells is 1 m. The arrangement between the producers and the microwaving wells may be one of two, overlapping or staggered. Figure 6.18 illustrates the difference between the two. In all the cases mentioned in Tables 6.4 and 6.5, the wells are overlapping except the last row in table 6.4.

Table 6.4 Different Producers/Microwave Arrangements (P = 100 kW)

Case	Power Level (kW)	Microwaving Time (Days)	Production Time (Days)	Total Time (Days)	Cum. Prod. (m^3)	Incr. %
1 Producer and 1 MW Antenna	100	50	40	90	43.2	----
1 Producer and 1 MW Antenna	400	50	40	90	164.0	380%
2 Producers and 2 MW Antennas	100	50	40	90	85.8	199%
3 Producers and 3 MW Antennas	100	50	40	90	129.5	300%
1 Producer and 3 MW Antennas	100	50	40	90	110.0	255%
2 Producers and 3 MW Antennas (Staggered)	100	50	40	90	114.9	266%

Table 6.5 Different Producers/Microwave Arrangements (P = 400 kW)

Case	Power Level (kW)	Microwaving Time (Days)	Production Time (Days)	Total Time (Days)	Cum. Prod. (m^3)	Incr. %
1 Producer and 1 MW Antenna	400	50	40	90	164	
2 Producers and 2 MW Antennas	400	50	40	90	406	248%
1 Producer and 3 MW Antennas	400	50	40	90	690.4	421%

Increasing the number of wells or increasing the power level increases the cumulative production. Combining both of them would increase the cumulative production further. However, it is clear from the table that it is not necessary to have

the same number of producers as the number of microwaving wells. That is clear by comparing the case where 3 producers and 3 microwaving wells are drilled to the case where only one producer is drilled instead of 3. The first scenario producers more oil but is it economical to drill additional two wells for this increment. Detailed economic analysis is required to make such a decision. It is may be more economical to heat larger areas of the reservoir by several microwaving wells and drill fewer number of producers.

Placing the producers and the microwaving wells in the staggered configuration (figure 6.18) may increases the cumulative production. The cumulative production after 90 days using a 100 kW microwave antennas is 114.9 m^3. That is 5% increase in the production when having 1 producer and 3 microwaving wells. But keep in mind that staggered configuration requires one more producer to be drilled. Economic analysis should be made before deciding whether to have overlapping, staggered wells, or only one producer and a group of microwaving wells.

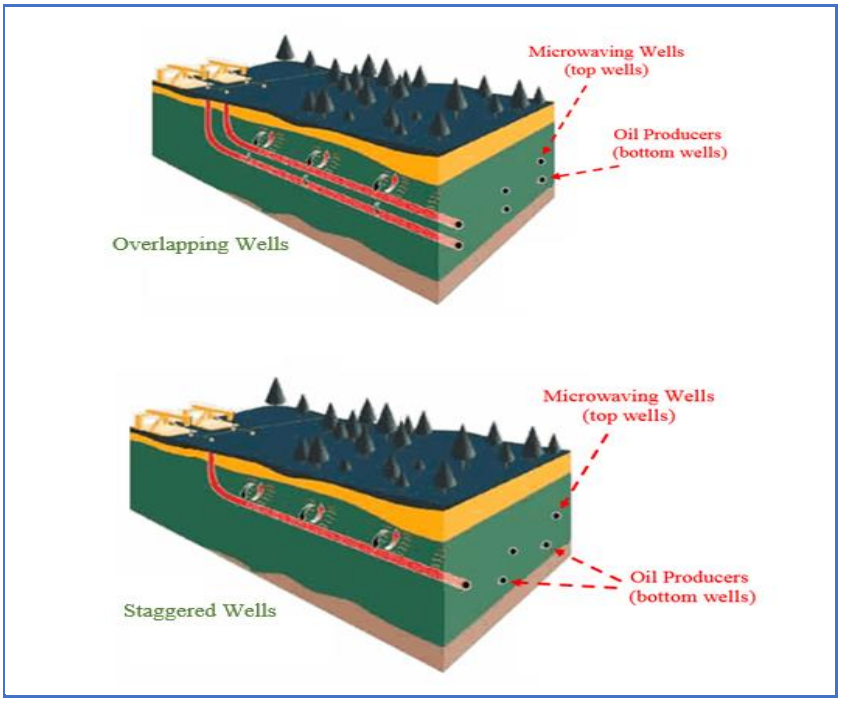


Figure 6.18 Overlapping vs. Staggered Wells

6.3.2 Cyclic Production/Microwaving Operation

In this technique, the reservoir is heated over a period of time then the production starts. When the oil production declines, the producer and the microwave are shut down for a certain period of time. During this time, the reservoir cools down and oil fills the produced pore space. The microwave is shut down to save energy and hence reduce cost. Then the cycle repeats itself starting with heating the reservoir using microwave. The cycle may be repeated several time. To illustrate the significant of this technique, two cases are discussed in this section. The first one includes two production cycles and the other one include three cycles. The cycle consists of a microwaving period of 50 days then a production period of 40 days. Then both the producer and the microwave shuts down for 30 days. In all the cases, 3 producers and 3 microwaving wells (overlapping) are drilled similar to the ones in figure 6.18.

In the first scenario, the reservoir goes through a cycle as mentioned above then everything shuts down for 30 days. Then another cycle starts. The oil production rate and cumulative production are shown in figure 6.19. The cumulative oil production at the end is 262 m^3. The total time of production is 80 days. If the reservoir is heated for 50 days then produced for uninterrupted period of 80 days (no shut in period), the production results are shown in figure 6.20. Although the production period is the same for both cases, the cumulative production of the cyclic operation is 22% more than the continuous production.

Similar to the first scenario, the second scenario is a cyclic operation but with three production/microwaving period and two shut in period. The production results for both a cyclic operation and an uninterrupted period are shown in figures 6.21 and 6.22. Notice that cyclic operation cumulative production is 460 m^3, which is a 60% more than the continuous production. Figure 6.23 illustrate the oil saturation contour map as function of time for the case with 3 cycles of production. As the oil produces, the oil saturation around the well decreases with time. Then, in the shut in period, oil fills the pores increasing the oil saturation around the well. After that the oil is produced again in the second production period and so on. Figure 6.24 presents the

temperature of one of the cells close to the microwave antenna. The temperature increases in the operating periods and the reservoir cools down when the microwave is shut down during the shut in periods.

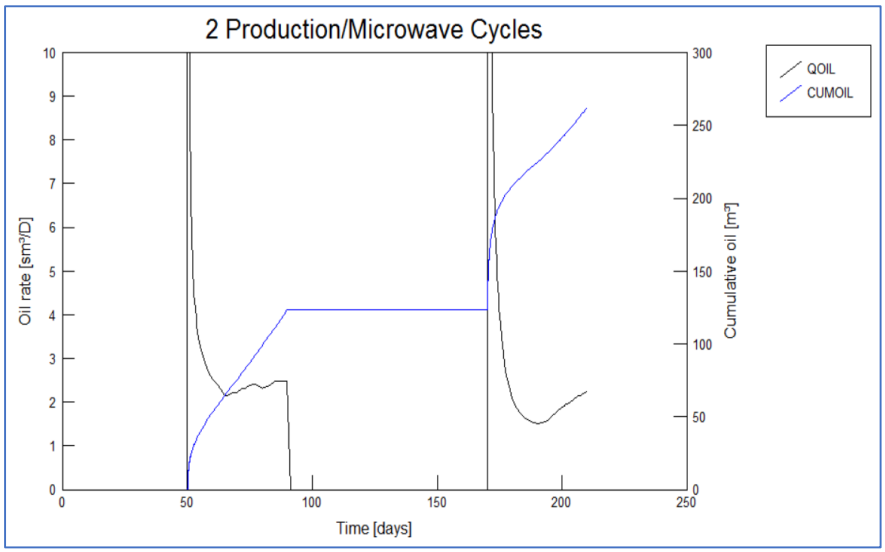


Figure 6.19 Production Results for 2 Operation Cycles

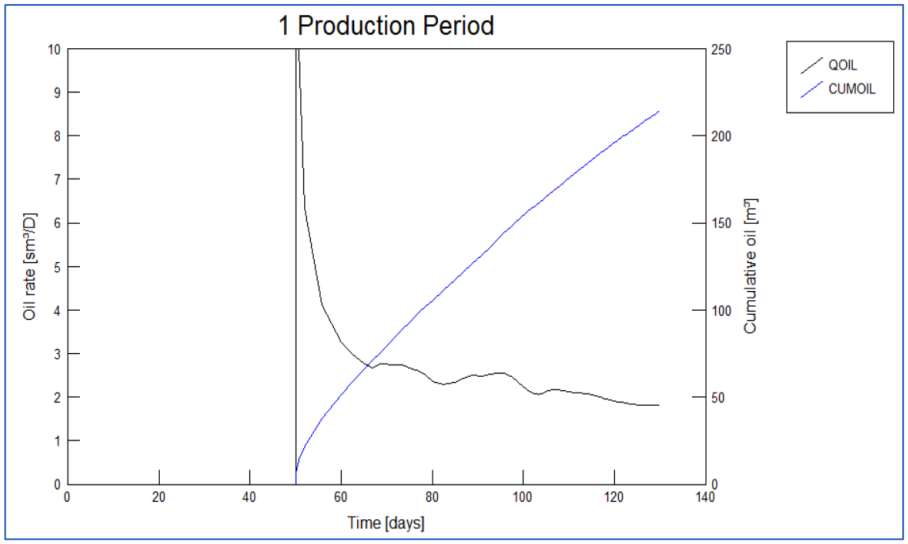


Figure 6.20 Production Results for 1 Period of Production of 80 days

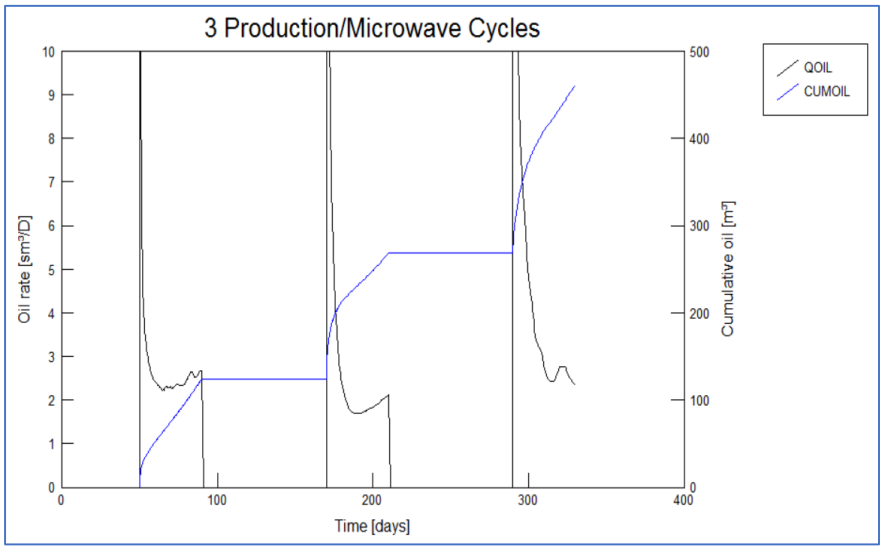


Figure 6.21 Production Results for 3 Operation Cycles

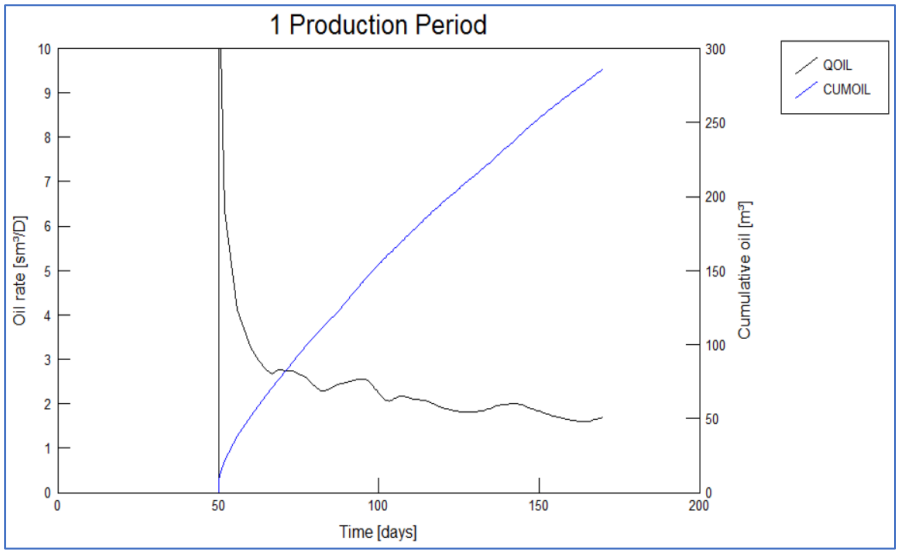


Figure 6.22 Production Results for 1 Period of Production of 120 days

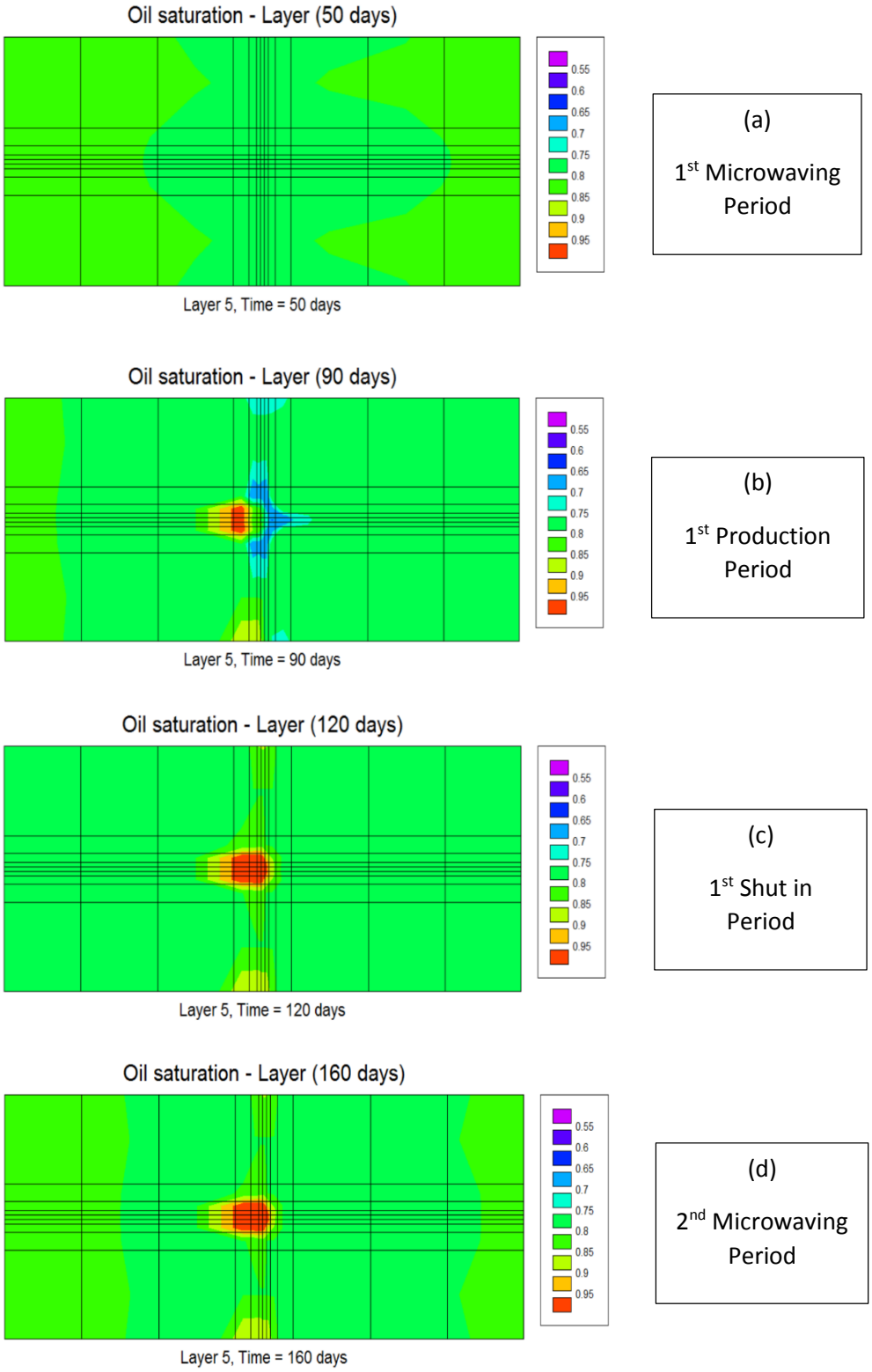


Figure 6.23 (a – d) Temperature Contour Map for 3 Operation Cycles

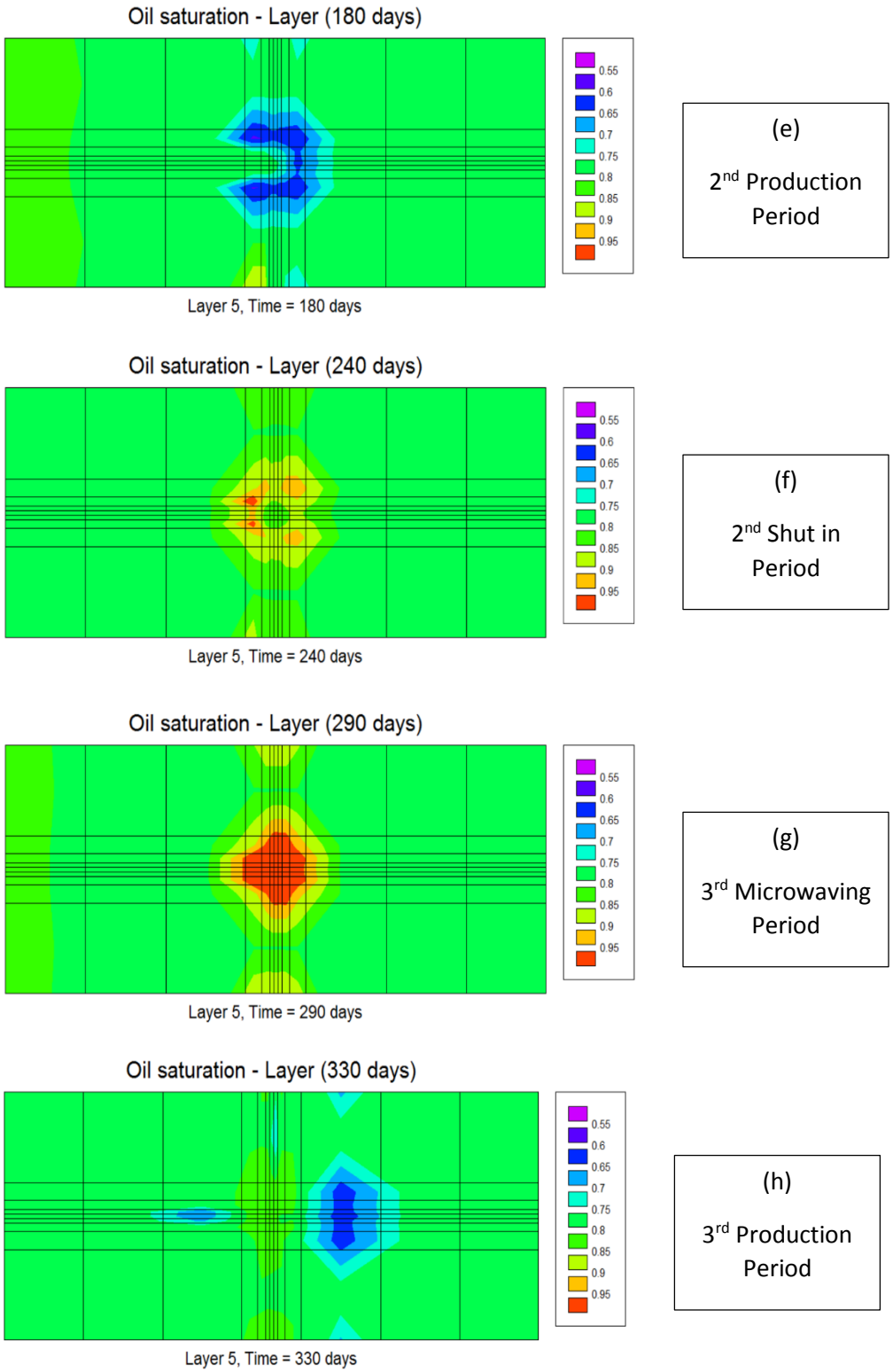


Figure 6.23 (e – h) Temperature Contour Map for 3 Operation Cycles

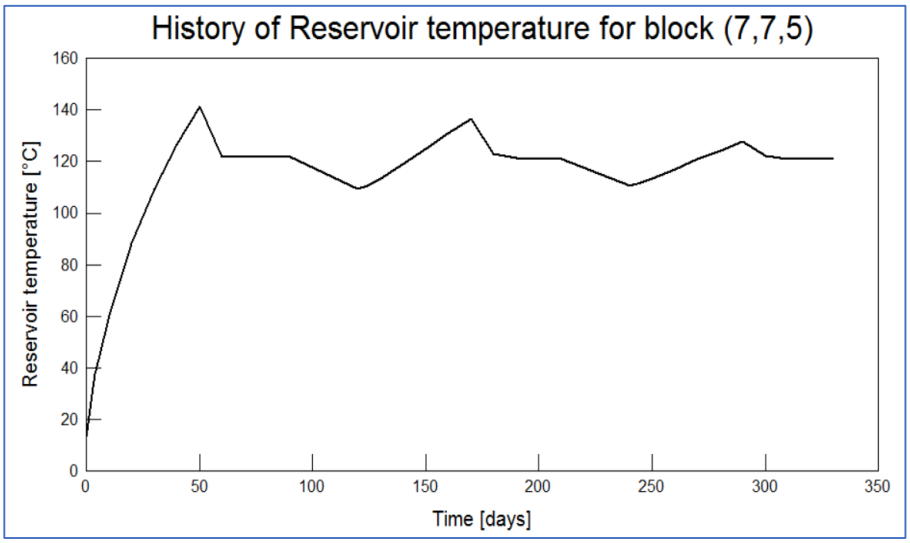


Figure 6.24 Reservoir Temperature for Block (7,7,5) for 3 Operation Cycles

6.3.3 Combining Microwave with Water Injection

One of the problems of heating heavy oil reservoirs with microwave is the lack of driving force. Microwave heating reduces the viscosity of the oil and hence it may be produced. Gravity and reservoir pressure drive the oil toward the oil producers. They may not enough to push the oil. Water may be used to push the heated oil toward the production wells. Combining microwave heating with water injection showed an improvement in the cumulative oil production. The water is injected through the same well as the microwaving well. The microwaving/injection well is drilled further from the producer than all the cases studied in this dissertation. This is because more oil of the reservoir is available for production since there an extra driving force (water injection).

Two cases are investigated. In the first one, two producer and two injector/microwave well are drilled. However in the second case, one of each is drilled. The production results for both cases with and without the water injection are shown in figures 6.25 through 6.28. In the first case, the cumulative oil production without water injection is 80.7 m^3. Applying water injection, the production jumps to 211.9 m^3. Similarly, in the second case the cumulative oil production increases if

water injection is applied. Combining water injection with microwave heating produced around 250% of what could have been produced without the water injection.

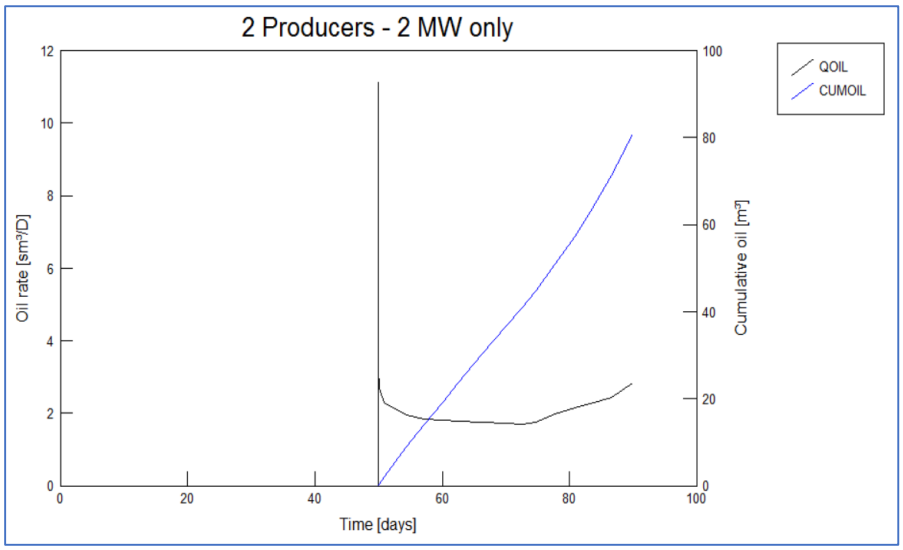


Figure 6.25 Production Results (2 Producers – 2 MW only)

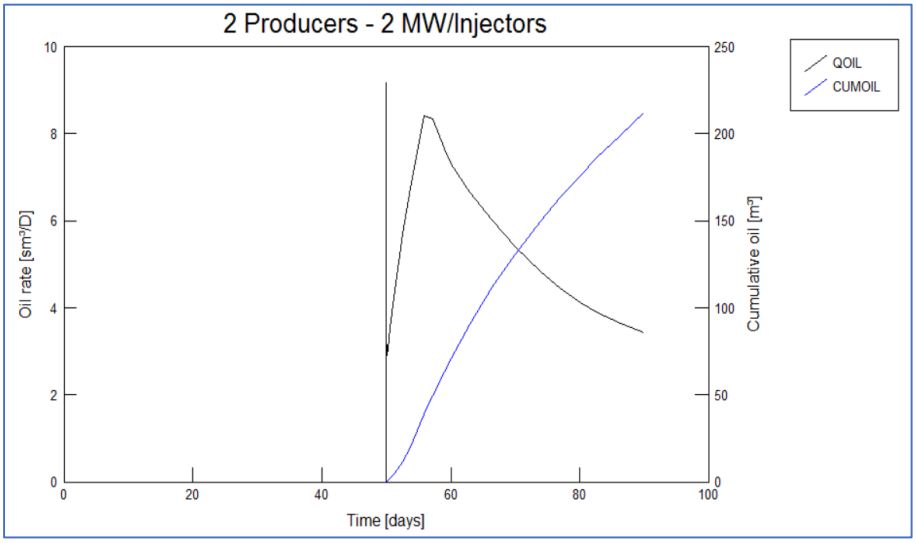


Figure 6.26 Production Results (2 Producers – 2 MW/Injectors)

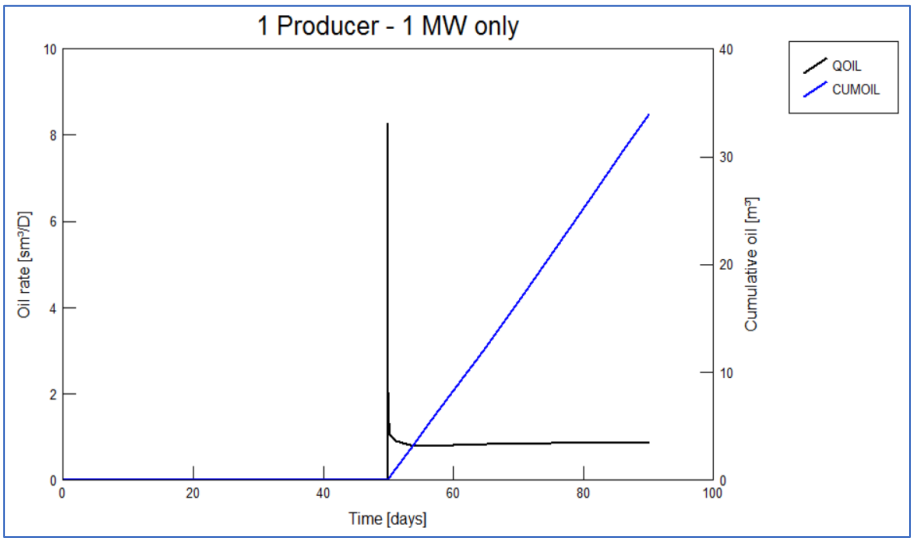


Figure 6.27 Production Results (1 Producer – 1 MW only)

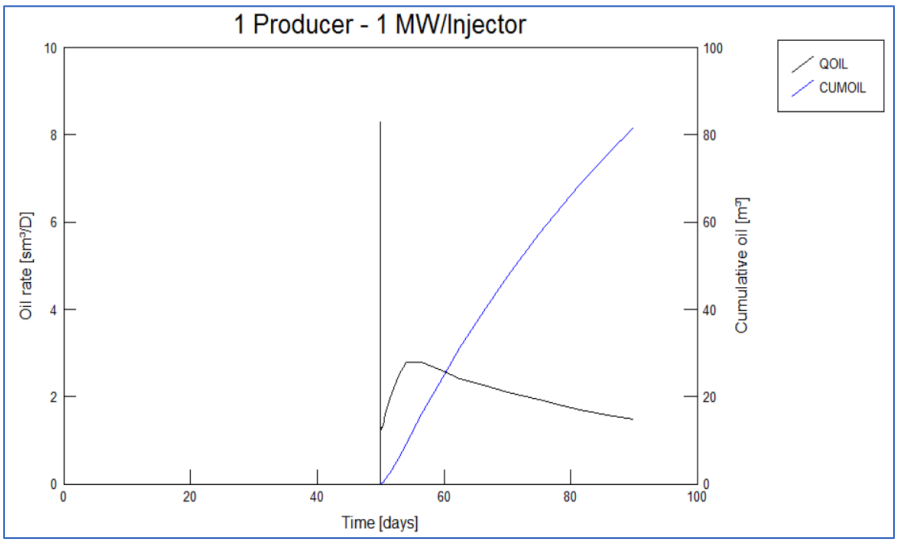


Figure 6.28 Production Results (1 Producer – 1 MW/Injector)

6.3.4 Use of Activated Carbon

The purpose of activated carbon is heat the reservoir where reservoir water is not sufficient to generate heat using microwave. In the base case (without the use of activated carbon) only one producer and one microwaving well are drilled. The total production after 50 days of heating and then 40 days of production is around 79 m^3. When a fracture is created around the microwaving well and filled with activated carbon, the production increases to 82 m^3. That is 3.5% increase in the production. More activated carbon around the microwaving well is needed to generate enough heat to produce more oil. This is possible in shallow formations where multiple fractures in different directions may be created similar to Vertical Single Well SAGD (Jamali (2014)). The fractures may be filled with activated carbon. This way more area around the wellbore may be heated using microwave and hence more heavy oil may be produced. According to the simulator, if a large area around the antenna is filled with activated carbon and heated using microwave, the cumulative production of the previous case may increase to 90 m^3; a 14% increase just by the addition of activated carbon.

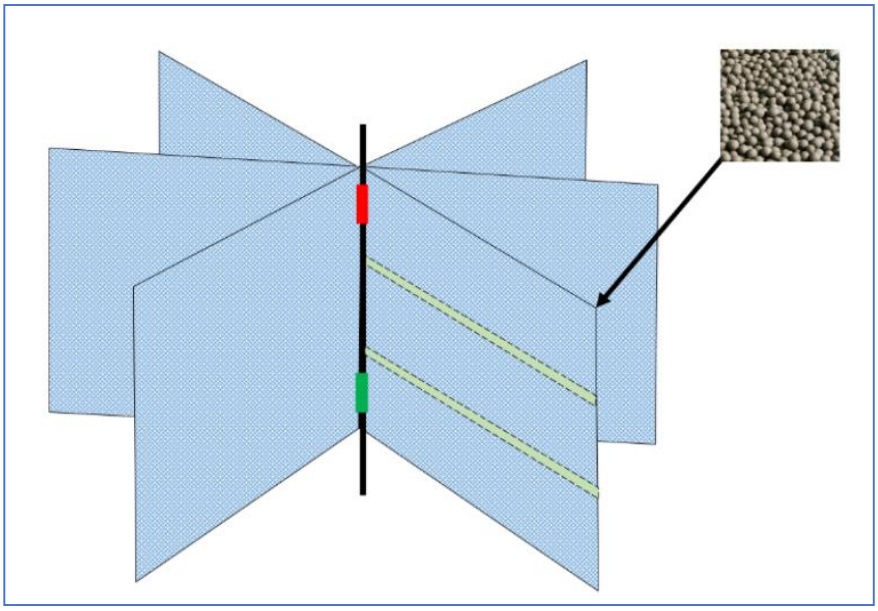


Figure 6.29 Vertical Single Well SAGD (Jamali (2014))

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary and Conclusions

1. Thermal recovery techniques are used to produce heavy oil reservoirs. In general, oil is heated and then produced due to a decrease in its viscosity.
2. The use of microwave is one of the thermal recovery technique. New techniques to improve the use of microwave to produce heavy oil reservoirs are studied experimentally and numerically in this dissertation.
3. A technique involves the use of microwave and activated carbon is investigated. In this technique, a hydraulic fracture is created in heavy oil reservoirs and filled with activated carbon. Then the fracture is heated using microwave.
4. Activated carbon heats up to very high temperature in very short period of time using microwave. The temperature of 20 ml of activated carbon needs less than 40 seconds to reach 800˚F.
5. Mixing activated carbon with water then heating it may improve its performance. The next time it is heated using microwave, it requires less time to reach a certain temperature.
6. Preheating activated carbon by any mean changes its reaction to microwave irradiation when it is reheated. The time required to heat activated carbon is cut by at least half if it is preheated. It seems that activated carbon has a memory that lasts for few weeks that affect its interaction with microwave.
7. Activated carbon and microwave may generate enough heat to create micro fractures in a synthetic core sample made of plaster. Further investigation on real core samples is needed.

8. Use of microwave and activated carbon may result in high temperature that may affect the wellbore integrity. Aluminum oxide may be used to fill the hydraulic fracture section close to the wellbore to solve this problem. Another idea involves operating the microwave antenna in a temperature window. As the temperature around the antenna exceeds a maximum limit, it shuts down. It woks again when the temperature reaches the lower limit of the window. The maximum limit is set based on the limits of the wellbore completion.
9. A thermal reservoir simulator developed by TAURUS is used for the numerical part of this study.
10. Microwave irradiations with lower frequencies goes deeper into the reservoir. As a result, 0.915 GHz frequency is selected for this study over 2.45 GHz.
11. A microwave with a frequency of 0.915 GHz and power level of 100 kW may go as far as 20 m into the reservoir after 1 month of heating. 2.45 GHz microwave may go up to 5 m.
12. 2.45 GHz microwave generates more heat than 0.915 GHz.
13. Increasing the power level of the microwave antenna results in generating more heat faster. That means more oil production as more oil is heated. There is a maximum limit above which increasing the power does not add much to the oil production.
14. How deep microwave irradiation may go into the reservoir depends strongly on the microwave frequency level and the time microwave irradiation is applied. Increasing the power level or the water saturation may increase the covered area slightly but their significant effect is on the amount of generated heat.
15. Several techniques are investigated to improve the performance of microwave as a thermal recovery technique. Namely, they are creating producers/microwaving wells network, cyclic production/microwaving

operation, combining microwave with water injection, and the use of activated carbon.

16. Creating a network of production and microwaving wells similar to the ones in water flooding may improve the performance of the whole process. It is not necessary to have oil producers as many as microwaving wells. Numerical results showed that having several microwaving wells that covers a large area of the reservoir and fewer number of producers may be sufficient to produce the reservoir.
17. An economic analysis is required to find the optimum power level and the number of producers and microwaving wells to produce heavy oil reservoir using microwave.
18. Cyclic operation of the microwave and production well may increase the cumulative oil production. Numerical study showed an increase between 20 and 60% in the cumulative oil production compared to uninterrupted production and microwaving periods.
19. Microwaving may be combined with water injection to push the heated oil. Numerical results showed that combining the microwave technique with water injection produces 250% the cumulative production that could have been produced utilizing the microwave only.
20. Utilizing activated carbon was studied numerically. The results showed that large amount of activated carbon is needed to heat and produce heavy oil reservoirs efficiently. A network of fractures may be created to accommodate activated carbon. This is possible in formations at shallow depths where the direction of the fractures may be set and several fractures may be created to cover a large area of the reservoir.
21. 3 invention disclosures has been filed about several techniques investigated in this PhD dissertation.

7.2 Recommendations

1. In the experimental part of this study, 2.45 GHz microwave was used. Investigation on microwave at lower frequencies such as 0.915 GHz is recommended because it may go deeper into the reservoir.
2. Heating real core samples filled with heavy oil and water using microwave. The production and pressure data may be recorded and analyzed.
3. Examining the MAC technique under pressure.
4. Further investigation on the memory of activated carbon where its interaction with microwave changes after being preheated.
5. Investigating the creation of micro fractures on real core samples when heated using microwave in the presence of activated carbon.
6. Numerical investigation of the performance of MAC technique with other recovery techniques. The MAC technique may reduce the viscosity of the heavy oil, but it does not push the oil toward production wells.
7. Optimization study of the cyclic production/microwaving technique to find the optimum time of every stage.
8. Optimization study to place producers, microwave antennas, and water injection wells for the best oil recovery.
9. Development of a technique to generate microwave irradiation downhole.

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