Application of Microwaves for Thermal EOR Methods

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Abstract

Heavy oil reservoirs represent about 70% of the total oil reservoirs. EOR methods must be applied due to the low primary recovery of heavy oil reservoirs. The low primary recovery of these reservoirs is based on the viscosity of the heavy oil. Thermal EOR methods are the best to apply to extract more heavy oil. On-site combustion, gravity drainage with steam, and cyclic steam injection are the most famous thermal EOR methods. However, there will always be a demand for more productive methods of improving production with lower usage costs. Moreover, the growing concern about the environmental component of oil production may prompt the need to look for more suitable and profitable ways. One of these methods is electromagnetic heating, which can be even more efficient.

This study compared the microwave heating method with the conventional thermal method. The effects of the microwave heating method on the viscosity of heavy oil and temperature alteration were analyzed. In addition, the effects of microwave power and water saturation were investigated on the impact of production efficiency using the experiment. From the experimental results, the microwave heating method gave better results in viscosity reduction. Overall, a higher power level showed a higher temperature alteration with a higher reduction in viscosity. In addition, higher water saturation gave higher results in temperature; however, from the efficiency side, the best choice for water saturation was identified, which is 10%.

Introduction

Enhanced oil recovery can be explained as extracting crude oil remaining in the reservoir after primary and secondary recovery stages. EOR can also be called tertiary recovery (Thomas, S., 2008). After the oil field's natural recovery (primary recovery), a massive amount of oil stays in formation. About 70% of original oil in place (OOIP) is unrecovered as reservoir pressure decreases after primary recovery (Mokheimer, et al., 2018). Other data states that 67% of oil remains trapped in the reservoir after the secondary and primary stages of recovery (Shafiai and Gohari, 2020). These two stages of oil recovery do not change the properties of hydrocarbons.

In contrast, EOR changes the properties of oil or formation, leading to more effortless movement of fluids in reservoirs. Moreover, EOR can recover as high as 75% of the OOIP, depending on the EOR technique (Mokheimer, et al., 2018). In addition, recovery factors correspond to the primary and secondary methods account for 20 to 25% (Sivakumar et al., 2020).

Figure 1 shows that EOR methods recover 45% of light oil during production, while EOR can recover 90% of heavy oil.

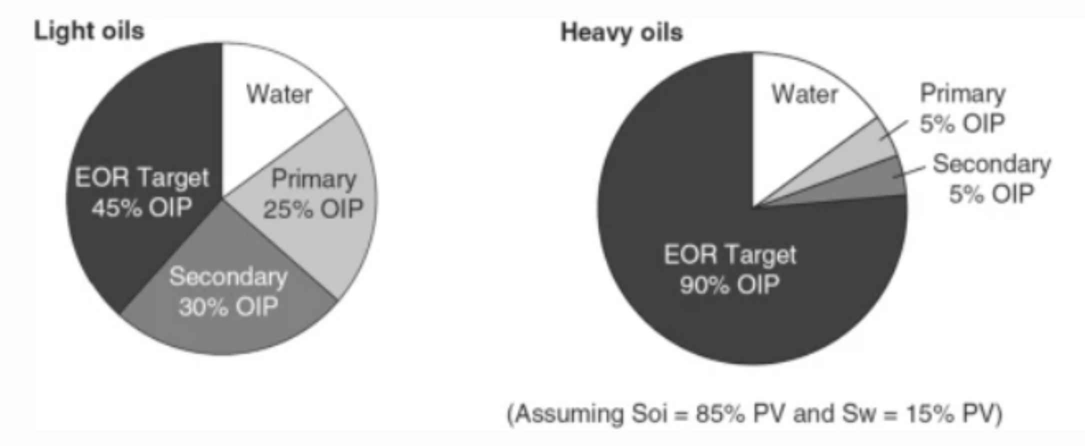


Figure 1. EOR target for different oil types (Shafiai and Gohari, 2020)

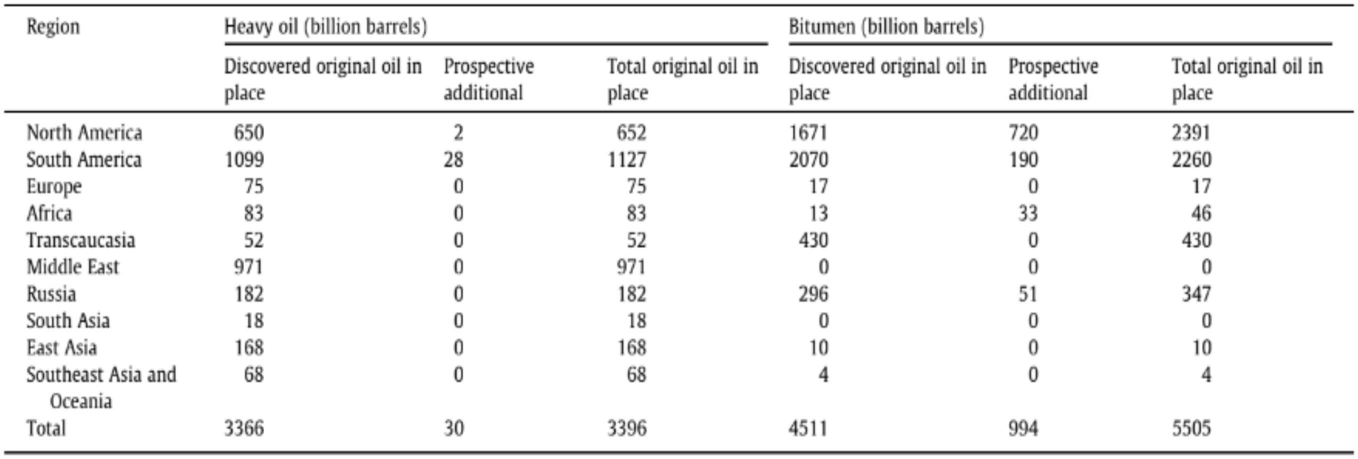
Many hard-to-recover reservoirs around the world are potential sources of oil. Low-permeability oil reservoirs and heavy and extra-heavy oil reservoirs have long been in the interest of many oil companies since easily extracted reserves are already in development (Greff and Babadagli, 2013). In addition, the majority of world oil reserves are characterized by heavy oil or extra heavy oil (Sivakumar, et al., 2020). It shows that heavy oil and low-permeability reservoirs play a crucial role as the primary source of oil at the moment. Moreover, technological challenges still do not benefit oil production in low recovery reservoir conditions (Xu, et al., 2020). It leads to demand for highly effective enhanced oil recovery methods for heavy and extra oil.

Most of the heavy oil is still in development. Nearly 70% of the remaining oil reserves are bitumen and heavy oil (Greff and Babadagli, 2013). After years, it can be seen that the importance of heavy oil and bitumen increases with time. The world reserves of bitumen and heavy oil are distributed among 192 heavy crude and 89 bitumen basins as shown in **Table 1**. It is calculated in **Table 1** that the world's heavy oil resources are approximately 3366 billion barrels, while bitumen is 4511 billion barrels. Furthermore, world heavy oil reserves are about 991.18 million tons, of which 126.74 billion tons are under extraction (Shafai and Gohari, 2020). Most of the heavy oil is located in sandstone (Petrowiki, 2016; Zhou and Sun, 2016). It explains the popularity of the thermal recovery methods for sandstone, which is illustrated in **Figure 2.**

The remaining heavy oil is conserved in formation due to poor mobility under reservoir conditions. Oil with an API of less than 22 is heavy oil, while oil with an API of less than ten is classified as super heavy and bitumen (Mokheimer, et al., 2018). The viscosity of heavy oil ranges from 50 mPa.s to 50,000 mPa.s under reservoir temperature and pressure (Shafai and Gohari, 2020). It makes producing heavy oils complex using the same methods as light oils. The thermal enhanced oil recovery was implemented not long ago to upgrade the heavy oil extraction. Thermal EOR nullifies the problem of high viscosity for such types of oils (Greff and Babadagli, 2013). In recent years, various comparatively new thermal EOR methods have improved the standard thermal recovery methods for heavy and extra-heavy oil production (Guo, Li and Yu, 2016). It shows the importance of thermal EOR methods in the global oil market.

The thermal method is an effective method to increase the productivity of heavy oil reservoirs. Thermal recovery processes mainly produce viscous, thick, and high-density oils with an API density of less than 20 (Mokheimer, et al., 2018). The use of thermal methods is limited by factors such as the low injectivity and small thickness of the oil-bearing zone (Hasanvand and Golparvar, 2014). Therefore, in recent years, people have increasingly been looking for alternative methods for heating heavy oil with more efficiency and extensive heat transfer capabilities as one factor.

Table 1. Reserves and distribution of heavy and extra heavy oil among world (Bera and Babadagli, 2015)



Region	Heavy oil (billion barrels)			Bitumen (billion barrels)		
	Discovered original oil in place	Prospective additional	Total original oil in place	Discovered original oil in place	Prospective additional	Total original oil in place
North America	650	2	652	1671	720	2391
South America	1099	28	1127	2070	190	2260
Europe	75	0	75	17	0	17
Africa	83	0	83	13	33	46
Transcaucasia	52	0	52	430	0	430
Middle East	971	0	971	0	0	0
Russia	182	0	182	296	51	347
South Asia	18	0	18	0	0	0
East Asia	168	0	168	10	0	10
Southeast Asia and Oceania	68	0	68	4	0	4
Total	3366	30	3396	4511	994	5505

The primary and secondary recoveries are cold production methods that do not affect the critical factor of heavy and extra heavy oils to make them mobile. High temperature also removes organic contaminants from soils much faster than cold production methods (Zihms, 2013). It proves the data on **Figure 1**, where EOR methods recover 90% of OOIP. **Figure 2** shows that most of the EOR methods used for heavy oils, primarily located in sandstones, are thermal recovery methods. Thermal EOR is the optimal and efficient solution for bitumen and heavy oil reservoirs. However, the hard-to-reach deep reservoirs or reservoirs with low permeability are unsuitable for conventional thermal methods and harm the environment (Bera and Babadagli, 2015).

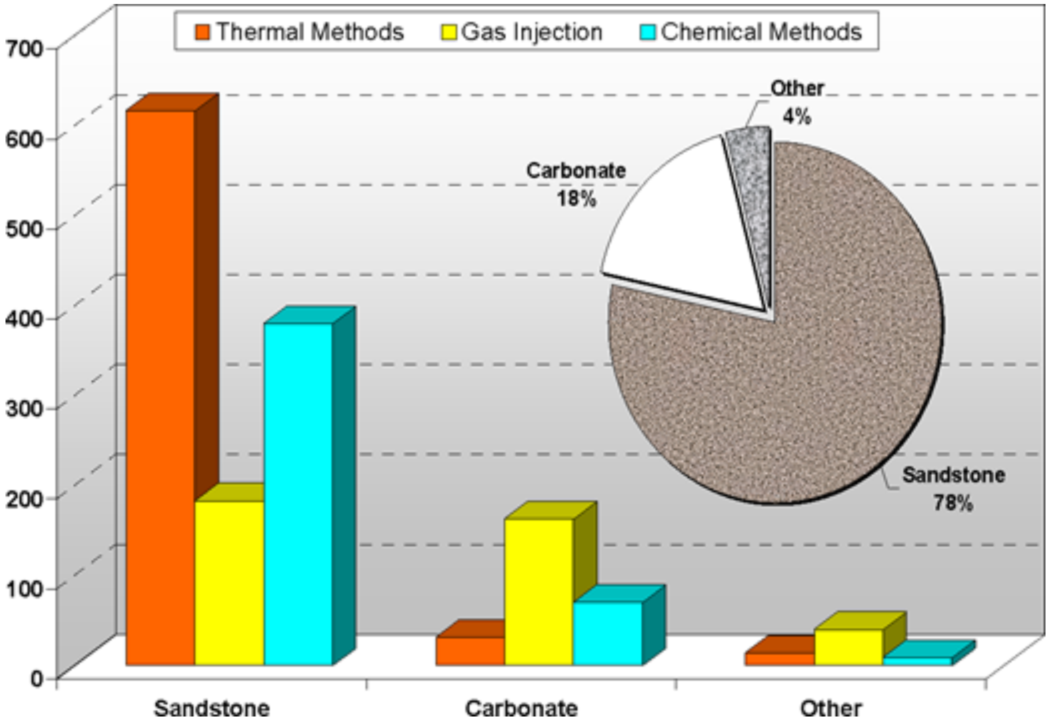


Figure 2. EOR field projects by lithology (Based on a total 1,507 international projects) (Manrique et al., 2010)

A primary concern of the project is the insufficient productivity of methods for heavy oil. Large reserves of heavy oil are still not developed. And heating oil with microwaves can be a key fact in solving the rapid depletion of oil reserves. Microwave heating plays an important role in the maintenance of delaying the expected peak of oil for decades (Jean Laherrère a d, Charles A.S. Hall b, Roger Bentley). This goal can be achieved only if this method allows you to extract oil more efficiently than traditional methods of increasing production. This study aims to investigate the differences between microwave heating and the conventional thermal method. To evaluate the effect of microwave heating, the project explores the differences between these methods and determines the potential benefits of microwave heating in terms of heating time and temperature. In addition, the project discusses the effects of power level and water saturation on the microwave heating efficiency.

Literature Review

Conventional Thermal EOR Methods

Nowadays, thermal recovery methods provide the most significant opportunities for extracting heavy oils and bitumen—thermal extraction methods based on oil displacement in the reservoir by heat carriers. The thermal EOR methods use thermal energy to decrease viscosity by increasing the temperature of the reservoir (Mokheimer et al., 2018).

Cyclic steam injection, in situ combustions, steam-assisted gravity drainage (SAGD), and steam flooding increase the temperature (Bera and Babadagli, 2015). These methods lead to the reduction of both viscous forces and interfacial tension.

Cyclic steam injection is the technology of steam injection when oil is produced with condensed steam from the same well, which can be seen in **Figure 3**. There are two stages during cyclic steam stimulation. The first one is the steam injection process during some period. The second phase is the flow direction is reversed to produce oil from the same well (Gu et al., 2015). However, monitoring and controlling the steam front is highly ineffective and leads to unpredictable behavior in this method. Also, the cost of steam generation increases with time (Owens and Suter, 1965). It makes cyclic steam injection methods costly.

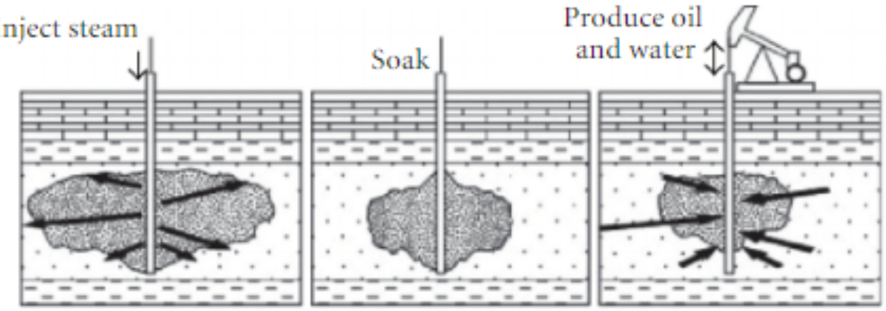


Figure 3. Cyclic steam injection (Zhou Y. et al., 2012)

In situ combustion and continuous steam, injection has distinct advantages that determine which of them will be used as a mechanism for the continuous drive of heavy oil, depending on the reservoir and environmental conditions. The currently available equipment for burning large crude oil can inject steam and air. In contrast, steam injection requires the supply of water, which is not necessary for combustion operations. On the other hand, air and natural pollution place certain restrictions on incineration operations (Bahadori, 2014). In general, this is one of the reasons why continuous steam injection is used more often than in situ combustions.

Steam-thermal effect on the formation is one of the standard thermal methods of increasing oil recovery. This process pumps steam from the surface into high-oil viscosity and low-temperature formation through special wells (Chertenkov et al., 2014). The typical steam injection process is illustrated in **Figure 4**.

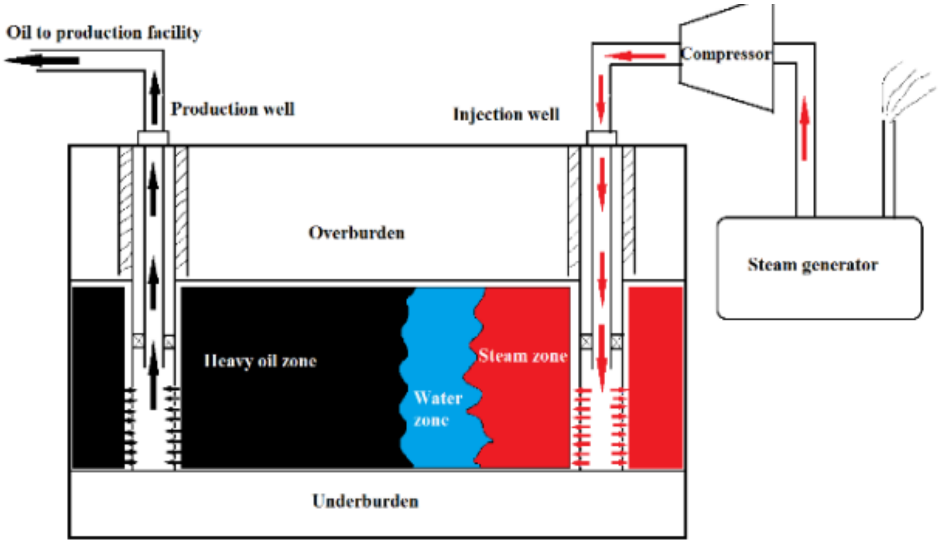


Figure 4. Typical steam injection process in a heavy oil/bitumen reservoir (Nassan, 2018)

The scheme of steam injection or steam flooding works based on: the evaporation and distillation of condensing hydrocarbons from crude oil, reducing residual oil saturation and improving relative permeability. In the steam zone, steam distillation is the predominant effect. The high temperature and the presence of the gas phase affect the liquids in the formations and vaporize the light ends, which are carried forward by the incoming steam front before condensing into the cooler part of the reservoir. The relatively heavier components of the oil, characterized by high vapor pressure, are left behind. This method depends on the oil composition in the formation, which is subjected to steam injection. Oil recovery in the area where the hot water stage begins is determined mainly by the characteristics of the oil used. If the oil's viscosity is sensitive to temperature rise and decreases sharply, then most of the oil will be extracted by a stream of hot water (Alvarez and Han, 2013; Ali, 1974). Due to the thermal expansion of the oil, approximately 3-5% of the oil is extracted on-site using this stage.

SAGD (steam-assisted gravity drainage) - is a method used to extract extra heavy oil or bitumen from underground oil sands deposits. The idea behind this method is to force steam into sands of oil deposition to heat it. It allows bitumen to flow better, so it can be extracted (Butler, 1994).

Two horizontal wells are drilled into the reservoir. Inside each well are two parallel pipes, one placed about 5 meters above another, as shown in **Figure 5**. The bottom is a production well, while the top is a steam injection well. After the transformation of water into steam is done at a nearby plant, it goes to the drilling location. After that, steam travels to a formation that contains oil through the upper well. It expands in all directions after leaving the well. Bitumen obtains heat from steam. It results in a reduction of bitumen viscosity reduction and allows it to flow easily.

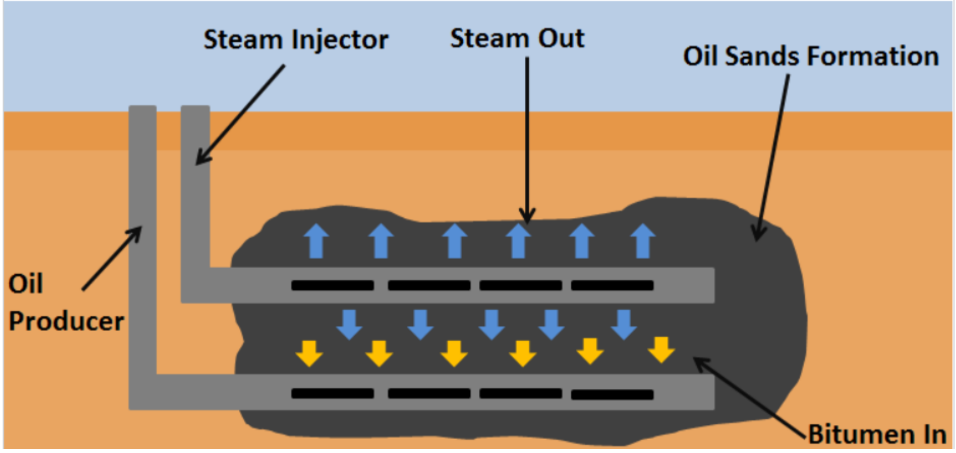


Figure 5. A SAGD setup to extract bitumen from an oil sand deposit (Energy Education, 2015)

The disadvantages of this method are that it is expensive with high water consumption and emissions. Extraction of bitumen by this method produces the highest amount of greenhouse gas (Mohan et al., 2022). It increases the cost of the method. Moreover, significant heat loss to the overburden and the part development of the sloped steam chamber are disadvantages of the steam-assisted gravity drainage method.

Each of the conventional methods of thermal EOR has favorable conditions under which it works. Furthermore, there are several weak points in each of them. The common problem can be highlighted by energy loss. The heat directionality can not be taken under control by conventional methods. It displays the fact that conventional methods reach their maximum productiveness. Consequently, this situation needs new ways to solve the defects of conventional methods.

Unconventional Methods

All that has been discussed before are traditional methods that are economically profitable to extract with current technological developments. There are also unconventional methods to improve oil production currently under development and study. Direct current heating, high-frequency electromagnetic heating (EM), and ultrasonic technology methods are unconventional methods with promising perspectives. These non-standard methods represent economic and scientific benefits for the oil and gas industry. They can solve the problem of extensive water usage, low permeable formations, thin pay-zones, and decrease heat loss of standard methods (Hascakir, Acar and Akin, 2009).

Moreover, new unconventional methods like high-frequency electromagnetic heating are not restricted by the depth and do not harm the environment (Wacker, et al., 2011). However, these methods still need to be studied for field application. Technological advancement is needed to use one of these methods.

Microwave Method

Microwaves are electromagnetic waves with wavelength ranges from tens of centimeters to a millimeter. Microwaves occupy a place between infrared radiation and ultrashort waves. In other words, they are located in interstitial positions. This intermediate position affects the properties of microwaves. Microwaves have the properties of both radio waves and light waves. Microwaves can be characterized by frequency and wavelength. In addition, they have the same speed as all electromagnetic waves in a vacuum. The frequency of microwaves varies in the range of 300 MHz – 300 GHz, and the wavelength ranges from 10-3 m to 1 m (from 1 mm to 1 m). Microwaves, which have higher frequencies and shorter wavelengths, propagate in space like visible light. Waves propagate almost in a straight line and show the same functionality as light: they are absorbed by some materials, reflected, and pass through some materials (Weinstein, 1988; Kong, 1975).

Microwaves are reflected from metal surfaces. Materials that reflect microwave radiation, especially strongly, are electrical conductors. The metal body can create an impassable border for them and prevent them from passing. Therefore, a microwave oven in homes for heating food has a metal structure. This prevents the penetration of microwave radiation onto the external surface of the device and the spread of radiation into the environment. When the electrical or magnetic properties of the medium in which the microwave moves change, electromagnetic waves are reflected and scattered. It can be a solid, a liquid, or air – any medium in which radiation propagates.

The microwave heating process is based on converting electromagnetic energy into heat energy. The process begins with polar molecules. The polar molecules can be found among hydrocarbons or other fluids and connate water. Polar molecules absorb energy from microwaves, leading to heat transfer to the reservoir. Circulatory motion in the polar molecules is detected at MW frequencies, which leads to a rapid collision with the other molecules (Sivakumar, 2020). In other words, the generation of heat is undergone by the collision at the frequency of the MW applied.

Microwave heating is an unconventional thermal method. This alternative method attracts more and more attention from researchers because EM can be obtained from primary energy sources like air and the sun. However, it also allows heat quickly and is environmentally friendly (Mutyala, et al., 2010; Abernethy, 1976). Moreover, microwave heating is being discussed in the scientific and industrial environment due to its positive effects on productivity and usability. One such effect is that microwaved can be directed to a specific area to improve oil recovery. Another positive effect, electromagnetic heating can make it possible to increase the extraction of heavy oil, ensuring uniform heating of the reservoir in the chosen area. **Table 2** represents the comparison of different types of EM heating methods.

Table 2. Comparison between different types of EM

Electromagnetic heating (EM)		
Inductive	Heat energy limited	The mainly can be used to improve flow in wellbore
High-frequency	Limited region of heating to near wellbore region	The most interesting and effective frequency, if the limitation of source power will be solved
Low frequency	Temperature distribution is varying	High dependence on the water-saturated portion of the interconnected pore spaces

EM heating can be described as "heating produced by the absorption of EM energy by the molecule information" (Shafai and Gohari, 2020). Three categories of electromagnetic heating are low-frequency, inductive heating, and high-frequency. In high frequency, the current is alternating. At high frequencies, molecules form dipoles due to the tendency to align, which leads to rotational movement. The velocity of the rotations is proportional to the frequency of current alteration. It causes dielectric heating. The polarity of fluids and frequency play a crucial role in the practical usage of EM heating (Eskandari et al. 2015). The choice of the category of EM for heating the reservoir depends on fluid properties. One of the main advantages is heating far from the source of EM energy. It also enables the penetration of viscous oil and rock matrices (Shafai and Gohari, 2020). In addition, EM heating is based on the volumetric heating process, which leads to more effectivity due to the high heating rate. At the same time, conventional thermal methods work with the effect of convection and conduction. Internal heating, greater productivity in narrow wellbore space and increasing profits, directional heating, and avoiding excessive heat loss within non-reservoir are other positive effects and prospects of the EM method application. As a result, the prospects of this method are up-and-coming, as seen from intensive research on this topic in recent years.

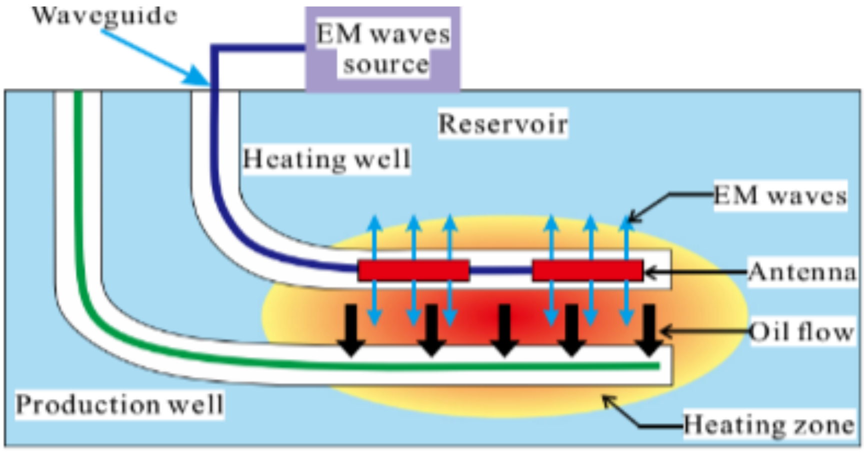


Figure 6. Horizontal well configuration diagram of EM heating (Wang and Gao, 2019)

Figure 6 shows the configuration of a horizontal well for heating EM, which is similar in structure to SAGD technology (gravity drainage using steam) (Wang and Gao, 2019). The antennas, which are inserted into the horizontal section of the upper wall. In comparison, the lower well extracts the oil. Under the influence of EM heating, crude oil begins to flow toward the lower-producing well under the influence of gravity. Ensuring sufficient heating power depends on the number of antennas distributed along the upper horizontal opening. The heat recovery of electromagnetic heating has the advantage of directional listening; namely, moving the antennas to the target of interest can control the heating area. Therefore, it can minimize the dissipation of excess of the thermal energy in the non-reservoir.

In addition, there are vertical well configurations that should be considered. As shown in **Figure 7**, there is one production well and one heating well with the heating source placed on the ground. Notably, the source sends waves to the waveguide, which propagates the EM waves to the antennas at a depth of the oil reservoir. After a time, radiated electromagnetic waves heat the formation and heat oil transport to the production well.

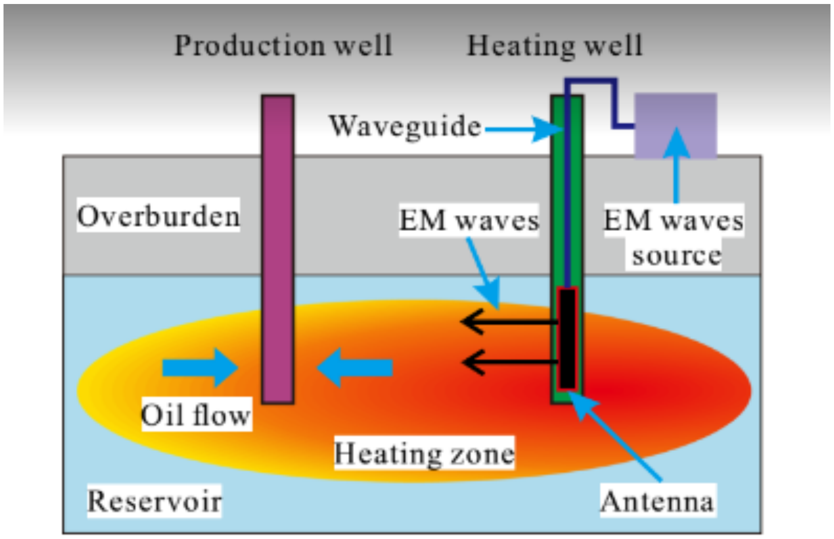


Figure 7. Vertical well configuration diagram of EM heating (Wang and Gao, 2019)

Different experiments and models were conducted, evaluated, and analyzed to understand the method works and whether it is suitable to choose for heavy oil reservoirs. In these studies, parameters affecting the performance of the MW EOR were analyzed, and the method's advantages and disadvantages were summarized.

Heavy oils accumulate mainly in the low-permeable zones. This situation makes conventional thermal EOR methods not economically efficient in some cases due to low permeability and high oil viscosity. Microwave radiation involves converting electromagnetic energy to thermal energy, which decreases the oil viscosity and affects the composition of the heavy oils. The comparison of a conventional thermal method and MW EOR was done by Sun et al. (2018) and illustrated in **Figure 8**. As can be seen, the water-separation rate is higher for microwave heating by almost five times and ten times for higher temperatures. **Figure 8** shows the time required to heat an oil sample to a specific temperature. According to **Figure 9**, it can be seen that microwave heating is much faster compared with conventional heating. This can be one of the advantages of the method as microwave heating can provide better efficiency in less period.

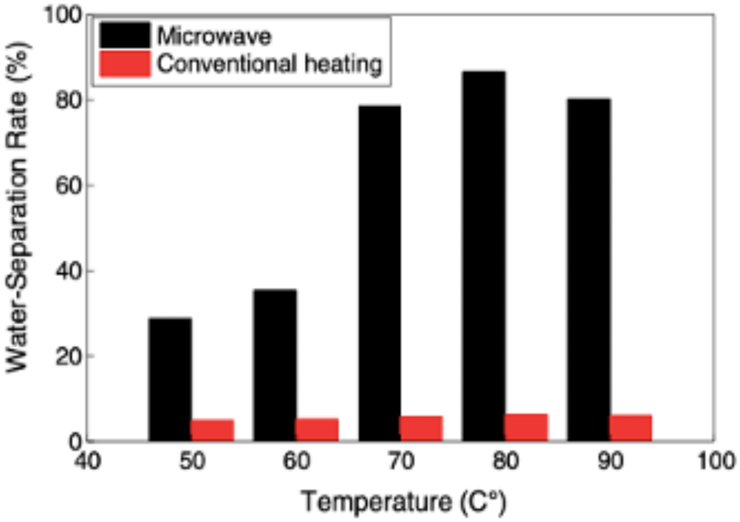


Figure 8. The comparison of microwave and conventional heating at different temperatures in water-separation rate factor (Sun et al., 2018)

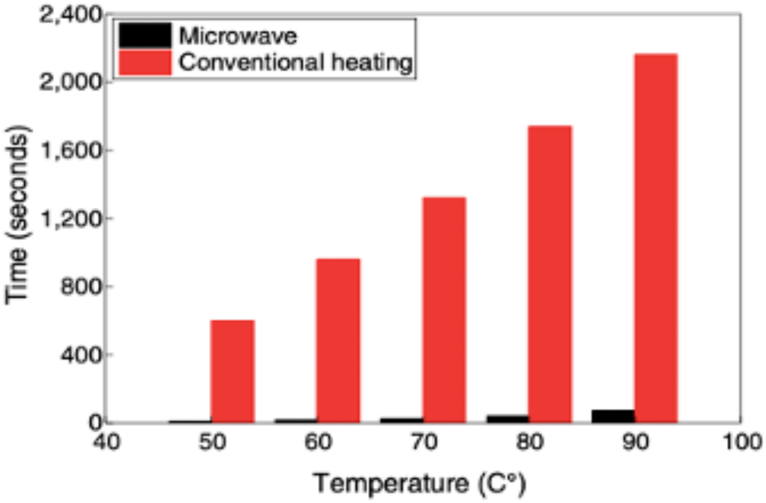


Figure 9. The comparison of microwave and conventional heating at different temperatures from the perspective of the speed of the operation. (Sun et al., 2018)

Pizzaro and Trevisan (1990) conducted a field test to stimulate the Rio Panon field, which was chosen due to its characteristics, which are suitable for the thermal EOR methods. The reservoir has low pressure and is located in a shallow depth with one single layer. The reservoir oil viscosity is 2500 high cp. Electromagnetic heating was chosen due to the steam injection applications' difficulties with the small formation thickness. **Figure 10** illustrates oil production by the MW and a conventional approach. It can be seen that after 1500 days, the total increase in enhanced production was 85.6%. This makes the MW method more favorable from the perspective of production efficiency.

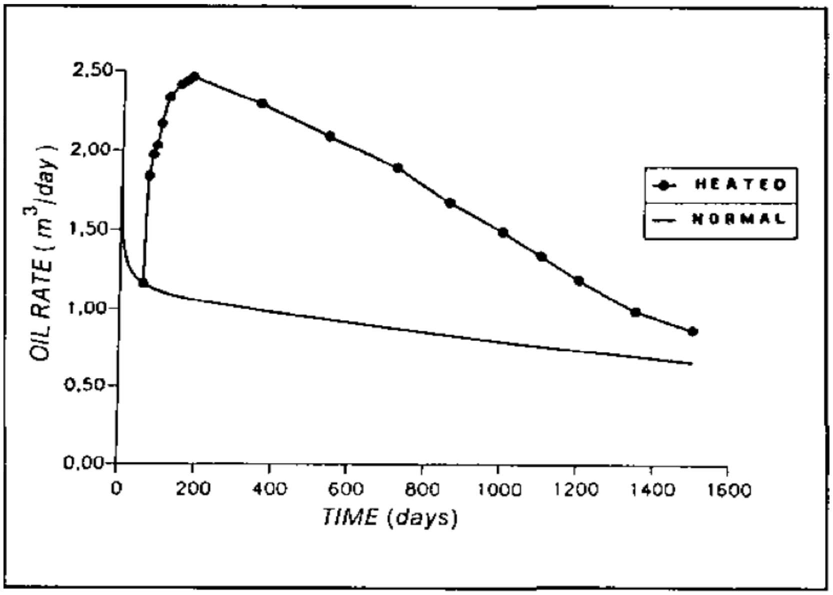


Figure 10. Oil rate for heated and normal methods in time period (Pizzaro and Trevisan, 1990)

Demiral et al. (2008) used a Vestel MD-GDX23A 1400 W microwave oven that operates at 2450 Mhz to conduct microwave tests with different heavy oils from reservoirs in southeast Turkey. **Table 3** represents the characteristics of heavy oil reservoirs. The main factor that was considered during the experiments was temperature. As temperature increases, the viscosity of oil decreases, which can provide better production at higher rates. In addition, different frequencies and wettability effects were considered during the experiment and summarized. **Figure 11** illustrates temperature variations for different water saturations for Bati Raman. As can be seen in **Figure 11**, the highest temperature was obtained with the highest percentage of water saturation (60%). It means that the presence of water is essential to achieve a high recovery factor by MW due to the polarity of water molecules. **Figure 12** shows cumulative oil production for different wettabilities at the same frequency. **Figures 11** and **12** show that the best results can be achieved for a water-wet system, although positive results were observed in all cases.

Table 3. The characteristics of heavy oil reservoirs (Demiral et al., 2008)

Field	**Bati Raman**	**Camurlu**	**Garzan**
Lithology	Limestone	Limestone	Limestone
Reservoir Temperature (^{o}F)	150	115	179
Reservoir Pressure(psia)	1750	1700	2320
Porosity (%)	18	21	6
Permeability (md)	58	40	3
Water Saturation (%)	21	18	31
API Gravity (degree)	13	12.2	18.5
Specific Gravity (g/cm^3)	0.9772	0.985	0.9433
Viscosity @ Res.Temp (cp)	592	700	33
Formation Water Salinity (ppm)	40,000-160,000	60,000	3,000-10,000
Original Oil in Place (10^6 STB)	1,850.0	377.437	53.0

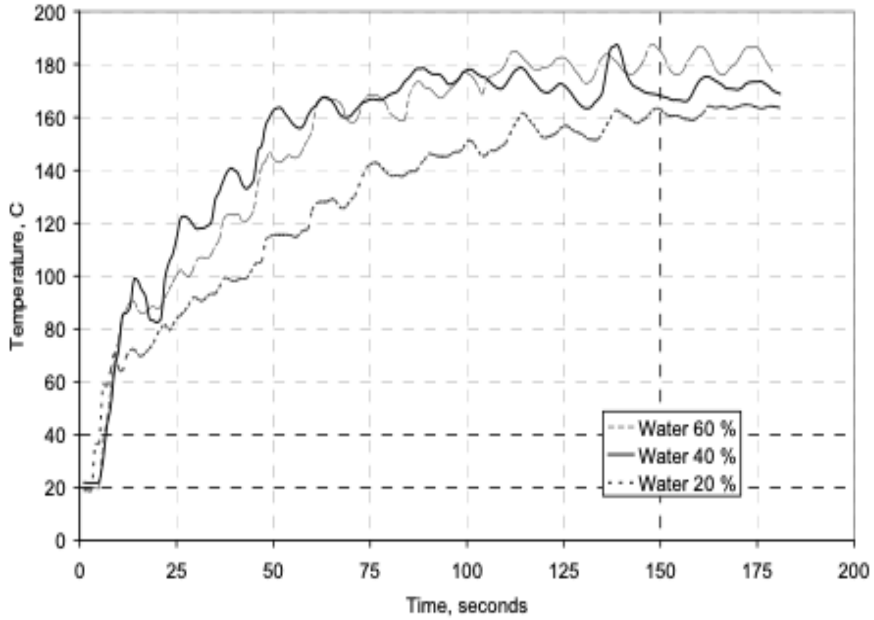


Figure 11. Temperature variations in water wet porous media for Bati Raman (Demiral et al., 2008)

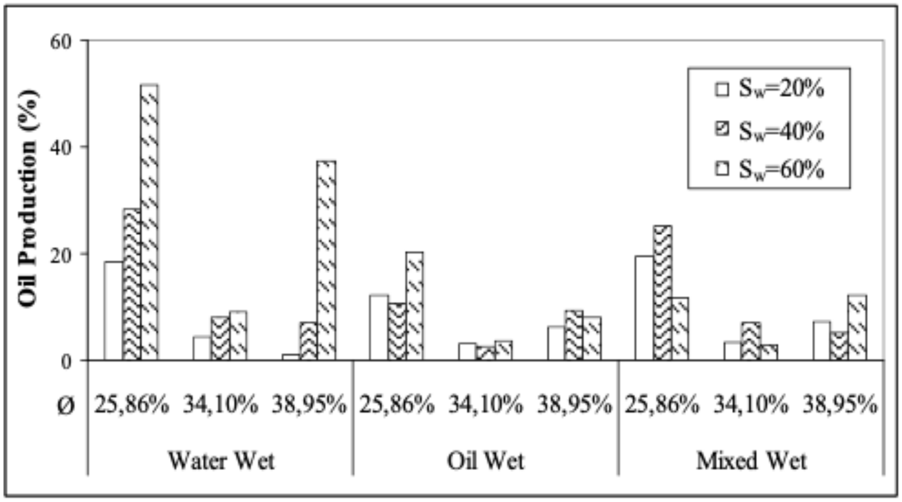


Figure 12. Cumulative oil production for different wettabilities (Bati Raman Crude Oil) (Demiral et al., 2008)

Alomair et al. (2012) analyzed three unconventional heating methods to obtain the production rate results. They investigated three different porous media, which include Berea sandstone, glass beads, and sand pack; however, due to the high porosity and permeability, Berea sandstone was excluded from the experiment, as unconventional heating is applicable for the low permeable formations. Three main approach designs were electromagnetic heating, electrical resistance heating, and microwave heating. All approaches were conducted with the same procedure, where sand packs were saturated with heavy oil. To provide better results, primary recovery was conducted at room temperature under the effect of gravitational forces, and then temperature increase was followed with three different approaches. **Figure 13** illustrates the maximum and minimum recovery for all three methods. As can be seen from **Figure 13**, all of the methods have a positive effect on the incremental recovery of oil. However, the best one was for electromagnetic and microwave heating, and the minimum recovery values were for electrical resistance. **Figure 14** shows the maximum and minimum operating times for each approach. From **Figure 14**, the operating time was the smallest for microwave heating, which means we can get better results in less time than the other two methods.

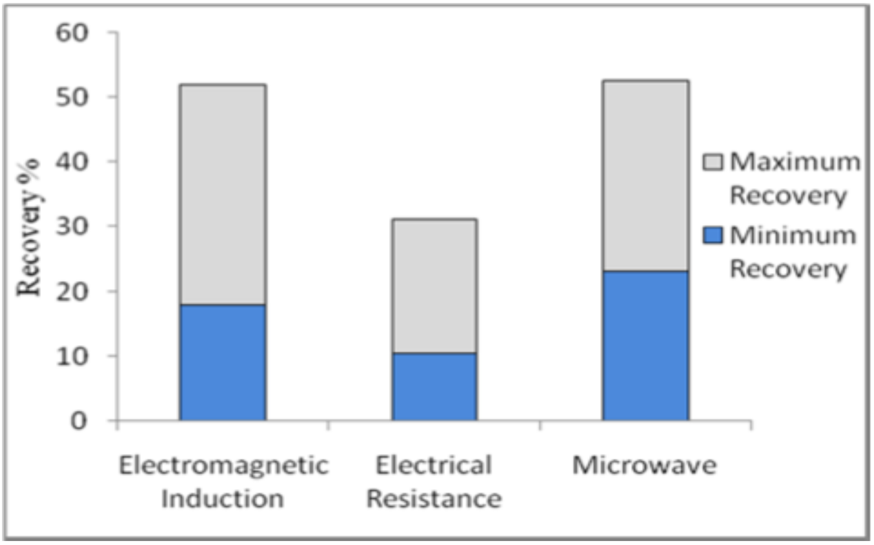


Figure 13. Maximum and minimum recovery for each method (Alomair et al., 2012)

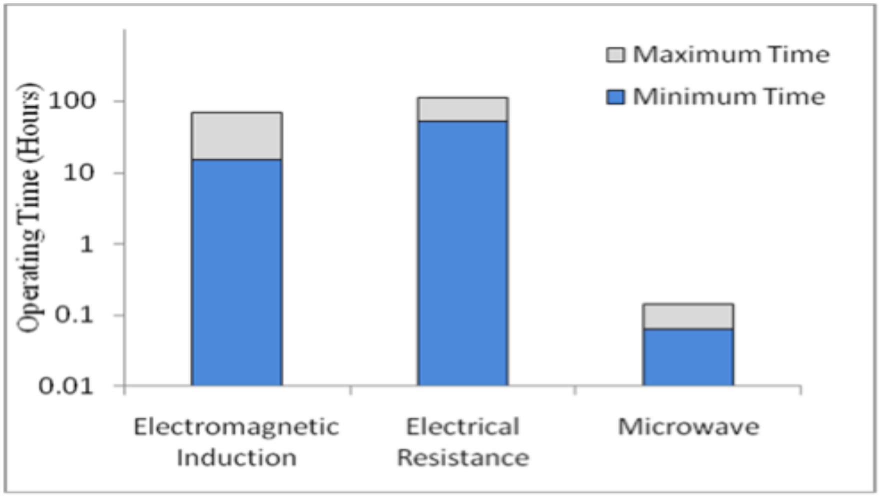


Figure 14. Maximum and minimum operating time for each method (Alomair et al., 2012)

Al-Farsi et al. (2016) compared microwave and conventional heating methods. **Figure 15** shows the oil recovery for microwave and conventional heating at different water saturations. As can be seen from **Figure 15**, microwave heating recovers three times more oil than a conventional one. **Figure 16** illustrates how much time is needed to achieve different temperatures for microwave and conventional heating at 20% water saturation. From **Figure 16**, rapid heating occurs with microwave heating. The reason for this result is the way of heating. In conventional heating, the heating process propagates from outside to inside; however, in microwave heating, it is heated internally due to the penetration of the microwave penetration.

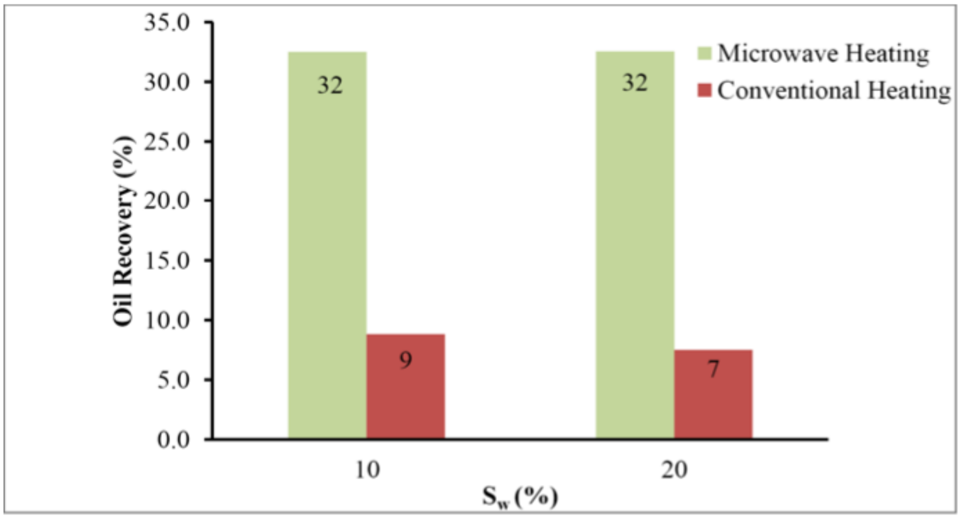


Figure 15. Comparison of oil recovery for microwave heating and conventional heating (Al-Farsi et al., 2016)

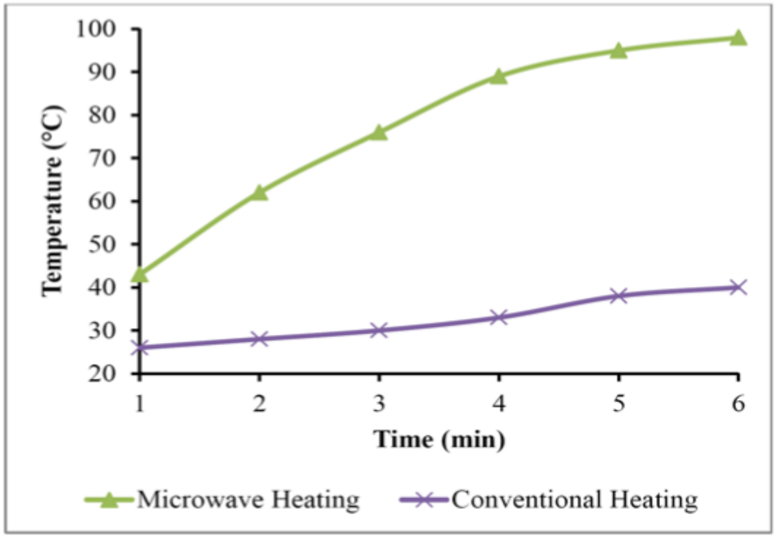


Figure 16. Temperature vs time for microwave heating and conventional heating at 20% water saturation (Al-Farsi et al., 2016)

Sahni et al. (2000) simulated the applicability of microwave heating in two different reservoirs. The first reservoir has sand zones, which are separated by impermeable shale layers. In addition, the first reservoir has very viscous oil (9541 cp). Preheating with low-frequency current (using two horizontal electrodes) was presented before the steam injection to analyze this reservoir. The second reservoir has an oil viscosity of 33 cp and low permeability, and the microwave source heated it at high frequencies. **Figure 17** shows the results for the temperature profile in the case of microwave heating. From **Figure 17**, it can be seen that temperature distributions have better results due to the deep layers that are used in comparison with the first model. The overall effect of the cumulative oil production for different powers and layers is illustrated in **Figure 18**. From **Figure 18**, the best results of microwave heating were obtained at high power and are almost twice as high as primary production.

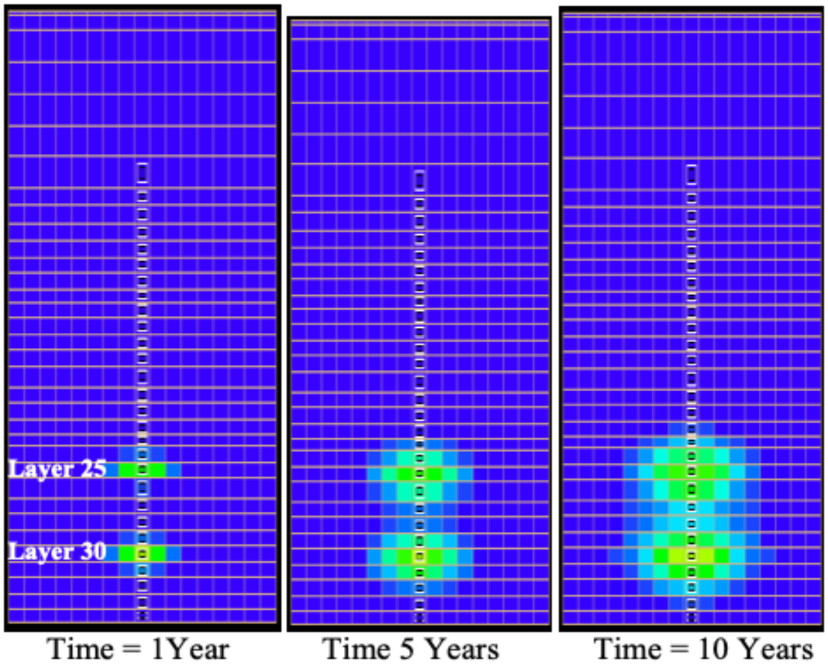


Figure 17. Temperature distribution for microwave heating (Sahni et al., 2000)

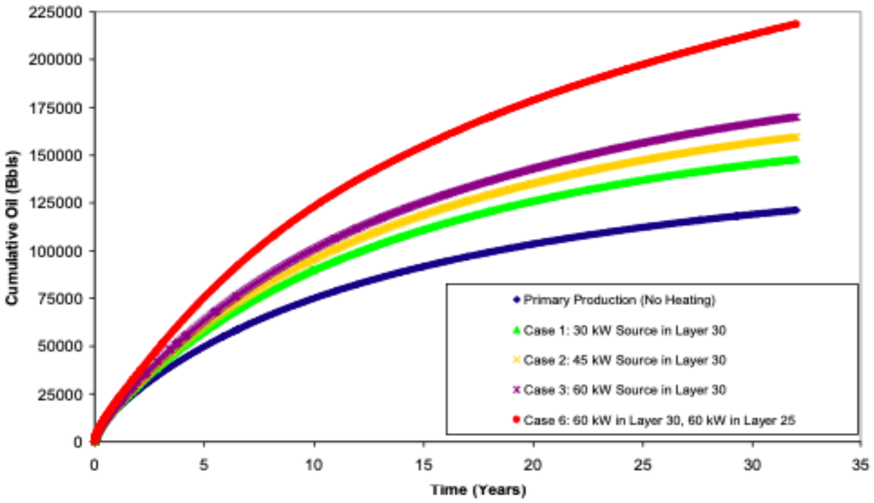


Figure 18. Cumulative oil production for various scenarios for microwave heating (Sahni et al., 2000)

Soliman (1997) developed a numerical model for the case of oil flow during microwave heating. He prepared simplified solutions to investigate the efficiency of oil production using microwave heating. After analyzing the calculations, he made up with the solution of doubling the efficiency by applying 100kW microwave heating. Production without heating was 30 bbl/day; however, applying the microwave heating method, it became 60 bbl/day—results related to the increase of the temperature, which led to a decrease in oil viscosity.

Peraser et al. (2012) considered a 2D EM model using a multi-physics simulator. Reservoir parameters were selected according to the Alaskan heavy oil reservoirs. In addition, they compared conventional thermal methods with EM heating. A Cyclic Steam Stimulation (CSS) model using CMG-STARS was built to study the conventional heating model. **Figure 19** shows the comparison of no heating production and EM heating production. As shown in **Figure 19**, cumulative oil production without heating is about 7,000 bbls, while with EM heating, cumulative oil production is approximately 21,000 bbls at the end of 1 year. This means that the production increased up to 200% with EM heating. **Figure 20** illustrates the comparison of EM heating and CSS production. From **Figure 20**, it can be seen that EM heating can produce more heavy oil compared to CSS thermal method. After three years, cumulative oil production with EM heating is about 80,000 bbls, while with CSS thermal method is only 37,000 bbls. This result shows that EM heating is more efficient than conventional thermal methods.

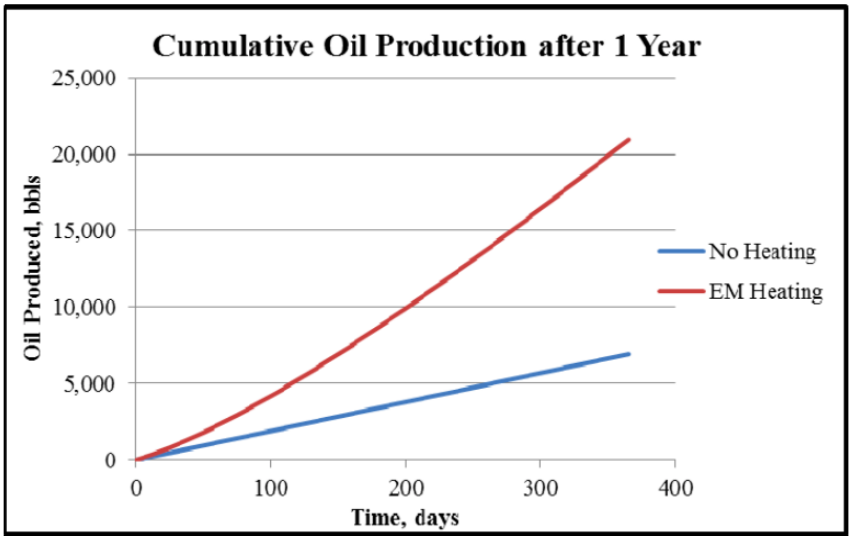


Figure 19. Cumulative oil production after 1 year of EM heating and without heating (Peraser et al., 2012)

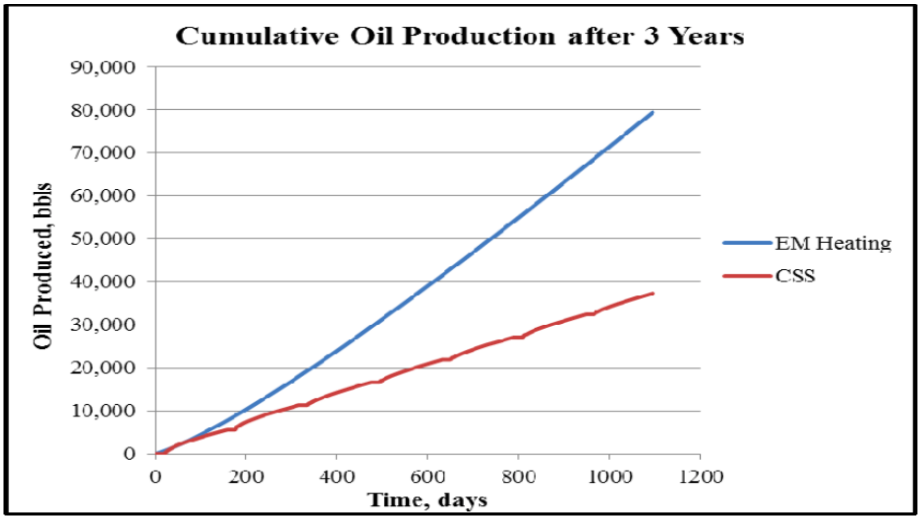


Figure 20. Cumulative oil production after 3 years of EM heating and CSS (Peraser et al., 2012)

To improve microwave heating, the combination of it with water injection was considered by Othman et al. (2017). As gravity and reservoir pressure are the primary sources of driving forces, if there is a lack of them, water can be one of the best solutions to push the oil to the surface. To investigate the numerical solution to the problem, two producers and two injectors/microwave wells were drilled in the heavy oil formation. **Figure 21** illustrates the relationship of oil rate concerning the time for the combination of microwave heating with water injection. Results shows that the combination can give a 150% increase cumulative oil production compared to the standalone MW method.

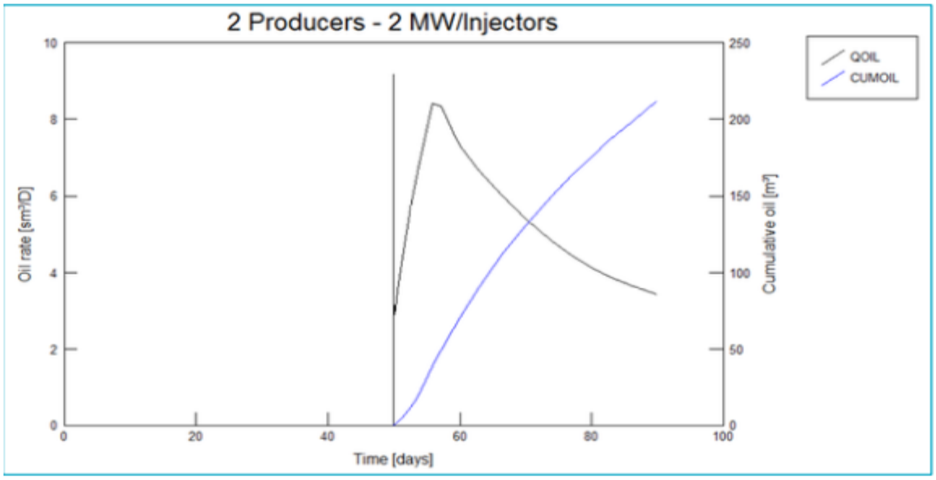


Figure 21. Production results for the combination of microwave heating and water injection (Othman et al., 2017)

To improve the performance of EM heating and more heat adsorption in porous media, the addition of nanoparticles was studied by Al-Farsi et al. (2016). They used nanomaterials such as

Fe and titanium oxide (TO) and then used them as catalysts in the process during microwave (MW) radiation. Injection of nanoparticles improves heat adsorption. The presence of nanoparticles can affect the optimal duration of MW radiation, which depends on the catalyst we use. This means that the quality of heavy oil is increased, which can lead to economic profit for the whole field. In order to understand the effect of nanoparticles on the oil recovery with the combination of microwave heating, **Figure 22** illustrates this relationship.

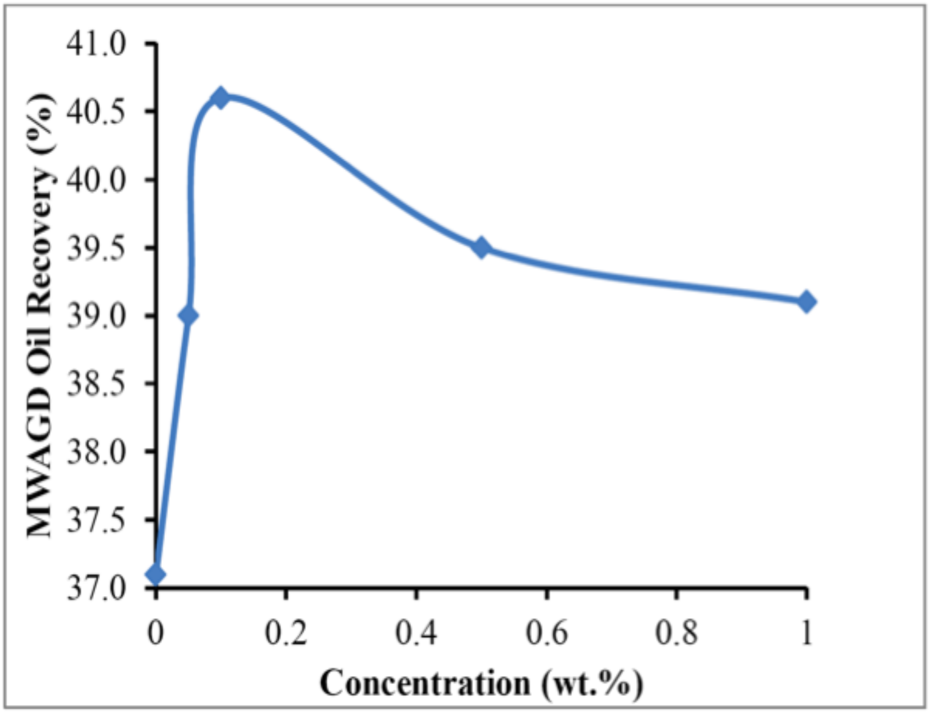


Figure 22. Oil recovery with the microwave heating and gamma alumina (Al-Farsi et al., 2016)

In addition, Shokrlu et al. (2010) investigated the effect of ceramic materials on microwave heating, known as an enabler, which has unique properties when exposed to microwave energy. When it heats up for a short period of time, it can reach 1000°C. The difference of this technique is that oil is heated up not directly by microwave radiation. Instead, ceramic materials convert electromagnetic energy absorbed from microwave heating to thermal energy. This leads to improvements in heat penetration depth and propagation into the reservoir. This approach shows significant improvements in the penetration depth from all studies. In addition, it can help to overcome the limitation of microwave heating regarding applying it in a deep and offshore reservoir. **Figure 23** illustrates the effect of ceramic materials on the average temperature dynamic compared to microwave heating without any ceramics. From **Figure 23**, the average temperature increased with the use of ceramics, which can lead to better results in the oil recovery factor.

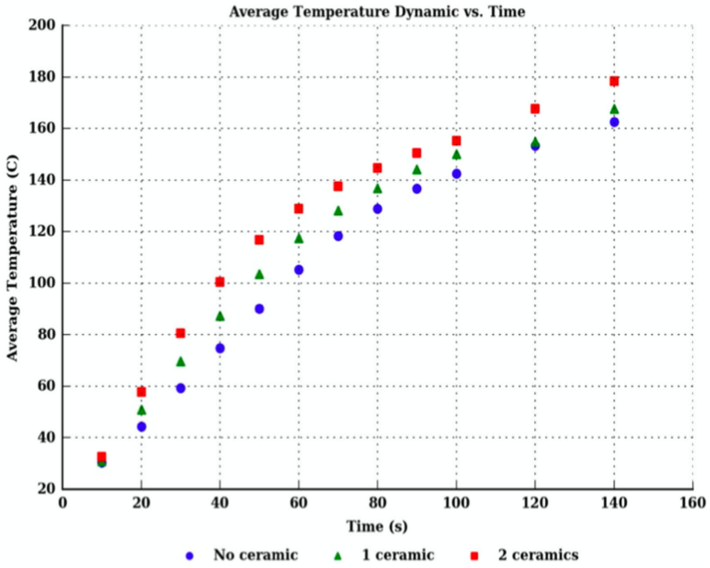


Figure 23. The effect of ceramic materials on the microwave heating temperature (Shokrlu et al., 2010)

To better understand microwave heating, the parameters affecting the method's efficiency were analyzed to determine the main criterion. Othman et al. (2017) show that the heat penetration depth can be controlled mainly by microwave frequency. In addition, research by Bientinesi et al. (2013) illustrates the effect of different frequencies on the temperature.

Another parameter that can affect microwave heating efficiency is power level. The power level can affect the amount of heat being generated significantly. Experiments conducted in 2017 by Othman et al. state that higher power levels of microwave heating can generate more heat and produce more oil. Moreover, power levels can affect the heat penetration depth. The recovery factor can be increased as the power level increases the amount of generated heat. Another experiment conducted by Alomair et al. (2012) investigated the effect of power level on oil production and temperature variation.

The last parameter that can affect microwave heating efficiency is water saturation. It is a crucial factor in the amount of heat generated by microwaves. As water is polar material, it has the highest tendency to increase the temperature of the whole formation with microwave heating. The higher the water saturation, the more heat can be generated. Al-Farsi et al. (2016) investigated the effect of water saturation on oil recovery with MWAGD (Microwave Assisted Gravity Drainage). To summarize, the advantages and disadvantages of the MW method are as follows.

Advantages of microwave heating method:

1. The energy necessary for applying microwave heating is approximately one-tenth the energy the process may produce (Ovalles et al., 2002).
2. Microwave heating has the minimum power consumption compared to other EM heating methods. **Figure 24** compares the maximum and minimum power consumption per unit production for all three methods. From **Figure 24**, it can be concluded that the microwave is the most advantageable in terms of power consumption compared to the results of the other two approaches (Alomair et al., 2012).
3. Microwave heating can be used even in shallow wells, which is difficult for other thermal heating methods. This makes it more efficient across all of the heating EOR methods (Mukhametshina and Martynova, 2013)
4. The amount of water necessary for applying the microwave heating method is not the key. As many countries do not have such an amount of water for the usage of aqueous thermal methods. The reason is the location of the countries (Mukhametshina and Martynova, 2013).
5. Microwave heating can provide better efficiency in less period. From **Figure 9**, it can be seen that microwave heating is faster compared with conventional heating (Sun et al., 2018).
6. Implementing microwave heating can result in better temperature increase results, meaning that the production rate would be higher with respect to time compared to other thermal EOR methods. (Mukhametshina and Martynova, 2013).
7. Microwave heating results in less amount of greenhouse gas emissions compared to other thermal EOR methods, which is advantageous for environment (Mukhametshina and Martynova, 2013).

Disadvantages of Microwave heating:

1. According to Othman et al. (2017), microwave heating method lacks a driving force, which can be solved with the addition of water injected simultaneously with microwave heating.
2. The microwave heating method is primarily applicable only in near wellbore locations and can mainly be used only for vertical wells (Mukhametshina and Martynova, 2013).

3. Corrosion associated with the wells investigated can cause an increase in the amount of money necessary for the method application (Mukhametshina and Martynova, 2013).
4. The frequency of radiation can affect the penetration depth. It can cause problems with designing. For example, high-frequency radiation, which can give the necessary production rate, can reduce the penetration depth, meaning that the heating area decreases (Mukhametshina and Martynova, 2013).

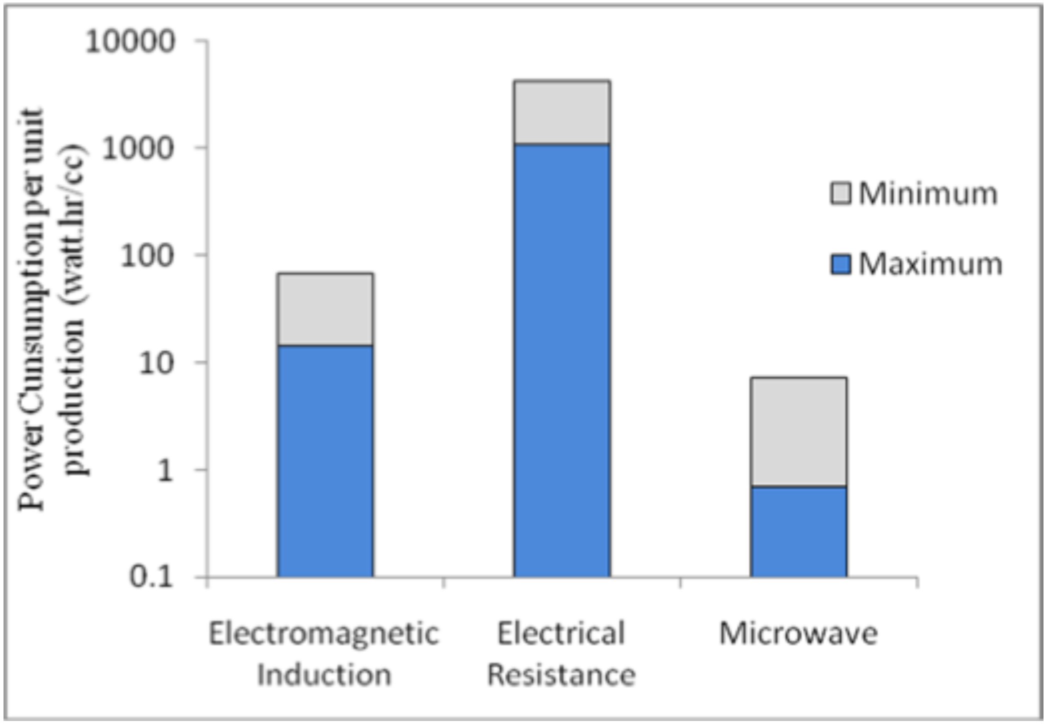


Figure 24. Maximum and minimum power consumption per unit production for each method (Alomair et al., 2012)

From all the information above, we have created the experiment for the project. This experiment focuses on the comparison between the conventional and microwave heating methods to prove that the microwave heating method would give better results in reducing the viscosity. In addition, the effect of the two parameters would be checked during the experiment. First, the effect of the power level of microwave heating would be considered to understand the relationship between the viscosity and power. Second, the effect of water saturation would be investigated to prove that higher water saturation gives better results in temperature and viscosity.

Methodology

The material aspect of the laboratory work consists of the materials used for the experiment - filtered oil from the Uzen oilfield and distilled water mixed in different proportions but having a total volume of 15 ml. Based on the practical work, it was decided to take 15 ml as the standard sample for the research. It was essential to ensure that the sample was heated evenly in the microwave oven, which could affect the results. Considering the Uzen oil, it is vital to mention its essential qualities of primary importance for our work. It has an API of 35. However, it has up to 29% paraffin and asphaltene content, creating production problems (Sparke et al., 2005). The viscosity of the oil is 8 cp at 63℃. KazMunaiGas provided the heavy oil.

When performing experiments, it is critical to have dependable equipment that can carry out the precise tasks required by the investigation. The viscosity of heavy oil after various heating techniques was measured in this experiment using various tools.

The rheometer, depicted in **Figure 25,** is the first apparatus utilized in the experiment. It is a laboratory tool to gauge how fluids react to external forces. This work assessed the viscosity of heavy oil following various heating techniques using a rheometer. Viscosity is a crucial factor in describing how fluids behave when they flow. Researchers can comprehend how temperature affects the flow behavior of heavy oil by measuring viscosity. The measurement on the rheometer was conducted based on the shear rate of 10 1s for all samples since porous media is about 10.

Figure 25. Rheometer

The Samsung ME712AR microwave oven, depicted in **Figure 26**, is the second apparatus utilized in the experiment. It is an oven that warms items using microwaves. In this investigation, heavy oil was heated using a microwave oven at various power levels. The maximum heating period for the oven is 35 minutes, and the power range is 0 W to 800 W. Researchers can heat heavy oil more quickly and effectively by utilizing a microwave oven.

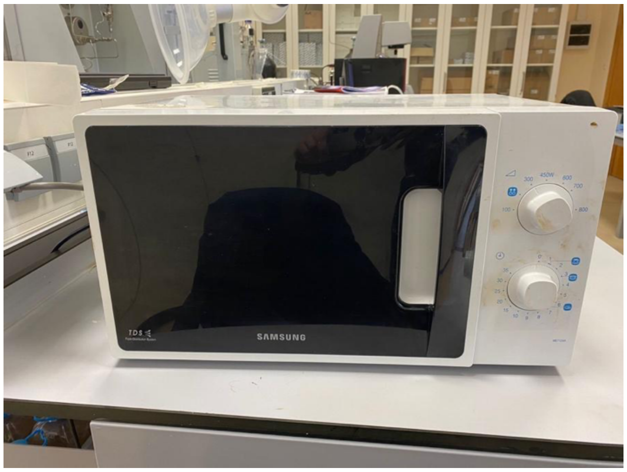


Figure 26. Microwave Oven

The third apparatus used in the experiment is the conventional laboratory oven, which is shown in **Figure 27**. It is an oven that is used in laboratory investigations. It was used in this study to compare the viscosity results with the microwave heating method and assess the effect of temperature on heavy oil at various saturations. This made it possible for scientists to compare the outcomes of using a microwave oven to those of using a more conventional heating technique.

Figure 27. Oven Used for Conventional Heating

Other experiments equipment includes a thermometer, timer, beaker, and pipette. The temperature of the heavy oil was monitored using a thermometer with a range of -50°C to +300°C and uncertainty of 1°C to assess how heating affected viscosity. The glass beaker guaranteed consistency in the amount used by precisely measuring 15 ml of heavy oil. The timer kept track of the heavy oil's heating process to ensure accuracy, measuring time correctly compared to the microwave oven timer. Finally, the pipette was used to inject the right amount of heavy oil into the glass beaker to ensure consistency throughout the experiment.

The efficiency of heavy oil heating by microwaves was studied through laboratory experiments. The main goal was to compare conventional heating methods with microwave heating. The main tasks were measuring the changes in viscosity, temperature, and time: a microwave oven and a standard laboratory oven were used for heating. The microwave oven had adjustable power, allowing it to vary the heating time and power to 300W, 450W, and 700W. Samples in a volume of 15 ml were separately heated in a conventional oven and a microwave oven with a constant temperature of 80°C. After certain intervals, the temperatures and viscosity were measured. Based on the data, graphs were constructed, and an analysis was carried out.

The experiment consists of two main parts. The first stage is heating heavy oil in a microwave oven. The accuracy of the data was analyzed based on the first test for the first stage of laboratory work. The accuracy was calculated based on the repeatability and accuracy of the data. The repeatability and accuracy of the results of the performed work were checked based on 3 attempts to heat heavy oil in a microwave oven under the same conditions.

To measure a 15 mL sample of pure crude oil (Sw=0%), a bottle containing filtered crude oil was first heated in a traditional oven until it reached a pourable state, allowing for the easy transfer of large volumes of oil without getting stuck in the pipette. Following heating, 15 mL of the oil, with the help of a pipette, was poured into a 100 mL beaker. The resulting sample was then covered with plastic wrap and allowed to cool to a temperature of 30 degrees Celsius, deemed the room temperature. The oil temperature was measured using a thermometer with a probe, and once the sample reached the desired temperature, it was placed in a microwave oven at 300 watts, 450 watts, and 700 watts. A timer was set for 1, 2, and 4 minutes during each heating time [t] at each power level. After the designated time, the temperature of the oil was measured in the vicinity of the minute using the thermometer, which only minimally reduced the sample's temperature. It is worth noting that a new sample was prepared for each power level. After measuring the temperature, the value was recorded in a table, and the same temperature was set on the viscometer.

Next, it is necessary to set the stress rate to 1 1s, while the time between viscosity measurement points was 10 seconds between each point.

Following this, the cone was positioned back to its initial location, and viscosity measurements were taken, recording data at a shear rate of 10, 1s for all samples. This procedure was later performed for oil samples with different water saturation [Sw] of 10% and 25%. As a result, we have 3 saturation variables and 3-time intervals for each of the heating powers. All results were recorded in tables for further mathematical analysis. Tables include the temperature and viscosity data entered. Each of them is recorded at a certain power level for microwave heating. There are also differences in water saturation and time for each power. For example, there are four possible saturation levels for 300 volts: 0%, 10%, 15%, and 20%. Moreover, each saturation has a heating time of 1, 2, or 4 minutes.

Furthermore, the temperature and viscosity are recorded for 300 volts, 0% saturation, and 1 minute of heating. Moreover, we have three of them. As a consequence, 72 variables for temperature and viscosity were recorded for the microwave heating investigation. In the case of regular heating, however, the maximum temperature of heating oil in a microwave oven was used for the temperature of the conventional oven. The table's structure is similar to that of microwave heating. As a result, 24 variables for temperature and viscosity were recorded during the experiment with typical heating.

The analysis of the results of the microwave heating method was based on variables such as heating time [t], water saturation [Sw], and heating power [W]. The samples' temperature [T] and viscosity [$\boldsymbol{\mu}$] were measured for efficiency determination. Also, they were used to construct the graphs of dependency of viscosity and temperature to time.

Experiments were conducted using both methods to compare the heating efficiency between microwave heating and traditional oven heating. Using a pipette, 15 ml of oil with zero water saturation [Sw] was extracted and transferred to a 100 ml beaker. The resulting sample was then covered with plastic wrap and cooled to 30 degrees Celsius. After checking the temperature of the sample using a thermometer, the sample was placed into the oven at a temperature of 80 degrees. Next step, the timer was used to measure time intervals of 1, 2, and 4 minutes so that a thermometer could be used to calculate the heating temperature during these periods. The water saturation of each sample in the tests varied from 0%, 10 and 25%. The temperature and viscosity measurement times also corresponded to 1 min, 2 min, and 4 min for each subsequent test.

Results and Discussion

Effect of power

In this work, we studied the effect of MW power on the temperature alteration. **Figure 28** shows the graph of viscosity versus temperature for different powers in the case of 0% water saturation. From **Figure 28**, it can be seen that the effectiveness of microwave heating with 0% saturation is increasing with the power level. It means that the higher the power level, the higher temperature and the lower the viscosity obtained. However, for some temperatures, the power level of 450W gives better results in viscosity. **Figure 29** illustrates the same relationship with 10% water saturation. From **Figure 29,** the same trend of microwave heating is obtained as in the experiment for 0% saturation. This means that the power level affects the efficiency of the technique; however, from the difference in 450W and 700W for some temperatures, it can be concluded that 450W is a better choice for a small period of time. **Figure 30 and Figure 31** show the same tendency; however, the main difference is in the temperature. **Figure 32** illustrates the viscosity vs. time graph for different power levels for 0% water saturation. From **Figure 32**, it can be seen that there is higher viscosity reduction in 4 minutes for 700W compared with 300W and 450W. **Figure 33** shows viscosity vs. time graph for different power levels in the case of 10% water saturation. **Figure 33** illustrates the same trend as **Figure 32**. **Figure 34** illustrates viscosity vs. time graph for different power levels in the case of 15% water saturation. It can be seen that in the case of 15% water saturation, there is almost the same reduction in viscosity for 700W and 450W in 4 minutes. **Figure 35** shows viscosity vs. time graph for different power levels for 20% water saturation. From **Figure 35**, 700W gave higher reduction in viscosity for the point at 4 minutes, however the difference between the results for 450W and 700W is small compared with the cases of 0% and 10% water saturations. **Figure 36** illustrates the temperature vs. time graph for different power levels for 0% water saturation. From **Figure 36**, it can be seen that there is higher temperature in 4 minutes for 700W compared with 300W and 450W and the maximum temperature is about 70°C. **Figure 37** shows the temperature vs. time graph for different power levels for 10% water saturation. From **Figure 37**, it can be seen that there is higher temperature in 4 minutes for 700W compared with 300W and 450W and the maximum temperature is about 74°C. **Figure 38** illustrates the temperature vs. time graph for different power levels for 15% water saturation. From **Figure 38**, it can be seen that there is higher temperature in 4 minutes for 700W compared with 300W and 450W and the maximum temperature is about 78°C. **Figure 39** illustrates the temperature vs. time graph for different power levels for 20% water saturation. From **Figure 39**, it can be seen that there is higher temperature in 4 minutes for 700W compared with 300W and 450W and the maximum temperature is about 82°C.

Overall, the effect of the power level on the temperature alteration is determined. Higher the power level, higher the temperature is gotten. This results in a better viscosity reduction due to the increased amount of generated heat.

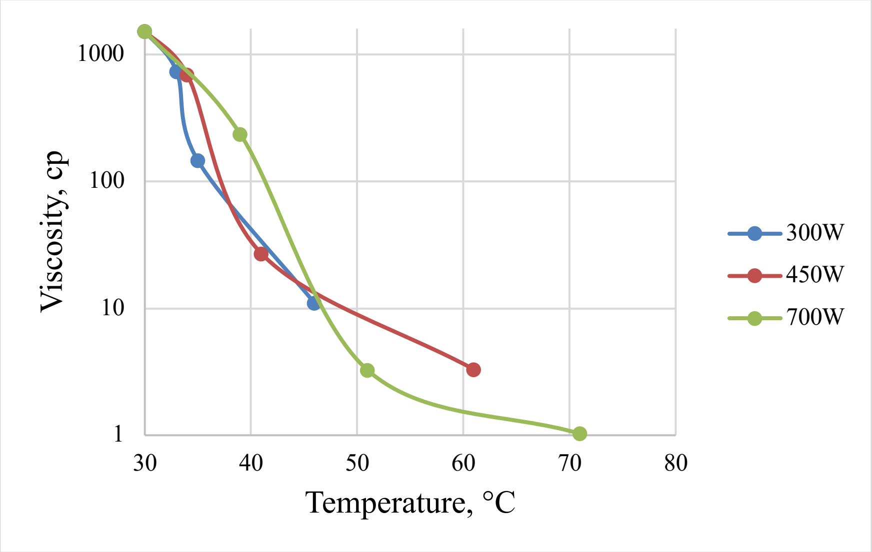


Figure 28. Microwave Heating for 0% Water Saturation for Different Powers

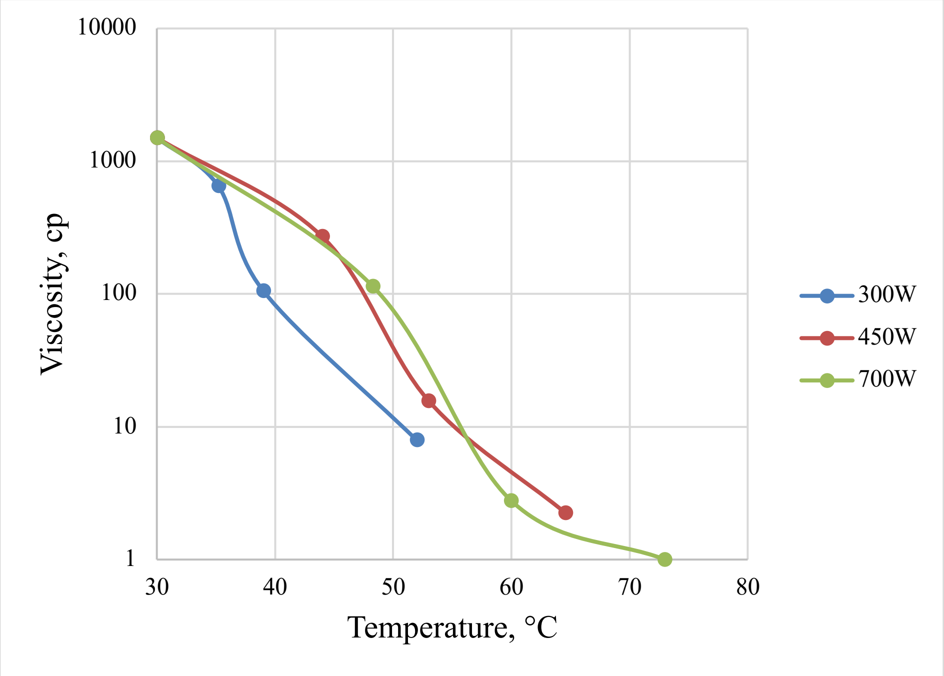


Figure 29. Microwave Heating for 10% Water Saturation for Different Powers

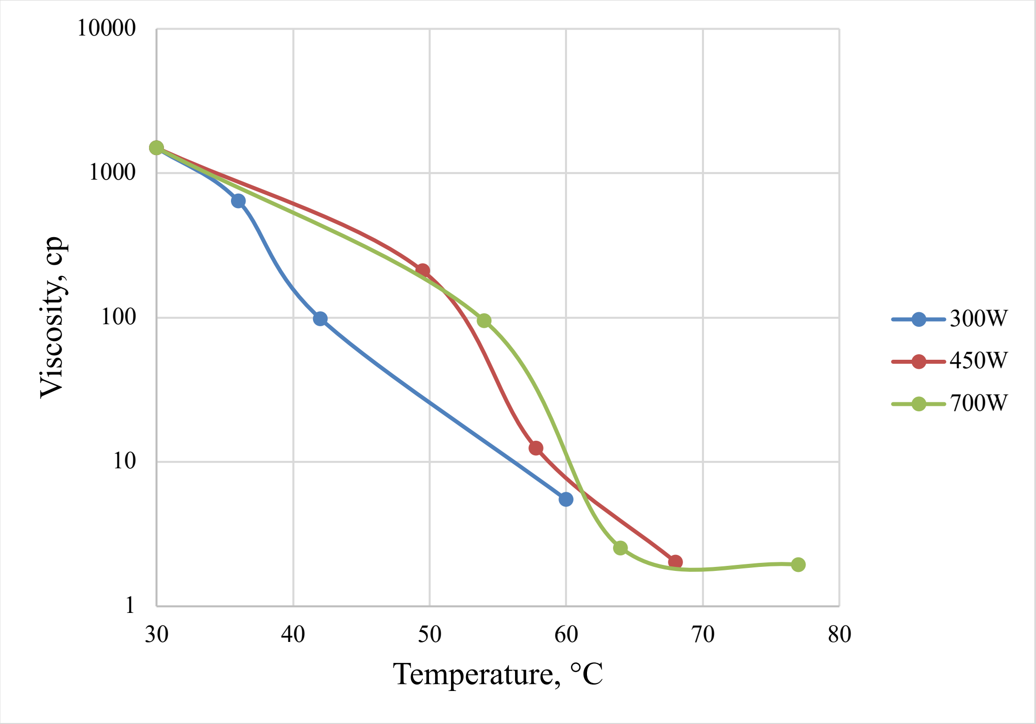


Figure 30. Microwave Heating for 15% Water Saturation for Different Powers (Temperature Perspective)

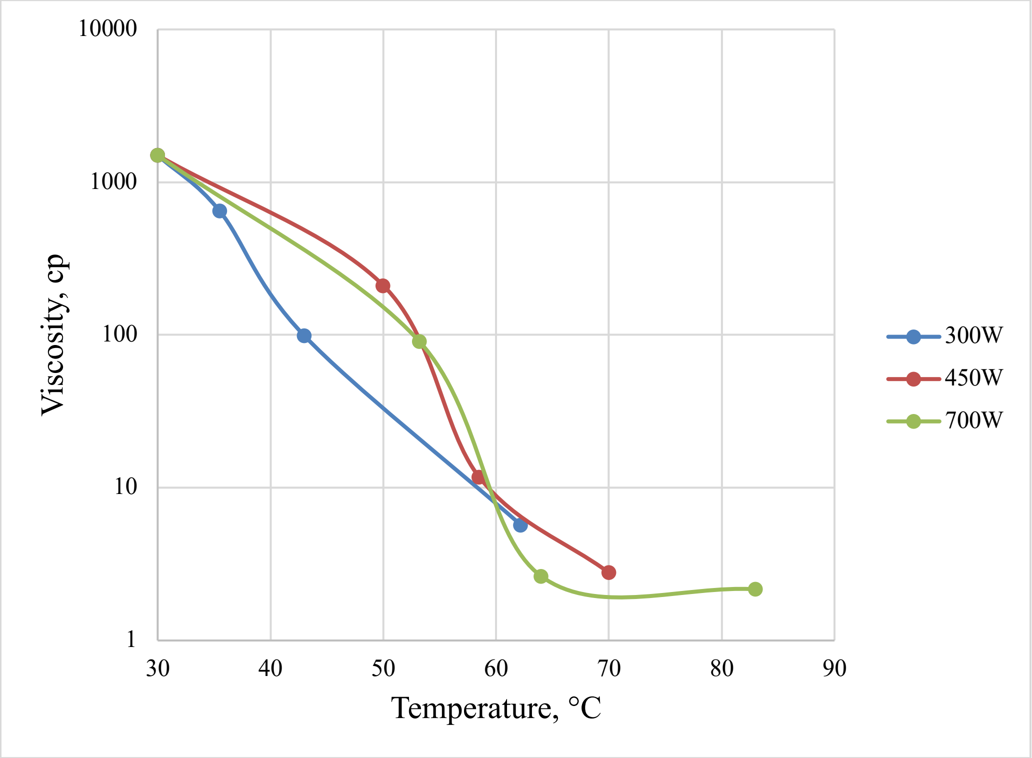


Figure 31. Microwave Heating for 20% Water Saturation for Different Powers (Temperature Perspective)

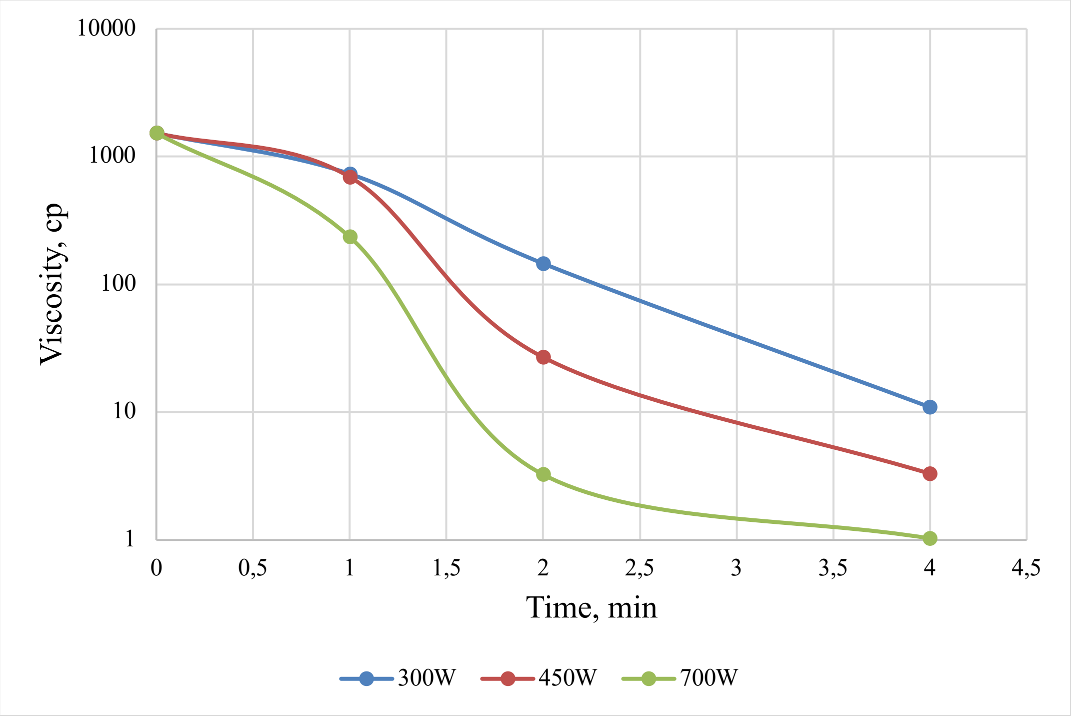


Figure 32. Microwave Heating for 0% Water Saturation for Different Powers (Time Perspective)

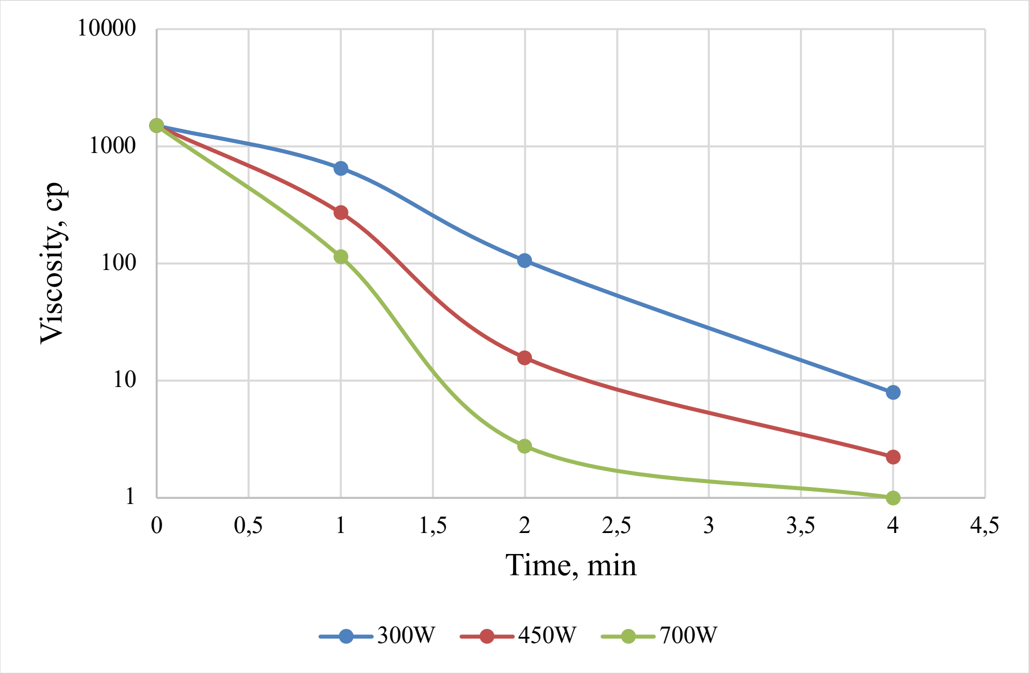


Figure 33. Microwave Heating for 10% Water Saturation for Different Powers (Time Perspective)

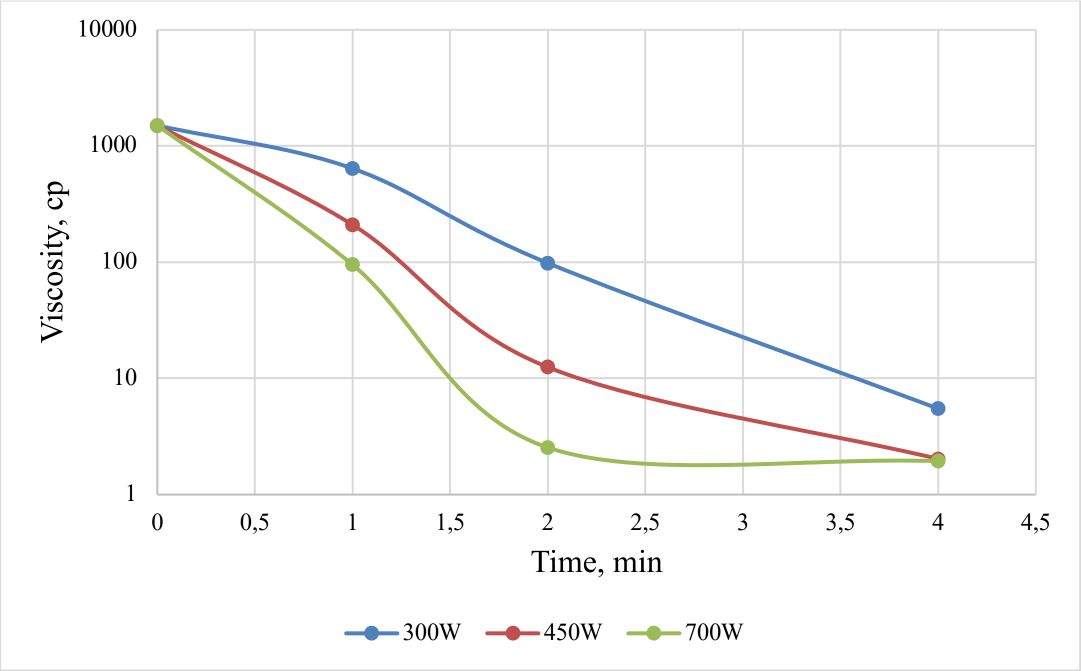


Figure 34. Microwave Heating for 15% Water Saturation for Different Powers (Time Perspective)

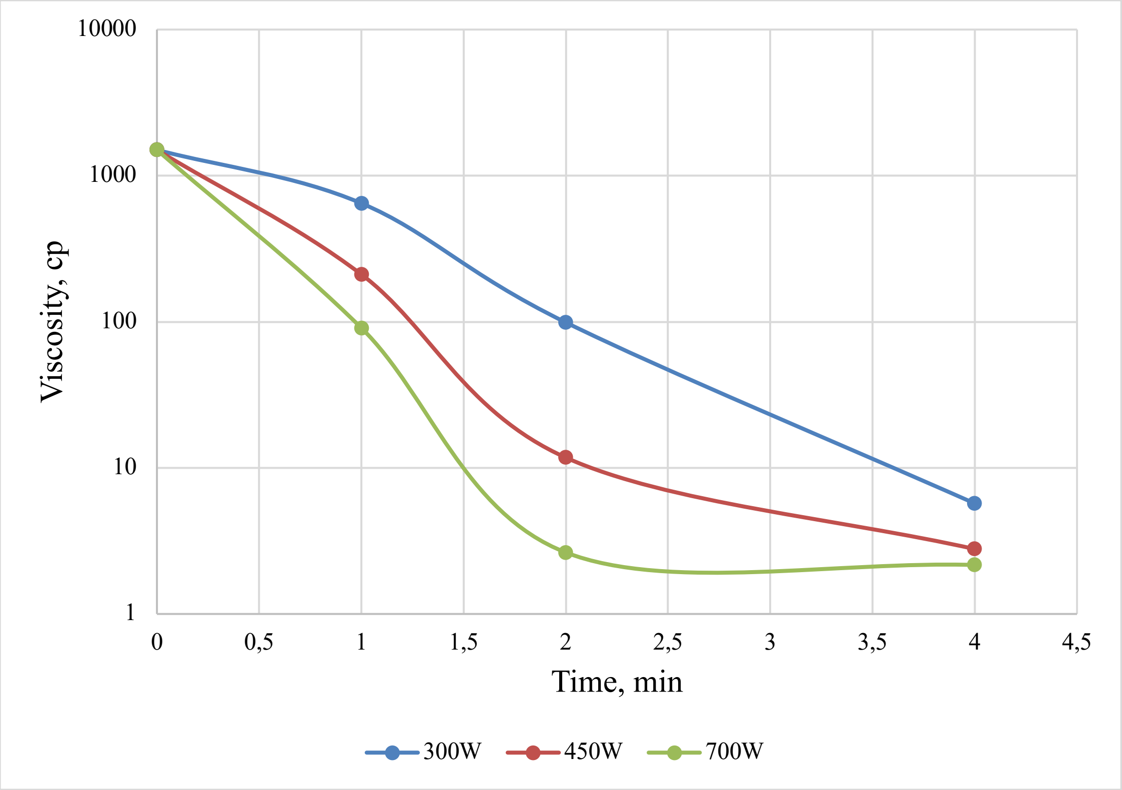


Figure 35. Microwave Heating for 20% Water Saturation for Different Powers (Time Perspective)

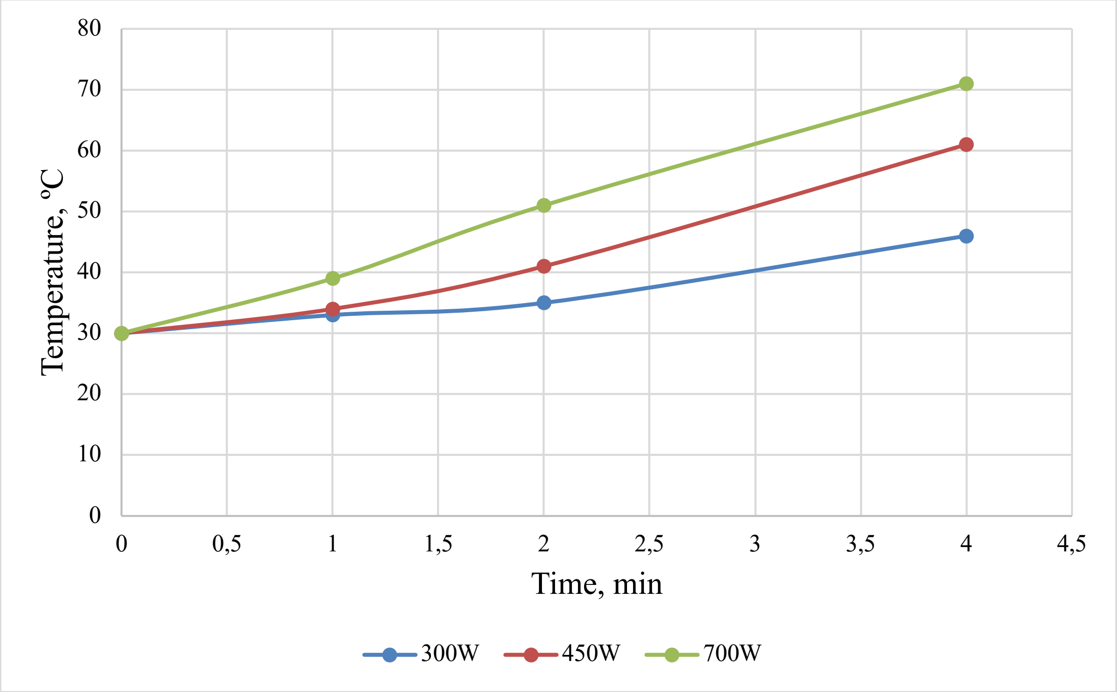


Figure 36. Microwave Heating for 0% Water Saturation for Different Powers (Temperature vs. Time)

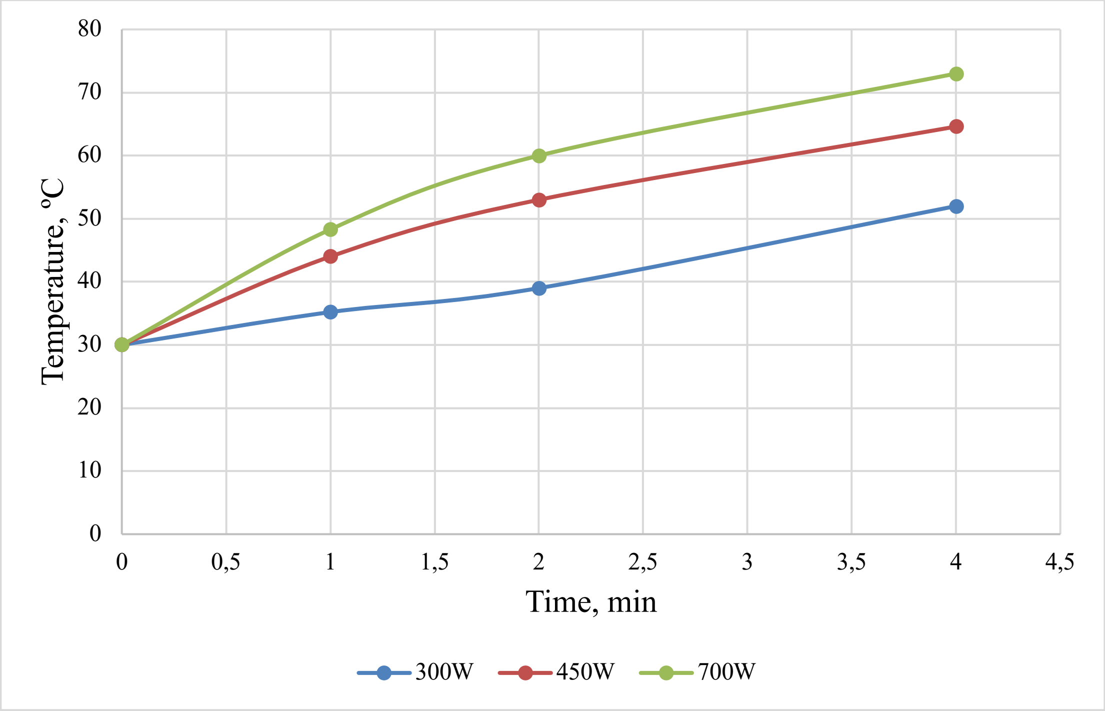


Figure 37. Microwave Heating for 10% Water Saturation for Different Powers (Temperature vs. Time)

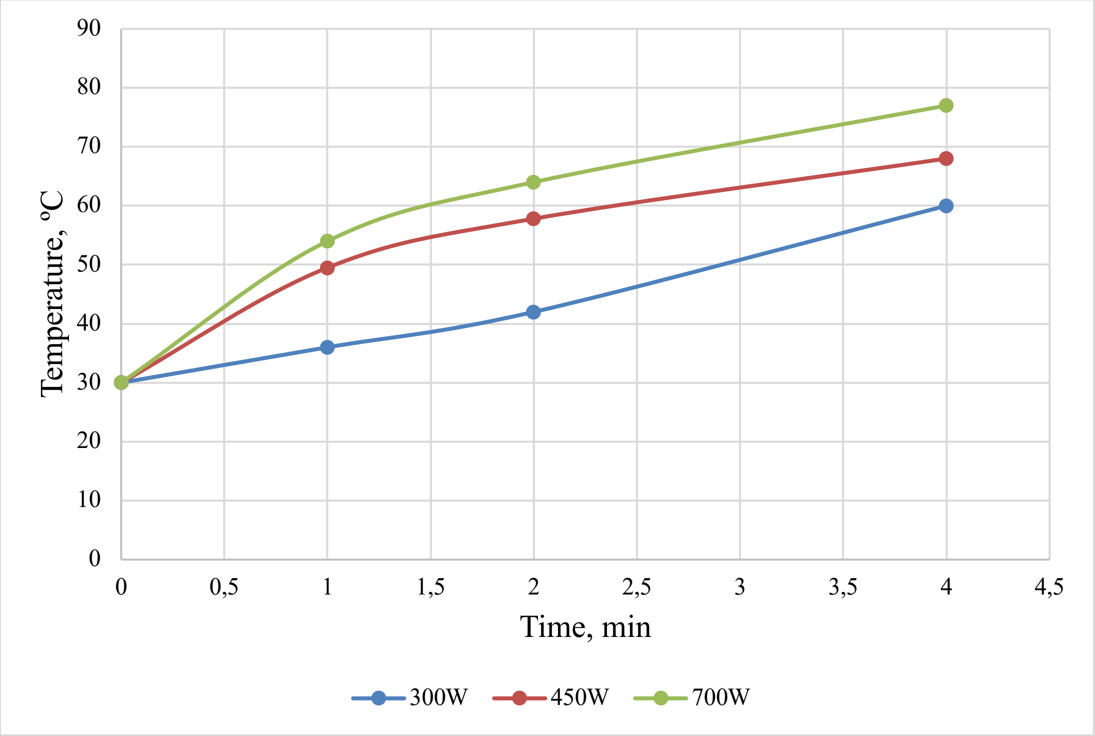


Figure 38. Microwave Heating for 15% Water Saturation for Different Powers (Temperature vs. Time)

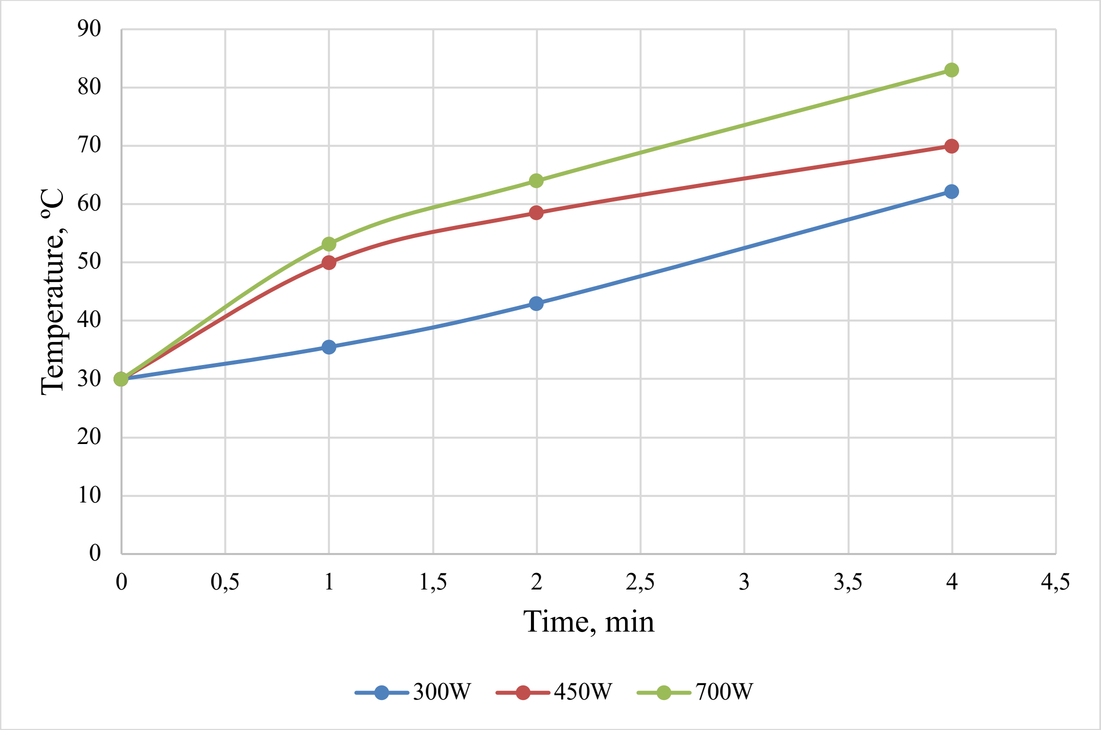


Figure 39. Microwave Heating for 20% Water Saturation for Different Powers (Temperature vs. Time)

Effect of Water Saturation

During the first part of the experiment, the effect of water saturation on temperature alteration was determined. **Figure 40** shows the viscosity versus temperature graph for different water saturations in the case of 300W power. From **Figure 40,** it can be seen that 10% water saturation gave the highest effect compared to the results for 0%. However, 15% and 20% are close to each other, which means that the efficiency is decreasing with increasing amount of water saturation. In addition, **Figure 41** illustrates that 20% water saturation gave worse results in viscosity compared to 15%. Moreover, **Figure 42** shows that 0% and 10% gave lower results of viscosity compared to 15% and 20% water saturation. From the above information, it can be concluded that 10% is the best choice for the microwave heating method in the case of 700W. **Figure 43** illustrates the viscosity vs. time graph for different water saturations for 300W power level. From **Figure 43**, it can be seen that there is higher viscosity reduction in 4 minutes for 15% and 20% water saturations compared with 0% and 10%. **Figure 44** shows viscosity vs. time graph for different water saturations for 450W power level. **Figure 44** illustrates the same trend as **Figure 43**; however, it can be seen that 10% gave better results compared with 20% water saturation in viscosity reduction for 4 minutes. **Figure 45** illustrates viscosity vs. time graph for different water saturations for 700W power level. It can be seen that in the case of 700W power level, there is almost the same reduction in viscosity for 0% and 10% water saturations and there is higher viscosity reduction compared with 15% and 20% water saturations in 4 minutes. The possible source of this difference can be the amount of water in the sample. As water has absorbed all of the heat generated by 700W. **Figure 46** illustrates the temperature vs. time graph for different water saturations for 300W power level. From **Figure 46**, it can be seen that there is higher temperature in 4 minutes for 20% water saturation compared with other water saturations and the maximum temperature is about 62°C. **Figure 47** shows the temperature vs. time graph for different water saturations for 450W power level. From **Figure 47**, it can be seen that there is higher temperature in 4 minutes for 20% water saturation compared with other water saturations and the maximum temperature is about 70°C. **Figure 48** shows the temperature vs. time graph for different water saturations for 450W power level. From **Figure 48**, it can be seen that there is higher temperature in 4 minutes for 20% water saturation compared with other water saturations and the maximum temperature is about 82°C.

Overall, there is linear relationship in viscosity reduction and water saturation. As water absorbs more heat and making the oil hotter, which makes higher viscosity reduction.

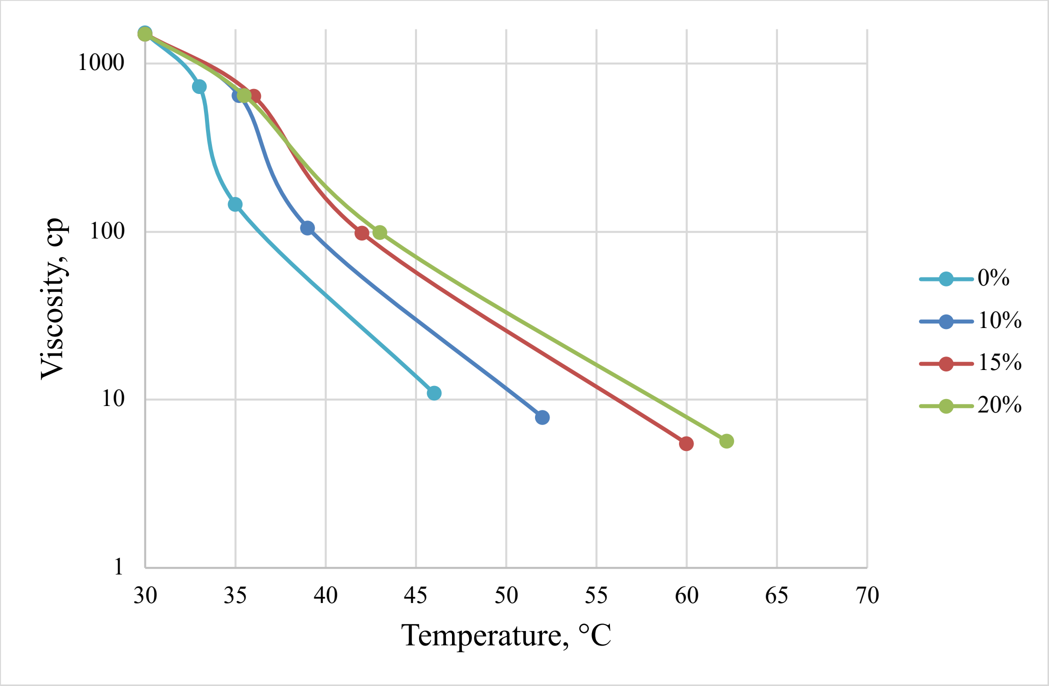


Figure 40. Effect of Saturation for Microwave Heating (300W) (Temperature Perspective)

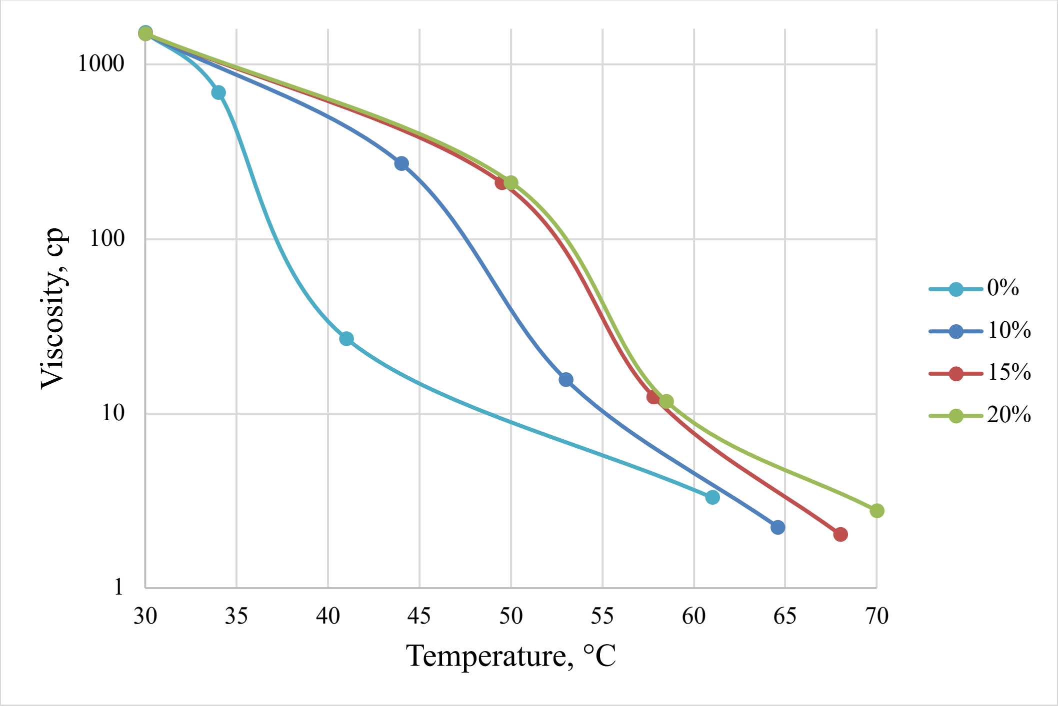


Figure 41. Effect of Saturation for Microwave Heating (450W) (Temperature Perspective)

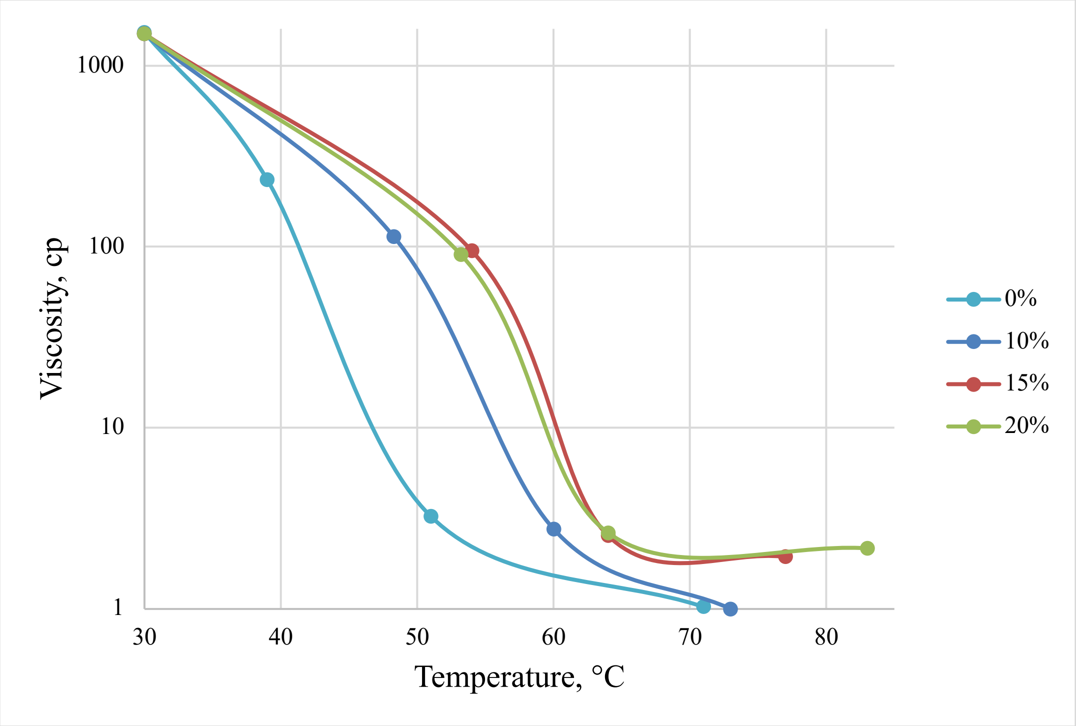


Figure 42. Effect of Saturation for Microwave Heating (700W) (Temperature Perspective)

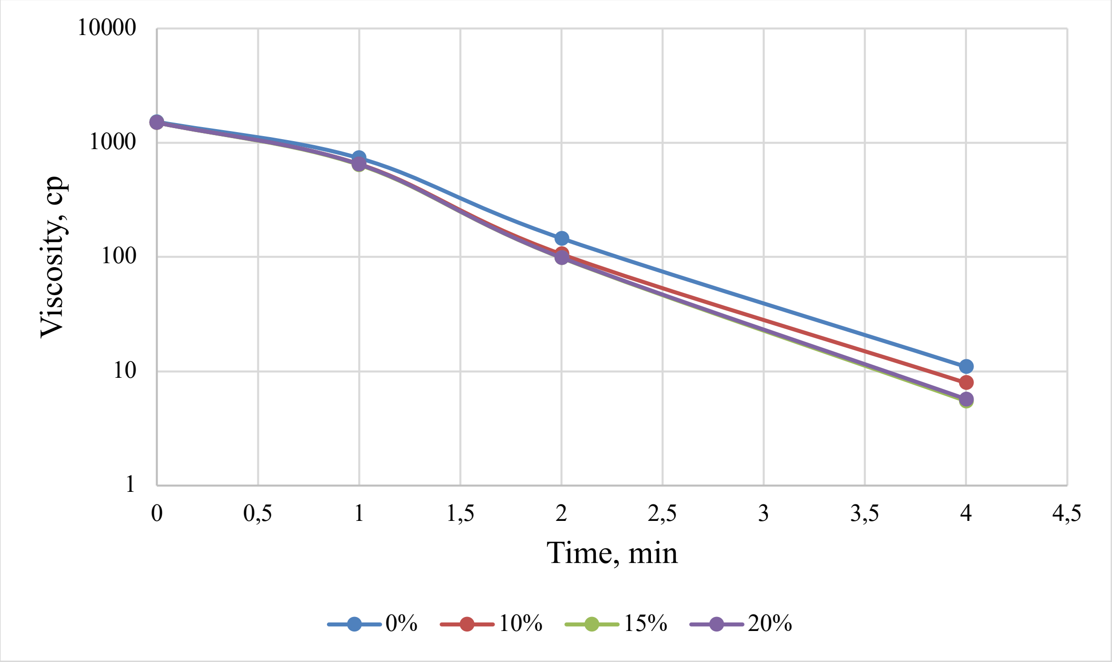


Figure 43. Effect of Saturation for Microwave Heating (300W) (Time Perspective)

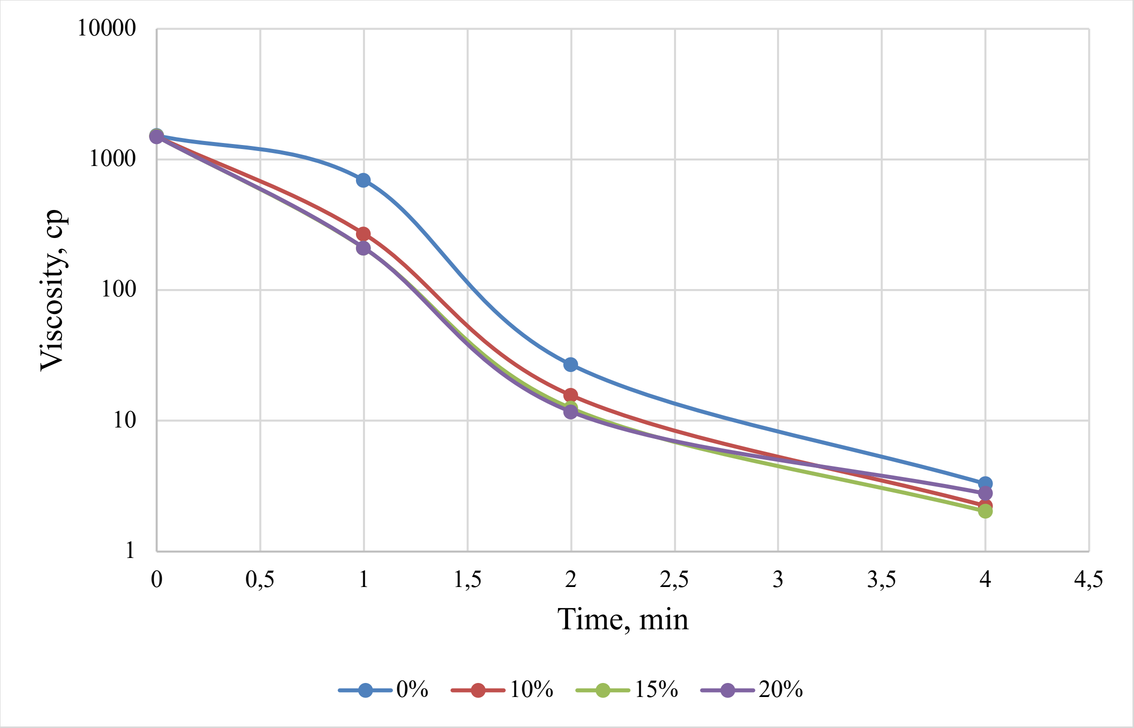


Figure 44. Effect of Saturation for Microwave Heating (450W) (Time Perspective)

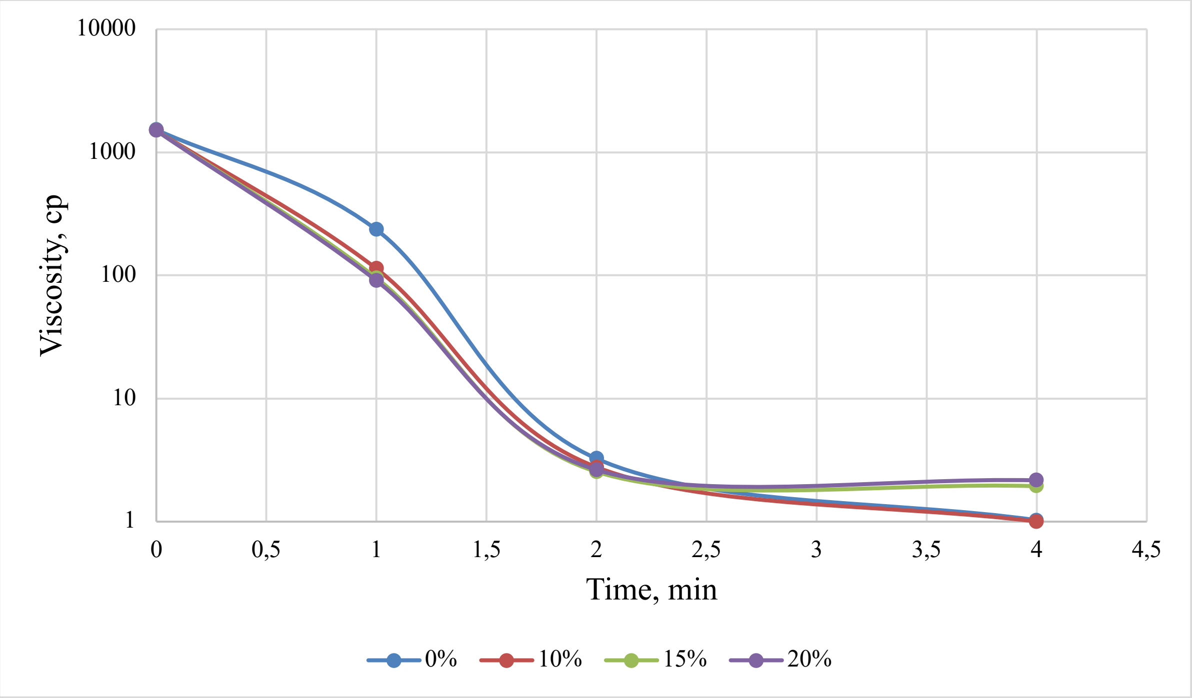


Figure 45. Effect of Saturation for Microwave Heating (700W) (Time Perspective)

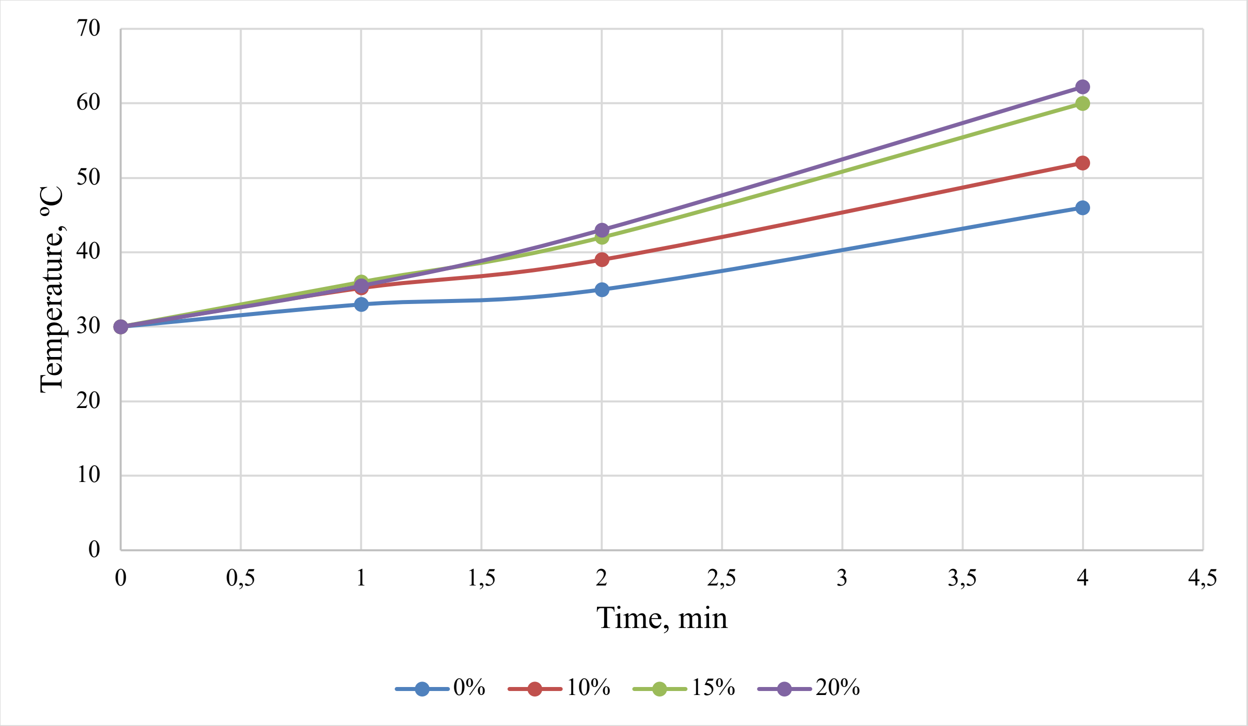


Figure 46. Effect of Saturation for Microwave Heating (300W) (Temperature vs. Time)

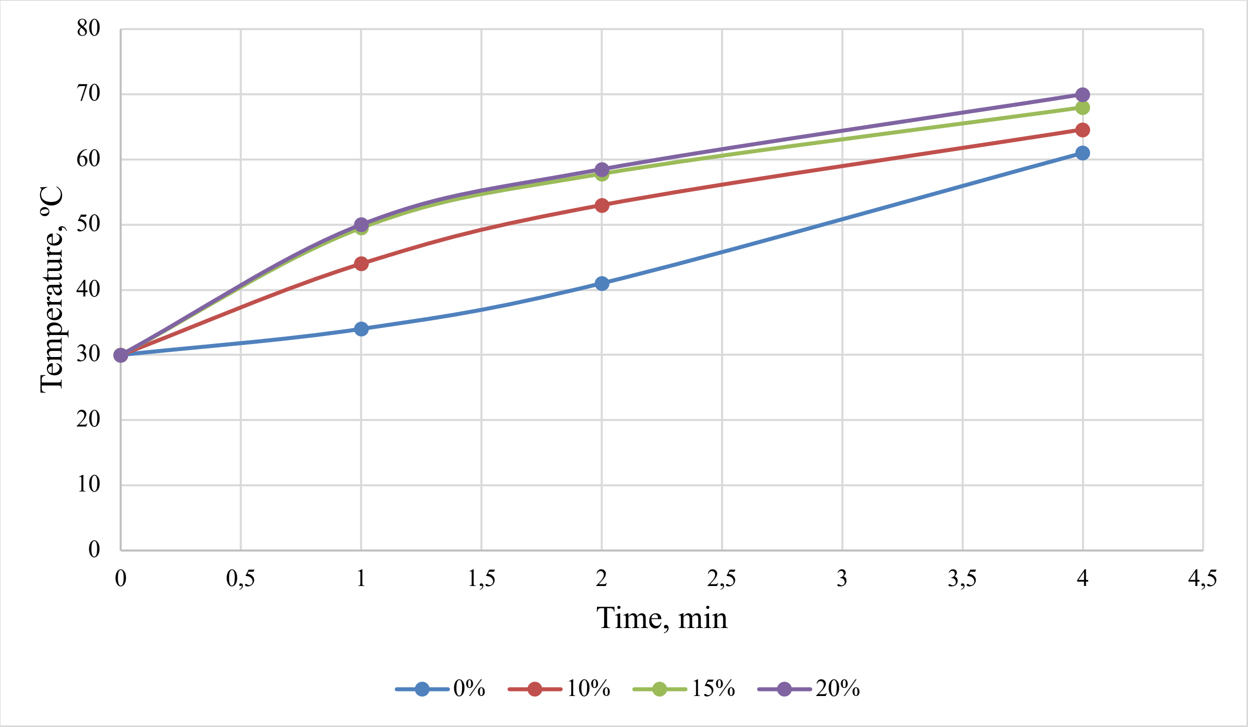


Figure 47. Effect of Saturation for Microwave Heating (450W) (Temperature vs. Time)

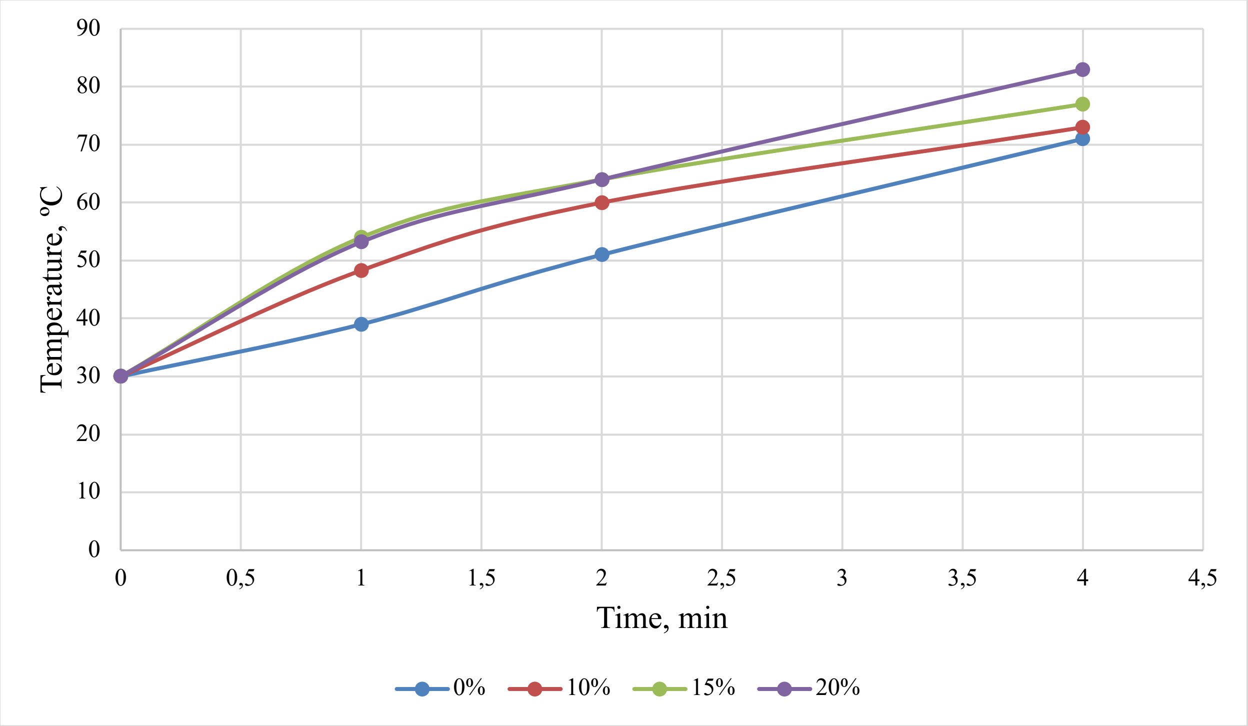


Figure 48. Effect of Saturation for Microwave Heating (700W) (Temperature vs. Time)

Conventional Heating Method vs. Microwave Heating Method

During the second part of the experiment, the efficiency of conventional heating method is compared with the microwave heating method. **Figure 49** shows the results of conventional heating for different water saturation in the perspective of temperature. From **Figure 49,** it can be seen that the highest temperatures were obtained for 15% water saturation. However, 10% saturation gave the lowest results for viscosity for 36 °C to 43 °C. **Figure 50** shows the results of conventional heating for different water saturation in the perspective of time. It can be seen that 10% and 15% water saturation gave higher viscosity reduction in 4 minutes compared with 20% water saturation. **Figure 51** shows the results of conventional heating for temperature vs time graph. It can be seen that the highest value of temperature is obtained with 15% water saturation. To compare the effectiveness of conventional heating method with microwave heating method we have chosen one point at 4 minutes for microwave heating method for different power and conventional heating method. The results are summarized in **Table 4.** As it can be seen from **Table 4**, the viscosity is lower for microwave heating method even for 300W compared with the conventional heating method. In addition, there is higher temperature value.

The following statements can be concluded from the results of the second part of the experiment:

- High water saturation is not such effective for conventional heating method
- 10% - 15% water saturations are the best choice for the conventional heating
- Microwave heating has higher rate in increasing of temperature and decreasing of viscosity compared to conventional heating method

Table 4. Microwave Heating Method and Conventional Heating Method Comparison

Parameter (4 min)	**Conventional Heating Method (15% Water Saturation)**	**Microwave Heating Method (300 W) (15% Water Saturation)**	**Microwave Heating Method (450W) (15% Water Saturation)**	**Microwave Heating Method (700W) (15% Water Saturation)**
Viscosity	8 cp	6 cp	3.5 cp	3 cp
Temperature	47ºC	60ºC	67 ºC	78ºC

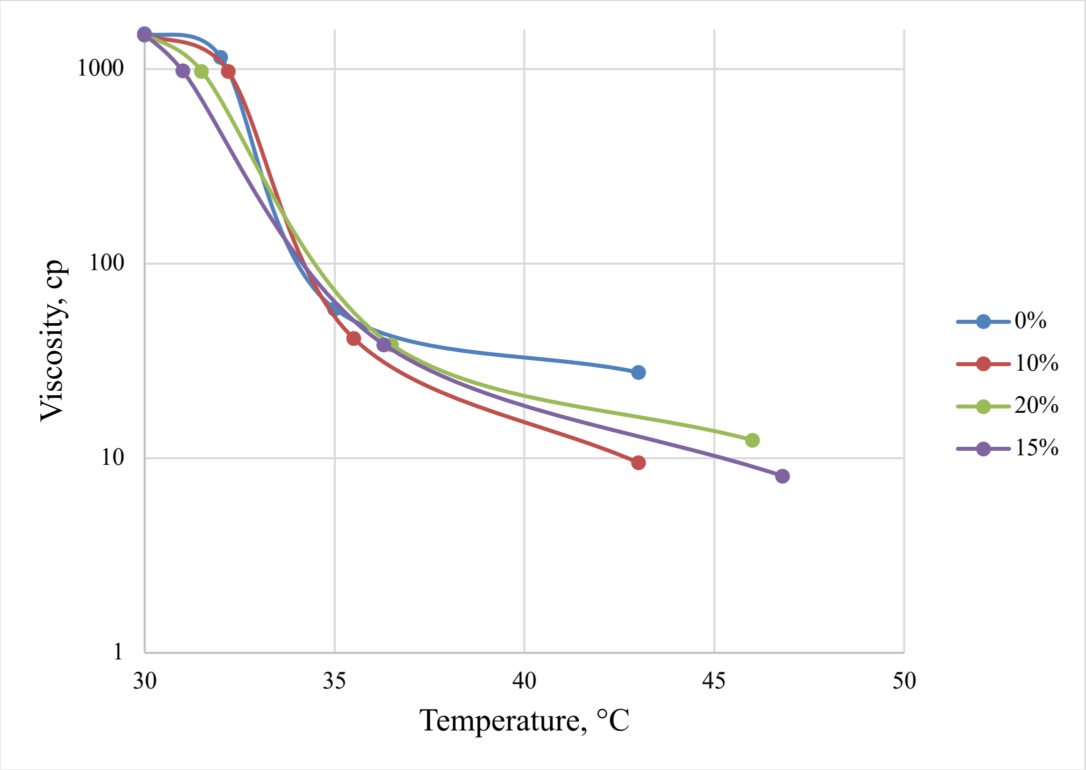


Figure 49. Conventional Heating Results for Different Saturations (Temperature Perspective)

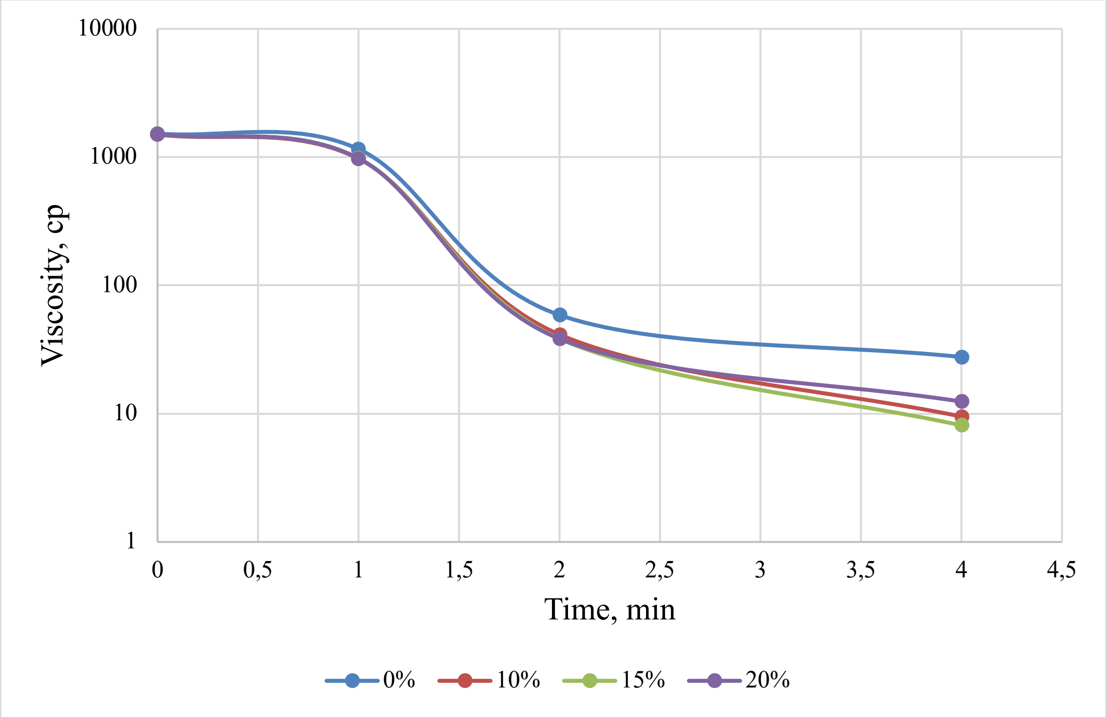


Figure 50. Conventional Heating Results for Different Saturations (Time Perspective)

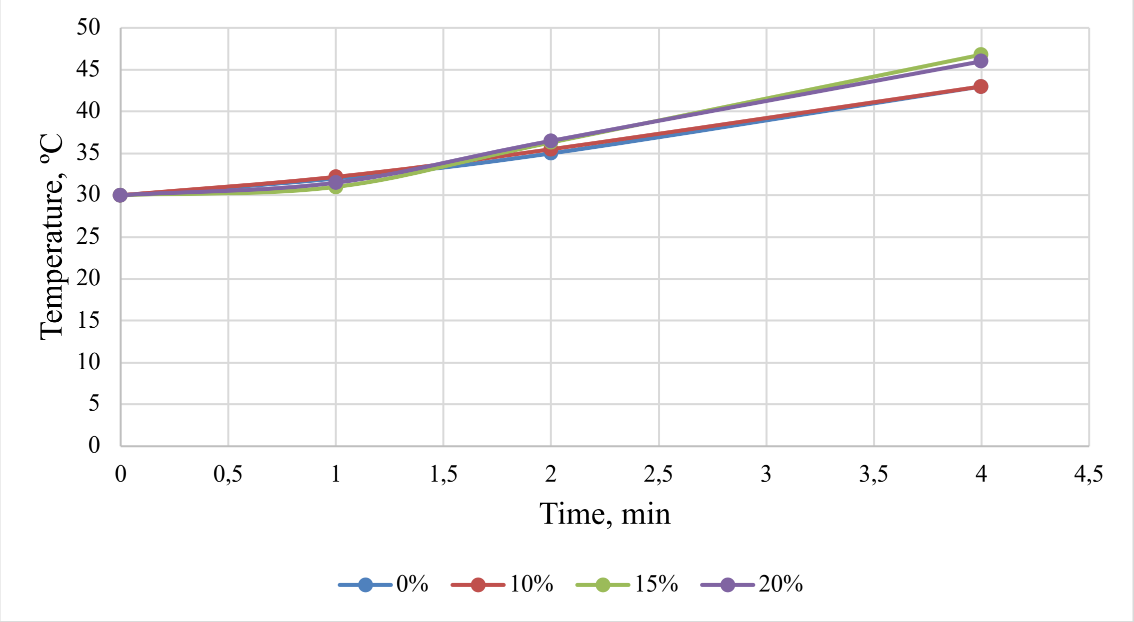


Figure 51. Conventional Heating Results for Different Saturations (Temperature vs. Time)

Possible Errors

During the experiment, there were some possible sources of errors and we have overcome some of them. The errors and the solutions are tabulated in the table below:

Table 5. Possible errors and solutions for the experiment

Gas emission during the microwave heating. This could lead to the uncertainties in the values of temperature and viscosity.	Paraffin film was used for the beaker to solve the problem with gas emission.
Uncertainties in the small amount of water and oil.	To overcome this error, we have used electrical pipette, which has uncertainty only ±1 micrometer.
Conventional microwave oven was used for the experiment.	**This error should be considered in further research**, as special microwave oven is required.
Possible change in molecular structure during microwave heating.	**This uncertainty should be considered in further research,** as special device for gas emission, which can evaluate the gases which were emitted should be used.
Slow temperature measurement using conventional thermometer.	**This uncertainty should be considered in further research.** For example, infrared thermometer inside the microwave oven can be used to identify the temperature immediately without any loss of heat to the environment.
Slow viscosity measurement using rheometer	**This uncertainty should be considered in further research.** Rheometer is slow in working which means that some of the temperatures as well as heat can be loosed. Even the heating from rheometer is not such effective because it can also affect the result for viscosity.

Conclusion

During the capstone project, we analyzed the primary information about microwave heating and conventional heating and summarized all the information in the introduction and literature review parts. To justify the literature information, the experiment was performed. From the results of the experiment, we have identified the following information, which answers all of our objectives:

- Microwave heating has a higher rate increasing of temperature and decreasing viscosity compared to the conventional heating method
- Microwave heating gives this trend: the higher the power level, the higher temperature and lower viscosity obtained
- 10% - 15% water saturations are the best choice for the conventional heating
- High water saturation is not much adequate for a conventional heating method
- 10% is the best choice for the microwave heating method

There was the main limitation of this project, which was the experimental part. During the experiment, we identified many possible sources of errors, some of which still needed to be solved.

From the above information about limitations, the main suggestion for further research is to solve the possible errors with the recommendation given in Table 9.

Overall, we have achieved our goal and objectives, and the results from the experiment were good enough to get the same conclusions as researchers get from the literature review. The main contribution of our work was that we have analyzed the microwave heating method for Uzen oil field, which was the first project in Kazakhstan.

Reference List

Abernethy, E.R. (1976). Production increase of heavy oils by electromagnetic heating. *Journal of Canadian Petroleum Technology*, *15*(03)

Al-Farsi, H., Pourafshary, P., & Al-Maamari, R. S. (2016). Application of Nanoparticles to Improve the Performance of Microwave Assisted Gravity Drainage (MWAGD) as a Thermal Oil Recovery Method. *SPE EOR Conference at Oil and Gas West Asia*. doi:10.2118/179764-ms

Alomair, O. A., Alarouj, M. A., Althenayyan, A. A., Al Saleh, A. H., Almohammad, H., Altahoo, Y., Alshammari, Y. (2012). Improving Heavy Oil Recovery by Unconventional Thermal Methods. *SPE Kuwait International Petroleum Conference and Exhibition.* doi:10.2118/163311-ms

Ali, S.M. (1974). Current status of steam injection as a heavy oil recovery method. *Journal of Canadian Petroleum Technology*, *13*(01).

Alvarez, J. and Han, S. (2013). Current overview of cyclic steam injection process. *Journal of Petroleum Science Research*, *2*(3)

Bientinesi, M., Petarca, L., Cerutti, A., Bandinelli, M., De Simoni, M., Manotti, M., & Maddinelli, G. (2013). A radiofrequency/microwave heating method for thermal heavy oil recovery based on a novel tight-shell conceptual design. *Journal of Petroleum Science and Engineering, 107, 18–30*. doi:10.1016/j.petrol.2013.02.014

Bahadori, A. (2014). Pollution control in oil, gas and chemical plants. *Springer International Publishing.*

Butler, R.M. (1994). Steam-assisted gravity drainage: concept, development, performance and future. *Journal of Canadian Petroleum Technology*, *33*(02), pp.44-50.

Demiral, B., Akin, S., Acar, C., & Hascakir, B. (2008). Microwave Assisted Gravity Drainage of Heavy Oils. *Proceedings of International Petroleum Technology Conference.* doi:10.2523/iptc-12536-ms

Greff, J., & Babadagli, T. (2013). Use of nano-metal particles as catalyst under electromagnetic heating for in-situ heavy oil recovery. *Journal of Petroleum Science and Engineering, 112, 258–265.* doi:10.1016/j.petrol.2013.11.012

Gu, H., Cheng, L., Huang, S., Li, B., Shen, F., Fang, W., & Hu, C. (2015). Steam injection for heavy oil recovery: Modeling of wellbore heat efficiency and analysis of steam injection performance. *Energy Conversion and Management, 97, 166–177.* doi:10.1016/j.enconman.2015.03.057

Guo, K., Li, H. and Yu, Z. (2016). In-situ heavy and extra-heavy oil recovery: A review. *Fuel*, *185*, *pp.886-902.*

Hamedi Shokrlu, Y., & Babadagli, T. (2010). Effects of Nano-Sized Metals on Viscosity Reduction of Heavy Oil/Bitumen During Thermal Applications. *Canadian Unconventional Resources and International Petroleum Conference.* doi:10.2118/137540-ms

Hasanvand, M.Z. and Golparvar, A. (2014). A critical review of improved oil recovery by electromagnetic heating. *Petroleum science and technology*, *32*(6), pp.631-637.

Hascakir, B., Acar, C. and Akin, S. (2009). Microwave-assisted heavy oil production: an experimental approach. *Energy & Fuels*, *23*(12), pp.6033-6039.

Kong, J.A. (1975). Theory of electromagnetic waves. *New York*.

Chertenkov, M.V., Loparev, D.S., Buslaev, G.V., Yusifov, A.A. and Klyavlin, A.V. (2014). Improvement of drilling technology for the Yarega heavy oil field development by SAGD method with counter producing and injecting wells. *In SPE Russian Oil and Gas Exploration & Production Technical Conference and Exhibition*. OnePetro.

Laherrère, J., Hall, C.A. and Bentley, R. (2022). How much oil remains for the world to produce? Comparing assessment methods, and separating fact from fiction. *Current Research in Environmental Sustainability*, *4*, p.100174.

Joseferd, R. (2015). Importance Of Porosity-Permeability Relationship In Sandstones: Petrophysical Properties. *IRC.*

Maes, J., Muggeridge, A. H., Jackson, M. D., Quintard, M., & Lapene, A. (2017). Scaling analysis of the In-Situ Upgrading of heavy oil and oil shale. *Fuel, 195, 299–313.* doi:10.1016/j.fuel.2017.01.072

Manrique, E. J., Thomas, C. P., Ravikiran, R., Izadi Kamouei, M., Lantz, M., Romero, J. L., & Alvarado, V. (2010). EOR: Current Status and Opportunities. *SPE Improved Oil Recovery Symposium.* doi:10.2118/130113-ms

Mokheimer, E. M. A., Hamdy, M., Abubakar, Z., Shakeel, M. R., Habib, M. A., & Mahmoud, M. (2018). A Comprehensive Review of Thermal Enhanced Oil Recovery: Techniques Evaluation. *Journal of Energy Resources Technology.* doi:10.1115/1.4041096

Mukhametshina, A., & Martynova, E. (2013). Electromagnetic Heating of Heavy Oil and Bitumen: A Review of Experimental Studies and Field Applications. *Journal of Petroleum Engineering, 2013, 1–7.* doi:10.1155/2013/476519

Mutyala, S., Fairbridge, C., Paré, J.J., Bélanger, J.M., Ng, S. and Hawkins, R. (2010). Microwave applications to oil sands and petroleum: A review. *Fuel Processing Technology*, *91(2), pp.127-135.*

Nassan, T.H. and Freiberg, S.N., 2018. Simulation of 1-D heat distribution in heavy oil reservoirs during steam injection process. *In Institute of Drilling and Fluid Mining Engineering. Freiberg University of Technology (TUBAF).*

Othman, H. A., Soliman, M. Y., & Settari, A. (2017). Techniques to Improve the use of Microwave to Produce Heavy Oil Reservoirs: Numerical Study. *SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition.* doi:10.2118/188118-ms

Ovalles, C., Fonseca, A., Lara, A., Alvarado, V., Urrecheaga, K., Ranson, A., & Mendoza, H. (2002). Opportunities of Downhole Dielectric Heating in Venezuela: Three Case Studies Involving Medium, Heavy and Extra-Heavy Crude Oil Reservoirs. *SPE International Thermal Operations and Heavy Oil Symposium and International Horizontal Well Technology Conference.* doi:10.2118/78980-ms

Owens, W.D. and Suter, V.E. (1965). Steam simulation for secondary recovery. *Journal of Canadian Petroleum Technology*, *4(04), pp.227-235.*

Peraser, V., Patil, S. L., Khataniar, S., Dandekar, A. Y., & Sonwalkar, V. S. (2012). Evaluation of Electromagnetic Heating for Heavy Oil Recovery From Alaskan Reservoirs. *SPE Western Regional Meeting.* doi:10.2118/154123-ms

PetroWiki. (2016). Heavy Oil.

Pizarro, J. O. S., & Trevisan, O. V. (1990). Electrical Heating of Oil Reservoirs: Numerical Simulation and Field Test Results. *Journal of Petroleum Technology, 42(10), 1320–1326.* doi:10.2118/19685-pa

Sahni, A., Kumar, M., & Knapp, R. B. (2000). Electromagnetic Heating Methods for Heavy Oil Reservoirs. *SPE/AAPG Western Regional Meeting.* doi:10.2118/62550-ms

Shafiai, S. H., & Gohari, A. (2020). Conventional and electrical EOR review: the development trend of ultrasonic application in EOR. *Journal of Petroleum Exploration and Production Technology.* doi:10.1007/s13202-020-00929-x

Sivakumar, P., Krishna, S., S., H., & Vij, R. K. (2020). Electromagnetic heating, an eco-friendly method to enhance heavy oil production: A review of recent advancements. *Environmental Technology & Innovation, 101100.* doi:10.1016/j.eti.2020.101100

Soliman, M. Y. (1997). Approximate solutions for flow of oil heated using microwaves. *Journal of Petroleum Science and Engineering, 18(1-2), 93–100.* doi:10.1016/s0920-4105(97)00007-7

Sun, N., Jiang, H., Wang, Y., & Qi, A. (2018). A Comparative Research of Microwave, Conventional-Heating, and Microwave/Chemical Demulsification of Tahe Heavy-Oil-in-Water Emulsion. *SPE Production & Operations, 33(02), 371–381.* doi:10.2118/187951-pa

Wang, Z. and Gao, D. (2019). A simulation study on the high-frequency electromagnetic heating heavy oil reservoir and analysis of influencing factors. *Arabian Journal for Science and Engineering, 44(12), pp.10547-10559.*

Wacker, B., Karmeileopardus, D., Trautmann, B., Helget, A. and Torlak, M. (2011). Electromagnetic Heating for In-situ Production of heavy oil and bitumen Reservoirs. In *Canadian Unconventional Resources Conference*. OnePetro.

Weinstein, L.A. (1988). Electromagnetic waves. *Radio i svyaz', Moscow*.

Zhang, Y., Adam, M., Hart, A., Wood, J., Rigby, S. P., & Robinson, J. P. (2018). Impact of Oil Composition on Microwave Heating Behavior of Heavy Oils. *Energy & Fuels, 32(2), 1592–1599.* doi:10.1021/acs.energyfuels.7b03675

Zhang, J., & Chen, Z. (2018). Formation Damage by Thermal Methods Applied to Heavy Oil Reservoirs. *Formation Damage During Improved Oil Recovery, 361–384*. doi:10.1016/b978-0-12-813782-6.00009-9

Zhou, Y., Li, F., Zhou, Z., & Ma, Y. (2012). Thermal Hydraulic Analysis Using GIS on Application of HTR to Thermal Recovery of Heavy Oil Reservoirs. *Science and Technology of Nuclear Installations, 2012, 1–15*. doi:10.1155/2012/676529

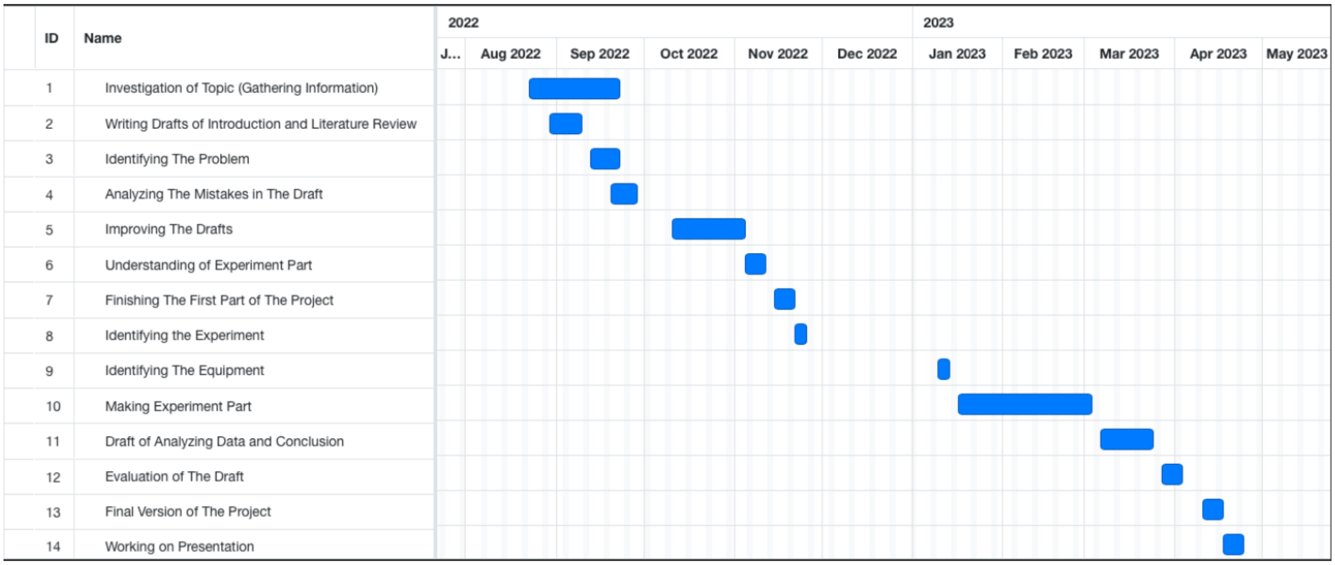
Zhou, S. and Sun, F. (2016). Sand production management for unconsolidated sandstone reservoirs. *John Wiley & Sons.*

Thomas, S. (2008). Enhanced oil recovery-an overview. *Oil & Gas Science and Technology-Revue de l'IFP*, *63(1), pp.9-19.* doi.org/10.2516/ogst:2007060

Xu, Z.X., Li, S.Y., Li, B.F., Chen, D.Q., Liu, Z.Y. and Li, Z.M. (2020). A review of development methods and EOR technologies for carbonate reservoirs. *Petroleum Science*, *17, pp.990-1013.* doi.org/10.1007/s12182-020-00467-5

Appendix

Table 6. Gantt chart



ID	Name
1	Investigation of Topic (Gathering Information)
2	Writing Drafts of Introduction and Literature Review
3	Identifying The Problem
4	Analyzing The Mistakes in The Draft
5	Improving The Drafts
6	Understanding of Experiment Part
7	Finishing The First Part of The Project
8	Identifying the Experiment
9	Identifying The Equipment
10	Making Experiment Part
11	Draft of Analyzing Data and Conclusion
12	Evaluation of The Draft
13	Final Version of The Project
14	Working on Presentation