CAPÍTULO 7

EXPERIMENTAL EVALUATION OF THE TEMPERATURE INCREASE DISTRIBUTION IN AN ELECTROMAGNETIC HEATING SYSTEM (EHS) INTEGRATED WITH IRON OXIDE NANOPARTICLE INJECTION FOR HEAVY CRUDE OILS

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ABSTRACT: This study investigates the use of radiofrequency (RF) heating combined with iron oxide nanoparticles to enhance heavy crude oil viscosity reduction. Traditional methods of applying heat to heavy oil reservoirs have limitations, prompting the exploration of more efficient alternatives like electromagnetic heating (EMH). The research focuses on assessing the temperature distribution in an EMH system with nanoparticle injection. A literature review identified key variables affecting the system, including temperature profile, applied power, water saturation, and nanoparticle presence. Experiments were conducted by irradiating RF waves onto reservoir-representative samples of sand, crude oil, water (with varying saturation), and nanoparticles in a reactor. A "one-variable-at-a-time" experimental approach allowed for the collection of data to develop a model of the system's thermal behavior with nanoparticle application. Temperature profiles were measured using thermocouples, and applied power was monitored. The data was used to create a heat transfer model simulating energy flow in the rock-fluid system under electromagnetic radiation, considering factors such as water saturation, crude oil properties, and nanoparticle concentration. A numerical simulator was integrated to estimate heat transfer based on the electromagnetic absorption coefficient, enabling process simulation at different scales. Results showed that iron oxide nanoparticles enhance EMH efficiency by improving radiation absorption, which reduces crude oil viscosity. The developed model effectively predicts the system's behavior under various conditions, providing a valuable tool for optimizing heating processes in the petroleum industry.

KEYWORDS: Radiofrequency heating, Heavy crude reservoir, Well stimulation, Microwaves, Nanoparticles, Absorption.

INTRODUCTION

In recent years, the potential of "heavy oil" reservoirs to increase reserves has gained attention due to high hydrocarbon demand and the depletion of conventional crude oil reserves. Extracting heavy hydrocarbons presents both an opportunity and a technological challenge due to their high viscosity, which reduces mobility. Advanced recovery techniques, particularly those focused on raising reservoir temperatures, are being researched to address these challenges (Bera & Babadagli, 2015).

Electromagnetic heating (EMH) utilizes electromagnetic waves to heat a reservoir, reducing oil viscosity. The setup includes an emitting antenna that irradiates dielectric materials in the reservoir, which absorb the waves and convert them into heat, with the oil receiving the energy (Chhetri & Islam, 2008).

While EMH shows promise, the technology has not yet reached the required economic feasibility for field-scale application. To move forward, it's crucial to characterize heat transfer through laboratory tests and numerical modeling.

This study aims to evaluate heat transfer in an EMH system integrated with iron oxide nanoparticle injection for heavy crude oil. Key indicators like temperature, time, distance, irradiated power, and applied power will be analyzed. Previous research has shown that combining EMH with nanoparticles can improve heating and crude oil properties.

FIELD APPLICATION BACKGROUND

Two field experiments at the Asphalt Ridge deposit near Vernal, UT, in 1981 heated oil sands in situ using gravitational drainage and autogenous push techniques. Approximately 25 m^3 of bituminous sands were heated in each experiment, with RF power input ranging from 40 to 75 kW. "Temperatures reached about 120°C in the first experiment and 200°C in the second" (Sresty et al., 1986). In 1986, commercial EM heating in Wildmere Field, Alberta, increased production by 2.23 tons per day from March to November, with one well's production rising from 1.59 to 4.77 tons per day, peaking at 9.54 tons per day. "Production increased by 2.23 tons per day from March to November" (Spencer, 1987). In 1987, a pilot test in Brazil's Rio Panon Field boosted production from 1.2 to 10 barrels per day after applying 30 kW of power for 70 days. "Production jumped from approximately 1.2 to 10 barrels per day after applying 30 kW of average power" (Pizarro & Trevisan SPE, 1990). In North Midway Field, Minnesota, a 25 kW generator raised temperatures from 90°F to 220°F at 650 feet depth after 40 hours, demonstrating RF heating's effectiveness. "After 40 hours of RF heating, the average temperature increased from 90°F to 220°F" (Kasevich et al., 1994). Finally, a 2013 electric heating study in the Congo reduced heavy oil viscosity, improving production rates and recovery. "This resulted in an increase in production rate and recovery factor" (Bottazzi et al., 2013).

EXPERIMENTAL SETUP BACKGROUND

In various laboratory and field studies, electromagnetic heating has been evaluated for its effectiveness in enhancing oil recovery. For example, a 55-gallon drum containing diatomite was heated with a 1 kW source at 50.55 MHz, reaching 150°C. A sample of heavy oil from Bakersfield was heated with a 200 W source at 144 MHz, reaching 130°C after 49 minutes of heating (Kasevich et al., 1994). In another laboratory experiment, a scale model of a heavy oil reservoir was used to study the combination of electromagnetic heating and gas injection with horizontal wells. The model, a 20 cm x 20 cm x 10 cm methacrylate container filled with sand, varied parameters like frequency, power, and salinity to assess their effects on temperature and production (Y. Hu et al., 1999).

In Venezuela, 650 W microwaves were used to heat cores saturated with different crude oils (24° API, 11° API, and 7.7° API). Temperature data taken at short intervals helped validate mathematical models predicting production for hypothetical reservoirs (Ovalles et al., 2002). A study in Turkey examined microwave heating's effect on oil recovery using a graphite core-holder filled with crushed limestone. It was found that high salinity water and saturation improved recovery, and continuous microwave heating yielded better results than cyclic heating (Demiral et al., 2008).

Furthermore, laboratory tests comparing electric resistance electrodes, electromagnetic inductors, and microwaves found microwave heating to be the most cost-effective, increasing oil recovery by up to 30% (Alomair et al., 2012). An experiment using a dipole antenna heated 2 tons of oil-impregnated sand to 200°C using 2.45 GHz microwave radiation (Bientinesi et al., 2013). Finally, combining electromagnetic heating with solvent-assisted gravity drainage (SAGD) demonstrated improved recovery rates when solvents like n-hexane and n-octane were used, suggesting this hybrid method is more cost-effective than simultaneous heating and solvent injection (L. Hu et al., 2017).

These studies highlight the potential of electromagnetic heating methods to enhance oil recovery, offering promising results in both laboratory and field conditions. However, further research is needed to optimize these techniques for large-scale application.

USE OF NANOPARTICLES FOR ELECTROMAGNETIC HEATING

Metal oxide nanoparticles, such as iron, nickel, and copper, can absorb microwaves and increase temperature, enhancing crude oil extraction through electromagnetic heating (Ali et al., 2020). Studies have shown that adding 0.5% iron powder reduced viscosity by up to 88% in Turkey's Bati Raman field (Hascakir, 2008). Nanoparticles improve heat transfer and reduce viscosity, with concentration, type, and size affecting results (Shokrlu & Babadagli, 2010). Experiments with 2.45 GHz microwaves and nano-metal catalysts demonstrated significant viscosity reduction, with nickel being the most efficient (Greff & Babadagli, 2013). Nickel nanoparticles also accelerated oil recovery, achieving higher recovery with less energy (Bera & Babadagli, 2017). These findings suggest nanoparticles enhance electromagnetic heating efficiency in heavy oil recovery.

MATERIALS AND METHOD

The designed prototype consists of two systems: the wave generator and the reactor. This prototype allows the emission of microwaves to the sample for up to 72 continuous hours, with a maximum operating temperature of 400°C and a maximum operating pressure of 30 psi, at which pressure the relief valves are activated.

Wave Generator System

The wave generator system is crucial, as it radiates energy to the sample and allows the waves to travel to the reactor. In the experiments, the applied power is 5.5 kW, and the frequency is 2.45 GHz. The magnetron, powered by a 10 kW generator, includes controls, alarms, a protection isolator, and a tuner. Radiation is transmitted through waveguides that direct the microwaves to a 10-foot long applicator. Additionally, the system includes a radiation leakage meter and a calibrated power meter at 10 kW both at the generator input and the waveguide output. The control panel manages and monitors the magnetron, which requires water cooling. The isolator protects the magnetron from reflected power, and the impedance coupler match this power.

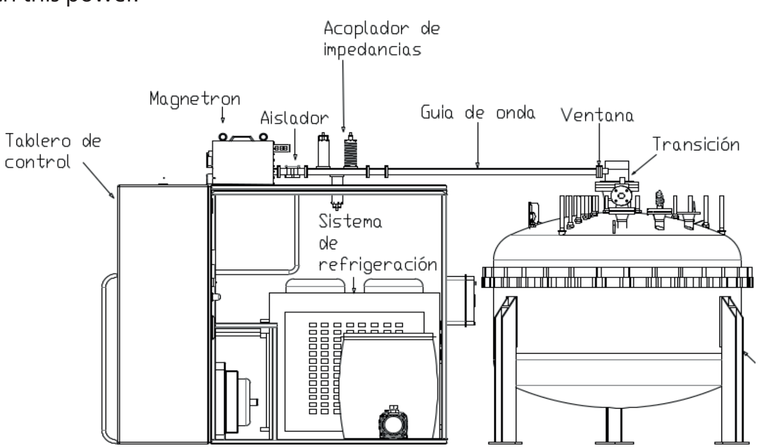

Figure 1- General diagram of the equipment

Source: produced by the author.

Rock-Fluid Container System

This system holds the sample for radiation application, where heating and potential chemical reactions occur. It consists of a cylindrical tank, 160 cm in diameter and 45 cm in height, containing a mixture of sand, crude oil, and water at a concentration representative of the reservoir. In the center, a 15 cm diameter cylindrical microwave applicator is installed. The reactor is a metallic container capable of withstanding 60 psi and includes various measurement devices, with thermocouples arranged radially at three lines to measure temperature at different strata.

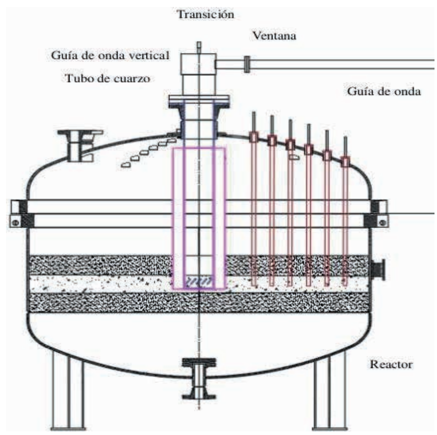

Figure 2- Diagram of the tank or reactor

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The system also includes a pressure gauge, a temperature gauge, a vent valve, a gas sample port, and safety features. It features a local temperature indicator located 5 cm from the container wall and at a depth of 15 cm.

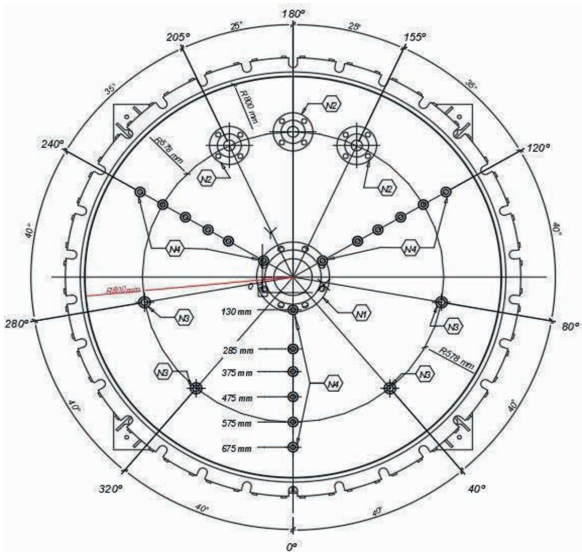

Figure 3 - Vertical view of the tank and arrangement of the thermocouples

Source: produced by the author.

Sample Preparation

The experimental materials include high-viscosity heavy crude oil (API gravity 11-12.5), Ottawa sand for the target stratum, and river sand for top, bottom, and base layers. The average porosity was 0.35. Freshwater or water with 500 ppm nanoparticles was used. Magnetic nanofluid, composed of graphene oxide (rGO) and iron oxide (Fe3O4), was provided by the LEAM lab. The heavy crude was dehydrated to 0.7% water content. Two fluids, freshwater and heavy crude, were used for saturation.

Proposed Saturation Models for the Study

The saturation model refers to the fraction of the porous volume of the sand occupied by fluids: water (with nanoparticle fractions in some cases), oil, and gas (nitrogen).

In this study, the sample preparation procedure and equipment operation will always be the same. To address the objectives, saturations will be varied, and nanoparticles will be implemented to assess their performance. Therefore, 9 tests are proposed.

Table 1 presents the properties such as the presence of nanofluid, the saturations of the layer, and the code for easier reference to each sample.

Sample code according to saturation	Sw (%)	So (%)	Sg (%)	Nanofluid present in 500 ppm
O30W301	0,3	0,3	0,4	NO
O30W302	0,3	0,3	0,4	NO
O30W303	0,3	0,3	0,4	NO
O30W60	0,6	0,3	0,1	NO
O30W60NP	0,6	0,3	0,1	SI
O30	0	0,3	0,7	NO
SECA	0	0	1	NO
W30	0,3	0	0,7	NO
W30NP	0,3	0	0,7	SI

Table - 1 Saturations of the stratum of interest and sample code

Source: produced by the author.

EXPERIMENTAL RESULTS

The heating behavior of dry sand, water-saturated sand (60%), and nanofluid-saturated sand (60% with 550 ppm nanoparticles) shows that water saturation helps achieve higher temperatures, as seen in Figure 4. However, when nanoparticles are added, the temperatures are not as high, but they stabilize over time.

In the comparison of heating behavior for crude oil-saturated sand, crude oil and water-saturated sand, and crude oil and nanofluid-saturated sand, Figure 5 demonstrates that sand saturated with only crude oil (sample O30) shows good heating performance, indicating that electromagnetic heating is effective in the absence of water. For the base case (sample O30W303), good heating occurs at the farthest thermocouples, but the temperature increase is less favorable near the antenna. When sand is 60% water-saturated, the temperature increase is not as favorable and does not surpass the O30W303 sample curve, except at later times and near the antenna. Nanoparticle implementation results in good temperature stabilization compared to the other tests. Although temperature increase is lower than in the other cases, the stability provided by nanoparticles allows for prolonged heating and reduced water evaporation.

Comparing heating behavior between water-saturated sand (sample W30) and crude oil-saturated sand (sample O30), Figure 6 shows that the O30 sample heats more smoothly, likely due to water vaporization. Temperatures near the antenna exceed 100°C for both samples, after which water vaporizes. Beyond this point, the

W30 curve exceeds the O30 curve, but at further distances, the O30 curve reaches higher temperatures, as the water vaporization does not occur. Thus, the presence of water vapor aids in elevating the system's temperature.

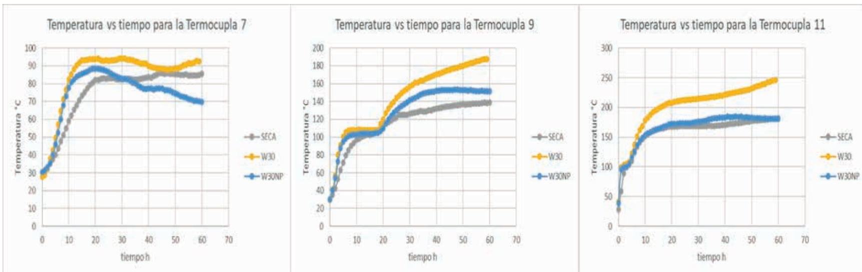

Figure - 4 Temperature over time for different stratum thermocouples for SECA, W30 and W30NP tests

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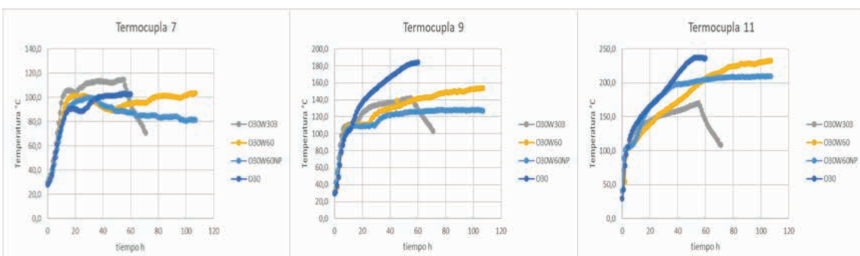

Figure - 5 Temperature over time for different stratum thermocouples for tests O30W303, O30W60, O30W60NP and O30

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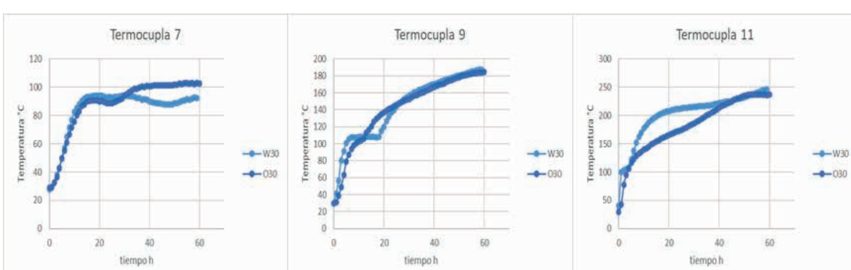

Figure - 6 Temperature over time for different stratum thermocouples for tests O30 and W30

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ANALYSIS AND DISCUSSION

In this section, the practical application of the proposed heat transfer model is described, focusing on how it can be integrated with commercial reservoir simulators, such as CMG, to model the thermal behavior of a reservoir subjected to electromagnetic heating. The importance of the developed model is highlighted as a tool for simulating heat and temperature distribution within a reservoir, thereby allowing for better estimation of production and recovery rates.

The model, based on applied power, fluid saturation, and the presence of nanoparticles, can predict how temperature increases affect crude oil production in a reservoir. Commercial simulators like CMG can accurately apply heat to different parts of the simulation grid. This makes the heat transfer model developed in this research a valuable tool for scaling laboratory experimental results to field conditions, enabling the simulation of electromagnetic heating processes under actual reservoir conditions.

A macro in Excel is proposed and used to apply the modified Abernethy model in reservoir simulators. The Abernethy equation is shown in (1).

$$P_{i+1}^{n} = P_i^n e^{-\alpha_i^n (dr_i)} \quad (1)$$

It communicates with simulators via keywords, specifying heat application to each cell. Users can input system conditions like nanoparticles, absorption values (α), and match parameters such as boiling temperature and heating strategy. The macro's functionality is validated through a conceptual simulation case for a heavy oil reservoir in the Llanos Orientales, using 60 kW power and α = 0.25.

Match of Temperatures with Experimental Data

To achieve the match, the TMPSET keyword is used to indicate to the simulator the target temperatures at each thermocouple. For stability reasons, this temperature is assigned to the entire 10 cm diameter sector around each thermocouple, in each layer. Similarly, historical CMG files (*.fhf) are created to easily compare the results obtained in the Results tool. Excel spreadsheets are used to automate the generation of the TEMPSET keywords with the necessary parameters to represent the historical information.

The match achieved for the first experiment is shown in Figure #1. Note that the simulation correctly reproduces the experimental data. Figure #2 shows another example of the match achieved, in this case for experiment number 4.

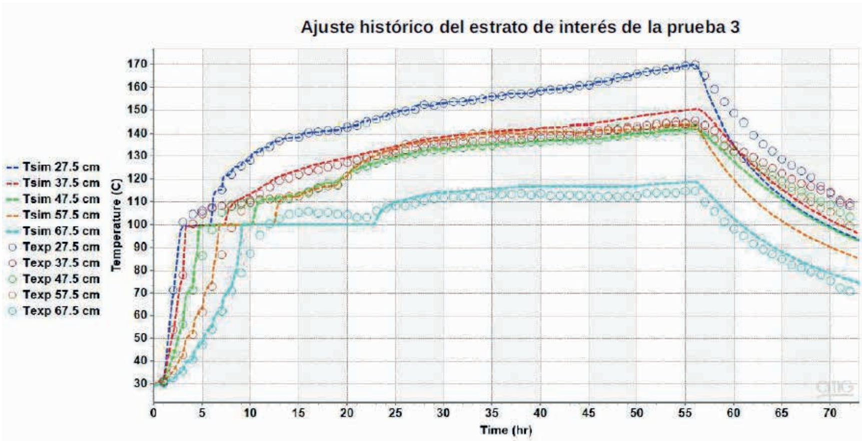

Figure - 7 match for the first experiment O30W301

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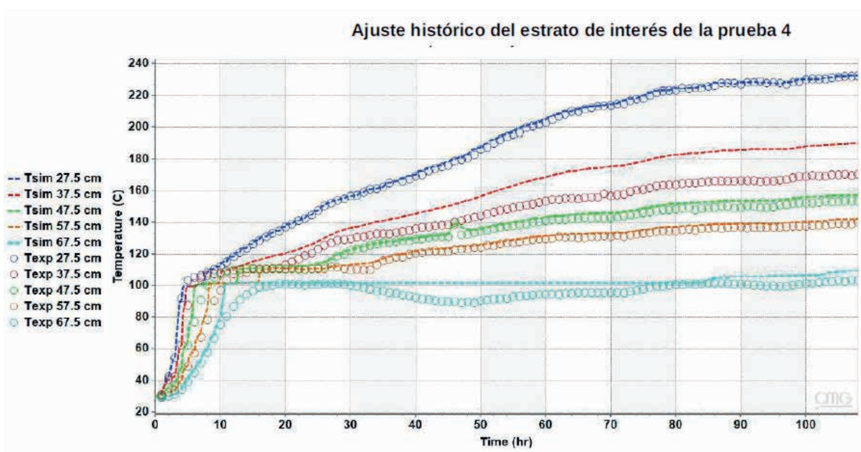

Figure - 8 Match achieved for the fourth experiment O30W60

Source: produced by the author.

This methodology is applied to all the experiments, allowing the estimation of the amount of heat transmitted in each case, according to the information provided by the simulator. The results are summarized in Table #1.

Experiment	Actual input power [kW]	Energy at 55 hours [J]	Average transfer rate [kW]	Ratio
O30W301	4.46	5.36E+08	2.71	0.61
O30W302	4.42	5.14E+08	2.60	0.59
O30W303	4.79	5.75E+08	2.90	0.61
O30W60	5.02	6.36E+08	3.21	0.64
O30W60NP	4.86	6.53E+08	3.30	0.68
O30	5.02	5.43E+08	2.74	0.55
SECA	5.22	5.51E+08	2.78	0.53
W30	5.16	5.95E+08	3.01	0.58
W30NP	5.16	6.51E+08	3.29	0.64

Table - 2 Saturations of the stratum of interest and sample code

Source: produced by the author.

The data of heat transferred to the system are analyzed using the model presented in equation (1), taking into account phenomena such as water evaporation. From this analysis, a characterization of the absorption value of the electromagnetic wave as a function of fluid saturation conditions and nanoparticle concentration is obtained (See Table #2). The model proposed in this work and the analysis and match methodology developed can be useful for the future scaling of the results obtained with the system and experimental setups presented.

CONCLUSIONS AND/OR FINAL CONSIDERATIONS

The experiments conducted on the electromagnetic heating prototype are analyzed based on the proposed experimental design, studying temperature behavior based on water saturation, oil saturation, and nanoparticle concentration. A reservoir simulator is used to reproduce experimental temperatures and match them with historical data, allowing determination of heat transfer in different reservoir sectors.

A heat transfer model is proposed, describing energy flow in a rock-fluid system subjected to electromagnetic radiation. The model is set up in discrete space and time, enabling integration with numerical simulators while accounting for property changes over time. This approach represents natural reservoir property variations, such as fluid saturation and nanoparticle presence.

The model estimates heat transfer based on power and electromagnetic absorption coefficient (α), which depends on fluid saturation and nanoparticles. A correlation was developed for estimating this absorption coefficient. The transfer model integrates with an algorithm that uses a commercial simulator to convert heat data into temperatures, simulating heating effects at various scales.

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