Scientific Contributions Oil & Gas, Vol. 48. No. 2, August: 1 - 9

SCIENTIFIC CONTRIBUTIONS OIL AND GAS
Testing Center for Oil and Gas
LEMIGAS

Journal Homepage:http://www.journal.lemigas.esdm.go.id
ISSN: 2089-3361, e-ISSN: 2541-0520

The Recovery Factor Analysis on Heavy Oil Under Electromagnetic Heating Treatment

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Manuscript received: March 27th, 2025; Revised: April 22th, 2025
Approved: May 12th, 2025; Available online: May 16th, 2025; Published: July 31th, 2025.

ABSTRACT - The use of electromagnetic heating mechanisms in heavy oil production operations is widely limited in Indonesia. In this context, there is a need for in-depth research regarding the effectiveness of the method. Therefore, this research aimed to discuss the efficacy of heating method through Recovery Factor (RF) analysis using imbibition with electromagnetic waves and the addition of nanopowder. The results showed that the speed of heating and RF imbibition using electromagnetic waves was higher than conventional imbibition. In addition, ferrous oxide nanopowder produced the highest heating speed and RF of 38.39% below the expected value. Further research could be conducted regarding changes in the wettability of rock due to electromagnetic heating and nanopowder required to answer the problem.

Keywords: electromagnetic, heavy oil, recovery factor, imbibition, nanopowder Ferro-oxide.

How to cite this article:

Gerry Sasanti Nirmala, Diyah Rosiani, Dedi Irawan, and Ismail Halim, 2025, The Recovery Factor Analysis on Heavy Oil Under Electromagnetic Heating Treatment, Scientific Contributions Oil and Gas, 48 (2) pp. 1-9. DOI org/10.29017/scog.v48i2.1737.

INTRODUCTION

Heavy oil is reported to possess a density of 20 American Petroleum Institute (API) or less. In this context, the production principle reduces the viscosity of crude oil or dissolves asphaltenes and other organic solids. Furthermore, Steam Flood is used for the thermal recovery of heavy oil by injecting superheated steam into a reservoir (Alomair et al. 2016; Permatasari et al. 2020; Tao 2022; Pratama 2022). This method is successfully implemented in Duri Field, Indonesia. Duri is the world's most extensive steam flood operation regarding oil production and steam injection (Abdurrahman 2017; Ludovika et al. 2020; Winderasta et al. 2022). Even though this shallow field is very effective in heavy oil production, steam injection has limitations such as heat loss in a deep formation, covering only thin pay zones, heterogeneity, and environmental situations (Abernethy 1976; Sivakumar et al. 2020, Wu et al. 2021).

Based on the description, heating method using electromagnetic waves is used to overcome the limitedness of steam injection (Afdhol et al. 2020). The reservoir works are pounded based on energy changing from waves into thermal energy. The increase in temperature reduces the viscosity of the fluid since the method is suitable for enhancing the recovery of heavy oil (Santoso et al. 2016; Sun et al. 2016; Jamaloei 2022). The reservoir heterogeneity, such as porosity, permeability, viscosity, and fluid density, become barriers to electromagnetic waves. However, this diversity is a driving factor in creating effective heating. Even though oil is a non-magnetic dielectric material (Kovaleva et al. 2010), brine with salinity content delivers more conductivity for the reservoir fluid to continue heating process.

An imbibition test was carried out to analyze the cumulative oil production and test the effectiveness of electromagnetic heating in oil recovery. Furthermore, a cylindrical core plug is immersed in the wetting phase, allowing spontaneous imbibition to occur. The imbibition rate is proportional to capillary pressure (Pc), which depends on saturation (Sugihardjo 2013). The increase in solution saturation occurs gradually from the front to all parts of the core plug. Subsequently, the imbibition capillary pressure decreases as the saturation of the wetting phase increases (Li et al. 2009; Cai et al. 2022)

METHODOLOGY

This research analyzed recovery factor (RF) due to electromagnetic heating through an imbibition test. Previously, RF analysis was carried out through conventional imbibition tests (Nirmala et al. 2022). A comparison was conducted between traditional imbibition using an oven heater and electromagnetic heating. The experimental results showed a high-speed heating difference between electromagnet process and the oven heater. However, the Ammot imbibition cell and equipment design were unsuitable, causing an oil spill during the fast heating process.

Design of electromagnetic imbibition

In this experiment, a better design was carried out regarding the test equipment. Figure 1 is the prior imbibition test design, consisting of the magnetron (microwave generator), and all the equipment arranged vertically. The magnetron is placed in the lowest position, followed by a circular waveguide and ammot imbibition cell. Meanwhile, a waveguide is a device that directs waves to focus on the object to be heated.

Figure 2 shows the test design for this experiment. In contrast to previous results, the magnetron was placed in a microwave oven, model P90D23L-ZS. However, the type of magnetron used was the same, which produced waves with a frequency of 2.45 Hz. The lid of the microwave oven was removed and a hole was made, allowing the imbibition cell rod to pass through the oven. The Ammot imbibition cell was modified by bending the tip, where a container could be placed to accommodate the crude oil obtained during heating process.

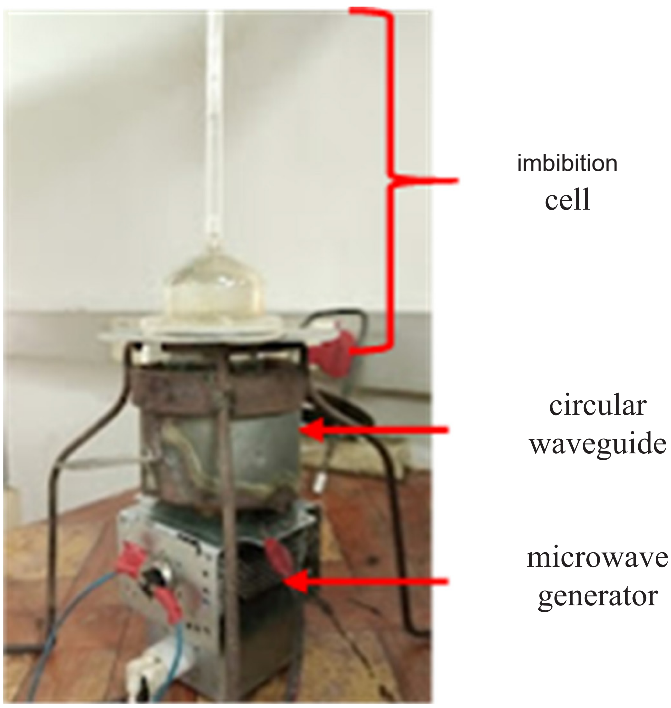

Figure 1. The prior imbibition test design (Nirmala et al. 2022).

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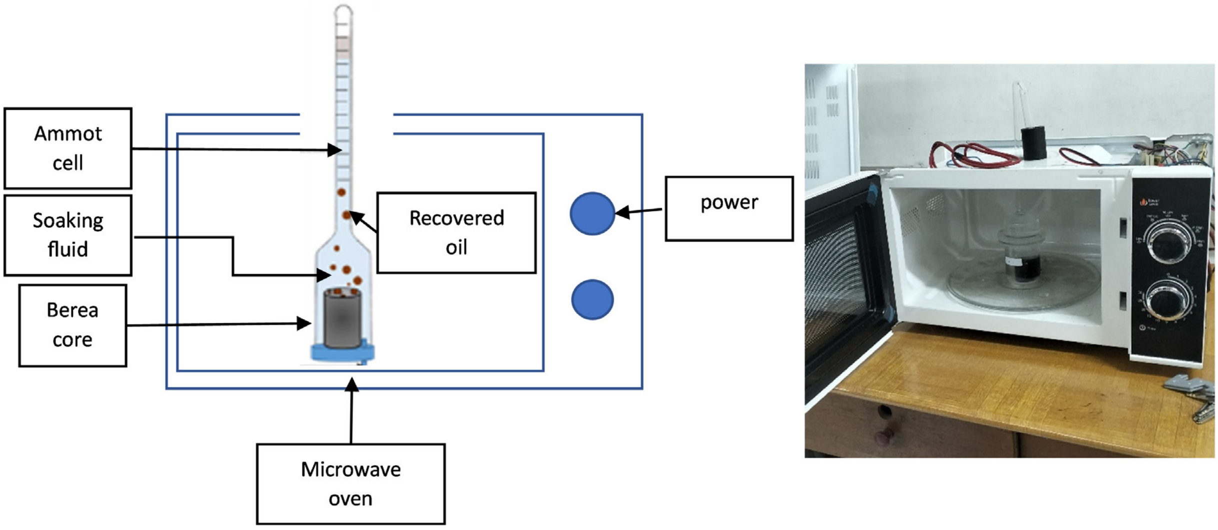


Figure 2. Schematic design for electromagnetic imbibition.

Sample on electromagnetic imbibition

Referring to previous research, nanopowder was added as an additive in the soaking solution. This was proven effective in increasing heating speed with electromagnetic heating (Indriani et al. 2018; Nirmala et al. 2022). A total of four nanopowders were added to the solution, namely nano-silica, nano-aluminum, nano-ferro, and nano-copper. This nanopowder was selected based on a previous experiment (Nirmala et al. 2022). Nanofluid was obtained by mixing brine with 0,2 % wt of nanopowder.

Based on the result, this research used 15 Berea core plug samples saturated with crude oil. The sample was placed in a modified Ammot imbibition cell on a microwave oven with varying power settings between 657 Watts, 792 Watts, and 900 Watts. Table 1 shows the core properties of the samples. Pore volume (PV) oil, liquid, and gas porosity were determined by the following formula with a crude oil density of 0,95 gr/ml and viscosity of 0,0176 cp.

$$PV_{oil} = \frac{Wett\ mass - Dry\ mass}{\rho} \quad (1)$$

$$\emptyset_{liq} = \frac{PV_{oil}}{V_{bulk}} x100\% \quad (2)$$

$$\emptyset_{gas} = (1 - \frac{V_{grain}}{V_{bulk}}) x100\% \quad (3)$$

The core has approximately PV oil of 3,16 – 3,64 ml, liquid porosity of 18,78 – 21,94%, and gas porosity of 21,65 – 23,89 %. The Darcy equation determines absolute permeability using the following formula.

$$k = \frac{Q\mu L}{A\Delta P} \quad (4)$$

Table 1. Core properties.

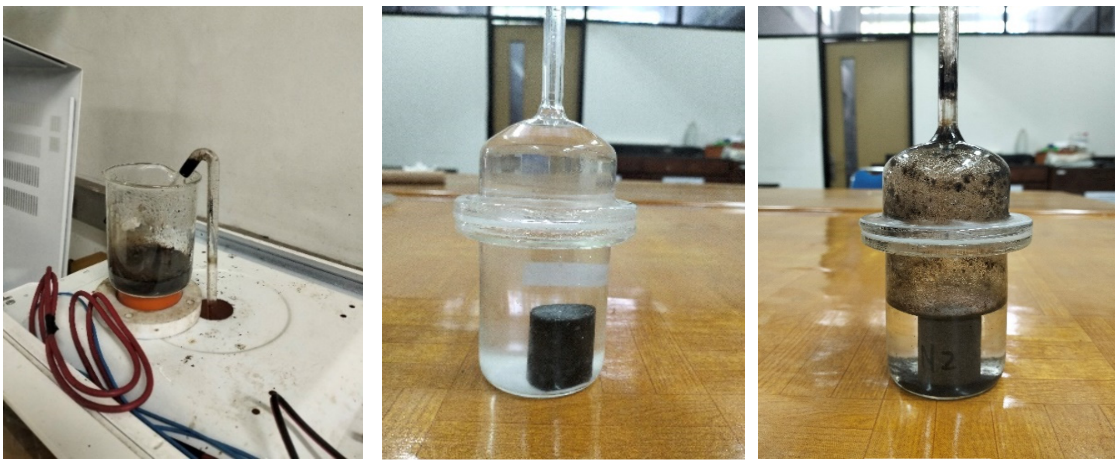
Core	Solution	V_{bulk} (cc)	V_{grain} (cc)	Dry Mass (gr)	Wett mass (gr)	PV_{Oil} (cc)	$\emptyset_{liq}$ (%)	$\emptyset_{gas}$ Corrected (%)	K (mD)
N1	brine	17,73	13,72	35,12	38,36	3,41	19,26	22,60	449
N2	brine	17,52	13,65	34,78	38,24	3,64	20,77	22,13	470
N3	brine	17,58	13,68	34,96	38,14	3,34	19,02	22,14	509
N4	Nano-aluminum	17,52	13,57	34,56	37,76	3,36	19,19	22,57	503

Table 1. Core properties (continued).

Core	Solution	V_{bulk} (cc)	V_{grain} (cc)	Dry Mass (gr)	Wett mass (gr)	PV_{Oil} (cc)	$Ø_{liq}$ (%)	$Ø_{gas}$ Corrected (%)	K (mD)
N5	Nano-aluminum	17,47	13,49	34,71	38,01	3,47	19,86	22,79	473
N6	Nano-aluminum	16,04	12,32	31,99	35,33	3,52	21,94	23,18	469
N7	Nano-ferro	16,86	12,83	34,08	37,09	3,17	18,78	23,90	477
N8	Nano-ferro	16,81	12,83	33,75	36,86	3,28	19,49	23,67	500
N9	Nano-ferro	16,66	12,80	33,70	36,72	3,18	19,08	23,18	496
N10	Nano-copper	15,74	12,06	31,72	34,82	3,26	20,74	23,36	468
N11	Nano-copper	16,66	12,83	33,64	36,65	3,17	19,00	22,96	496
N12	Nano-copper	16,25	12,47	32,83	35,96	3,30	20,29	23,23	483
N16	Nano-silica	16,40	12,69	32,63	35,63	3,16	19,26	22,63	488
N17	Nano-silica	16,09	12,69	32,56	35,63	3,23	20,08	21,16	479
N18	Nano-silica	16,20	12,69	32,55	35,65	3,26	20,13	21,65	482

RESULT AND DISCUSSION

Figure 3(a) shows electromagnetic heating imbibition process. In previous experiments, heating speed was very high since the spontaneous imbibition of crude oil occurred quickly. The new design allowed the containment of oil for improved analysis. Figure 3(b) is the core before the imbibition and was saturated with crude oil before immersing in a solution. Meanwhile, the core in Figure 3(c) was originally saturated with oil after the imbibition. This could be proven by the appearance of the number (number 12) previously written on the core plug wall.



(a) (b) (c)

Figure 3. (a) The process of electromagnetic imbibition, (b) the core plug before electromagnetic imbibition, (c) the core plug after electromagnetic imbibition.

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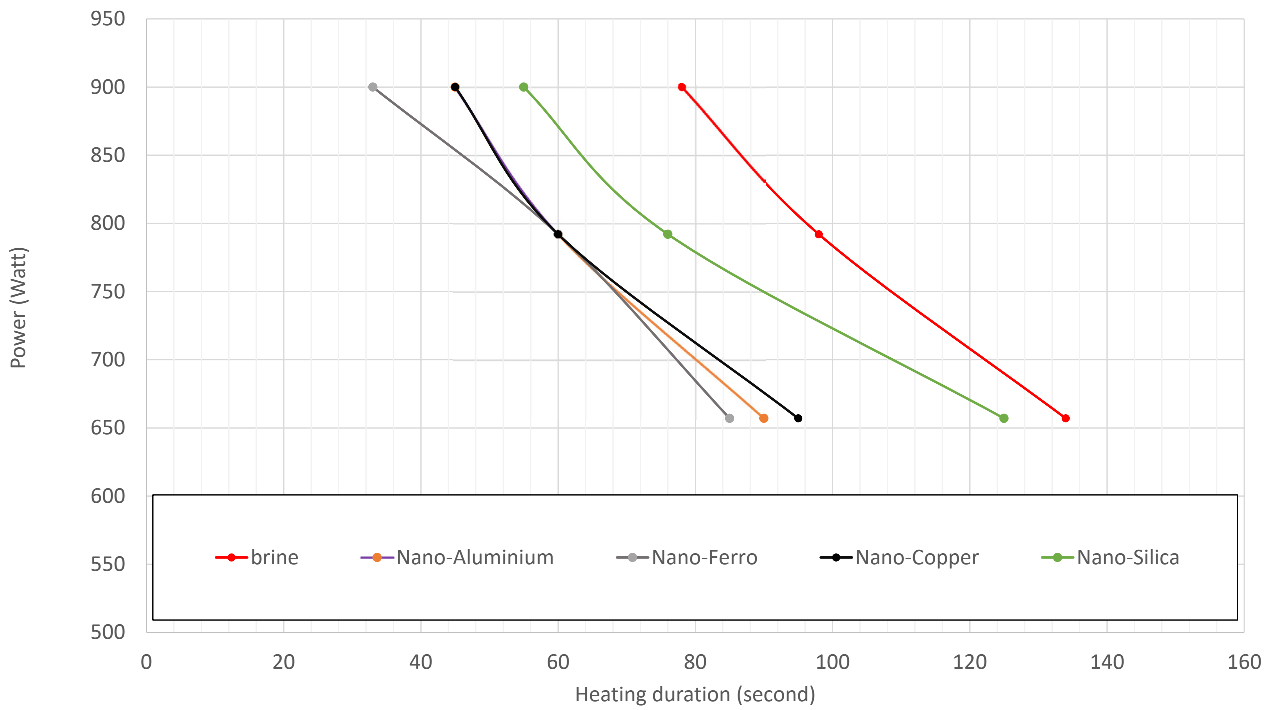

Figure 4. Heating duration during electromagnetic imbibition.

Recovery factor analysis during electromagnetic imbibition

In electromagnet imbibition, spontaneous imbibition occurs in seconds. The increase in electricity power has a direct effect on heating speed. As shown in Figure 4, a high power (900 Watts) increases heating speed by 41.8% and 20.4% when compared to medium power (657 Watts) and medium-high power (792 Watts), respectively. This was consistent with previous research where the power used was directly proportional to heating process and temperature achieved (Indriani et al., 2018; Nirmala et al., 2019). In this experiment, the temperature was not tested due to the magnetron's high frequency which disrupted the sensor system.

The use of nanopowder increased heating speed. In the solution with nanopowder, heating speed was increased than in brine-containing solutions. The increase in heating speed affected the oil recovery percentage. Table 2 and Figure 5 present the oil recovery and the high speed of electromagnetic imbibition. The implementation of high-speed in oil wells reduces production time and costs. RF percentage is still limited. The core was clean after the imbibition process but the best RF value was 38.39 % for nano-ferro solution. Several oil was left in the core after comparing with the oil PV calculated in Table 2. This is far from RF expected in laboratory-scale tests, where the results must be close to 100% before testing the method in the field.

Table 2
Summary of oil recovery during electromagnetic imbibition

Solution	Heating Time (second)			Cumulative Oil (ml)			Recovery Factor (%)		
	Medium (657 W)	Medium-High (792 W)	High (900 W)	Medium (657 W)	Medium-High (792 W)	High (900 W)	Medium (657 W)	Medium-High (792 W)	High (900 W)
Brine	134	98	78	0,3	0,45	0,5	8,92	12,97	14,20
Nano-Aluminium	90	60	45	0,9	1,1	1,1	26,36	30,23	32,91
Nano-Ferro	85	60	33	0,9	1,2	1,22	28,42	36,63	38,39
Nano-Copper	95	60	45	0,65	0,7	0,7	19,92	22,12	21,23
Nano-Silica	125	76	55	0,95	1,1	1,1	30,08	34,04	33,74

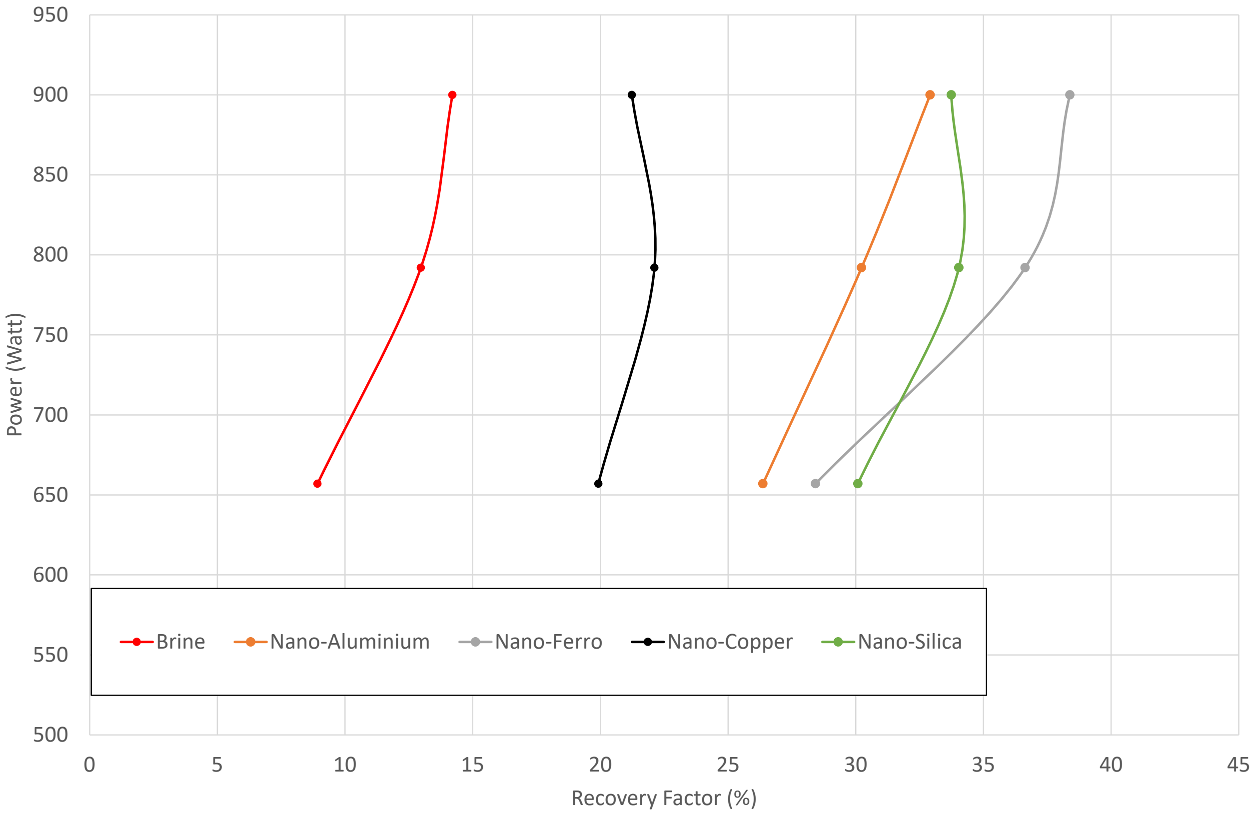

Figure 5. RF due to electromagnetic imbibition.

Wave is inversely proportional to the frequency andheat penetration of the method is very short. This has become the basis of suspicion of the remaining oil in the core. Electromagnetic waves travel at the speed of light (c = 3,108 m/s) in a vacuum. The maximum wavelength is 12.24 cm in a vacuum with the magnetron frequency of 2.45 GHz. This wavelength is representative of the penetration of electromagnetic heating in the reservoir. Heat penetration achieved in a vacuum is 12.24 cm and can be reduced due to the heterogeneity of the reservoir. This causes a reduction in heat penetration decreasing the expected viscosity and RF gain.

The effect of nano-Ferro on electromagnetic heating has been widely investigated and proven to be accurate. Hu et al. (2018) reported that EM heating did not affect Berea sandstone and Indiana carbonate due to the transparency of quartz and calcite to EM waves. The result showed that the method was more susceptible in shale reservoirs. Further testing could be carried out regarding the effect of nanopowder in wettability alteration. The lack of effectiveness of EM heating on the Berea core plug and the influence of nano Ferro on the wettability properties might answer the low oil recovery in RF tests.

The comparison between conventional and electromagnetic imbibition

A comparison between conventional and electromagnet imbibition was made using data from previous experiments. In conventional imbibition, crude oil took 23 hours in brine solution for the first spontaneous release. The use of nanopowder significantly increases heating speed and only 1 hour was needed for the crude oil to be spontaneously released. The total time needed for the conventional imbibition process was 96 hours and the test was stopped after the oil release phase. This limited the solution's ability to statically stimulate the recovered oil.

Concerning the similarity between the tests, nano-ferro produced the most significant oil recovery. Meanwhile, the least recovery was in the brine solution without nanopowder. This was consistent with electromagnetic imbibition, where RF calculations showed similar results. The use of nanopowder in the solution increased RF, which included nano copper, nano aluminum, nano silica, and nano ferro. The use of aluminum and nano-silica produced similar RF in electromagnetic imbibition.

Table 3. The Comparison between conventional and electromagnetic imbibition.

Solution	Conventional Imbibition				Electromagnetic Imbibition		
	Duration of first spontaneous release (hour)	Total heating duration (hour)	Vol of oil recovery (ml)	**Recovery Factor (%)**	Total heating duration (second)	Vol of oil recovery (ml)	**Recovery Factor (%)**
Brine	23	96	0,3	8,83	78	0,45	14,2
Nano alumunium	1	96	0,8	20,88	45	1,1	32,91
Nano ferro	1	96	1,03	30,79	33	1,2	38,39
Nano copper	1	96	0,48	13,19	45	0,7	21,23
Nano silica	1	96	0,6	18,79	55	1,1	33,74

Since heat source is an electromagnet, the magnetic and conductivity properties of nanopowder are essential factors in the effectiveness. Magnetic properties are known as susceptibility, which is the ability of a material to transmit induction. Nano-ferro used in the imbibition test is ferro oxide (Fe_2O_3 in the form of hematite) proven to be the best in viscosity reduction (Yang et al. 2015), as presented in Table 4.

Table 4. Nanopowder properties (Palacky 1987).

Properties	Nanopowder			
	ferro oxide	**copper oxide**	**aluminum oxide**	**silicon dioxide**
Chemical formula	Fe_2O_3	CuO	Al_2O_3	S_iO_2
Molar mass (g/mol)	159,687	79,545	101,96	60,08
Color	brownish red	black	white	yellowish white
Density (g/cm3)	5,242	6,315	3,987	2,196
Magnetic susceptibility (χ) (cm^3/mol)	$+3586,0\cdot10^{-6}$	$+238,9\cdot10^{-6}$	$-37,0\times10^{-6}$	$-29,6\cdot10^{-6}$
Flashpoint(°C)	76,5	72	71,2	72
Pourpoint(°C)	40,8	39,5	40,9	40,6

Ferro oxide has a magnetic susceptibility of $+3586.10^{-6}$ cm^3/mol and is a paramagnetic material with weak attraction properties. The nature of this attraction is influenced by electrical induction, which is the use of electrical power. Therefore, the power of a magnet is directly proportional to the tensile strength. This causes heating speed and RF of nano-ferro solution to be the highest.

CONCLUSION

In conclusion, the observation of electromagnetic heating feasibility was conducted under an imbibition test. An imbibition test was carried out using an electromagnet as heat source to adapt the Ammot cell design for microwave ovens. Electromagnetic heating provided more heating due to high frequency and the use of nanopowder as catalysts. Meanwhile, RF increased with electrical power, and nanopowder was added to the imbibition solution. Electromagnetic heating could produce high RF but experimental results showed a maximum oil recovery of 38.39% in nano-ferro solution. This was 1.7x higher than RF in brine and proof of nano-ferro in the effectiveness of electromagnetic heating. Further analysis could be carried out on heating penetration and the wettability alteration of samples under electromagnetic heating.

ACKNOWLEDGEMENT

The authors are grateful to the Enhanced Oil Recovery Laboratory, Bandung Institute of Technology, for assisting and supporting this research.

GLOSSARY OF TERMS

Symbol	Definition	Unit
A	Area, cm^2	
c	Speed of light, 3,108 m/s	
k	Permeability, mD	
L	Length, cm	
ΔP_s	The pressure difference, psi	
Q	Production rate, bfpd	
V_{bulk}	Bulk volume, cc	
V_{grain}	Grain volume, cc	
$\emptyset_{liq}$	Liquid porosity, %	
$\emptyset_{gas}$	Gas porosity, %	
χ	Magnetic susceptibility, cm^3/mol	
μ	Viscosity, cp	
API	American Petroleum Institute	
RF	Recovery factor	
PV	Pore Volume	

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