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Design of Magnetron Cooling Method Based on Heat Exchanger System for Microwave Heating Application

Gerry Sasanti Nirmala[1,2,*], Doddy Abdassah[1], Erdilla Indriyani[2], Anugerah[3], Sudjati Rachmat[1], Taufan Marhaendrajana[1] & Achmad Munir[4]

[1]Petroleum Engineering Study Program, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesa No.10, Bandung 40132, Indonesia
[2]Oil and Gas Production Engineering Department, Polytechnic of Energy and Minerals "Akamigas", Jalan Gajah Mada No.38, Mentul, Karangboyo, Kec. Cepu, Kabupaten Blora, Jawa Tengah 58315 Indonesia
[3]PetroChina Int., Jabung Ltd, Menara Kuningan Lt.17 - 27, Jalan HR. Rasuna Said Blok. X-7 Kav. 5, Karet Kuningan, Setiabudi, RT.6/RW.7, Kuningan, Karet Kuningan, Kecamatan Setiabudi, Jakarta Selatan, DKI Jakarta 12940
[4]Radio Telecommunication and Microwave Laboratory, School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Jalan Ganesa No.10, Bandung 40132, Indonesia
*E-mail : gerrynirmala@gmail.com

Highlights:

- Review of the proper material to use for microwave heating applications.
- Preliminary design of a magnetron cooling system.
- The effect of the coolant used in a heat exchanger on the magnetron.

Abstract. Microwave heating is a novel thermal recovery technique developed for heavy oil reservoirs. Particulary in deep reservoirs, it allows more effective thermal recovery to counter heat loss.. The magnetron as a microwave generator works based on cavity resonant vibrations and it needs an appropriate cooling system to avoid damage to its cavity elements. In this paper, the design of a cooling system based on a heat exchanger as well as the investigation of the proper material and coolant to fit the microwave characteristics are proposed.

Keywords: *cooling system; heavy oil reservoir; magnetron; microwave; thermal recovery*.

1 Introduction

A magnetron is a microwave generator frequently used in microwave ovens. It consists of a cylindrical anode arrangement and a transmitter antenna. It was developed in 1921 and was given the name 'magnetron' by Albert W. Hull [1]. In the petroleum industry, it is used in thermal recovery called electromagnetic (EM) heating technique. It works based on energy conversion from waves to thermal energy. This heating mechanism is by emitting high-power

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electromagnetic waves into a heavy oil well in order to radiate the water particles in the reservoir. Then the reservoir temperature is rise and the viscosity of the heavy oil decrease [2]. In this study, the frequency of 2.45 GHz is applied. It's the Industrial, Scientific, and Medical (ISM) frequency band. The electromagnetic waves to heat conversion occurs when it encounter rocks and fluids in oil reservoirs. Thus, the high electrical conductivity of the oil in the reservoir fluids producing heat which can accelerate the oil's viscosity degression. Finally, further energy absorption in the reservoir yields higher oil productivity.

As the high-performance electronic equipment, magnetrons require a proper cooling system to counter heat and power dissipation inside its components. This paper proposes a method in order to cooling down the magnetron when microwave heating is implemented in an oil well. The flexible and effective cooling system is required to reduce the heating up of the magnetron due to the size limitations of the oil wellbore.

Electronically, cooling methods can be divided into three main methods, i.e., passive air cooling, forced air cooling, and forced cooling using a coolant. Forced cooling works better than the passive cooling method, however it also has several disadvantages, such as limited-service life, noise, and power consumption [3]. Another widely developed cooling technique is a heat exchanger (HE) system using a heat pipe. This method is the best choice for electronic coolers due to it has a small size and weight, high thermal conductivity, and can be placed in confined spaces where there is no opportunity or possibility to accommodate a conventional fan [4]. It is also used as an internal cooling method for mechanical components [5-7], for which it has been proven to be effective and efficient.

A heat exchanger system seemed to be the best option for magnetron cooling. However the HE material and cooling fluid also need to be selected. Using data from a prior experiment, the heat absorption calculated into an oil and sand pack to determined the maximum electrical conductivity. If an appropriate HE material and cooling fluid are used It is expected that the heat reduction from the magnetron will occur effectively if an appropriate HE material and cooling fluid are used.

2 Magnetron Cooling Design

2.1 Microwave Generator

In previous studies, microwave ovens have been used as wave generating equipment for microwave heating techniques [2,8]. A microwave oven is modified depending on the purpose of the experiment. The magnetron has to be installed directly in a wellbore therefore it is removed from the microwave circuit and equipped with a thermostat as a temperature controller [2,8-10]. This arrangement can be seen in Figure 1.

Physically, a magnetron consists of an anode as a cylindrical solid copper block, a cathode, and a filament at the center of a tube supported by filament leads [1]. The filament leads are large and rigid enough to keep the cathode and filament structure fixed. There are cylindrical holes around its circumference, called resonant cavities. A narrow slot runs from each cavity to the central portion of the tube, and split the inner structure into equal cavities segments. When a single resonant cavity oscillates, it triggers the neighboring cavity to oscillate at a phase delay of 180 degrees. The resonators generate a microwave structure.

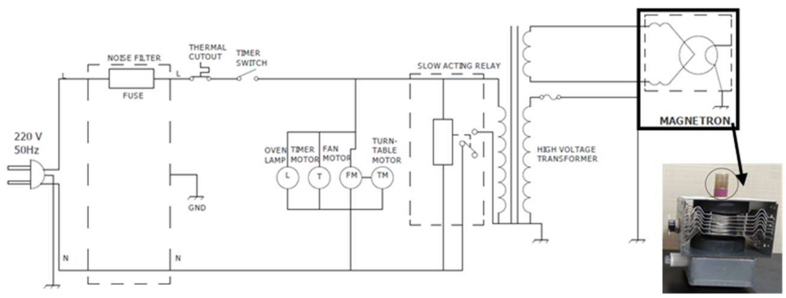

Figure 1 Microwave generator circuit.

The energy vibrations between the resonant cavities in the anode block generate heat in the copper tube, which needs to be cooled down immediately. Normally, there are fins on the side of the magnetron to dissipate the heat [2,8-10]. This is certainly not possible in an actual oil well due to the limited available space and lack of air circulation in the well. Therefore, a cooling method must be designed based on the principle of a heat exchanger, which is expected to be able to support the operation of microwave heating stimulation in actual oil well conditions.

2.2 Heat Exchanger System for Cooling Design

A heat exchanger is a device to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact [11]. It is widely used in air conditioning, refrigeration, petroleum refineries, natural gas processing, and other utilizations in high-pressure environments. The heat exchanger design is simply a series of shells and tubes equipped with baffles in the compartment to support the heat exchange process. Most heat exchangers have multiple passes to increase the flow velocity in the tubes. The medium on the tube side flows forward along a U-turn tube and another fluid flows in counter-current to the shell-side flow. Through the tubes flows a high pressure condition, corrosive media, and products with high fouling tendency, while on the shell side are viscous products. Furthermore, baffles are also integral to the shell and tube heat exchanger design. The baffles are designed to support the tube bundles and direct the fluid flow at maximum efficiency. The design and arrangement of the shell and baffle are discussed in the standards of the Tubular Exchanger Manufacturers Association (TEMA) [12].

There are several criteria for choosing the geometry of a heat exchanger construction, which consisting of tubes, plates, or extended surfaces, depending on the needs [13]. A tubular heat exchanger consists of circular tubes, where one fluid flows inside and other fluids flow outside the tube. This arrangement can be further classified as a double pipe heat exchanger, a shell and tube heat exchanger, or a spiral tube heat exchanger. Using a fiber-reinforced plastic (FRP) water hose, a simple experiment was carried out to examine the effect of the cooling fluid used for the magnetron. FRP is a composite material made of a polymer matrix reinforced with fiber. This material was chosen due to non-metal based and has high thermal conductivity (1.06 W/m.K) and low electrical conductivity (10^{-15} to 1 $\Omega^{-1}.m^{-1}$) [13]. The water hose was wrapped around a silica glass container to house the magnetron. A cooling fluid was injected into the hose while the magnetron was working through a microwave generator as explained in Section 2.1.

Taking into account the limited space in an actual oil well (±12 to 90 cm) [14], a heat exchanger with single-phase liquid cooling looks to be the best choice. The heat exchange occurs due to the conduction process between the fiber hose and convection between the coolant inside it (Figure 2).

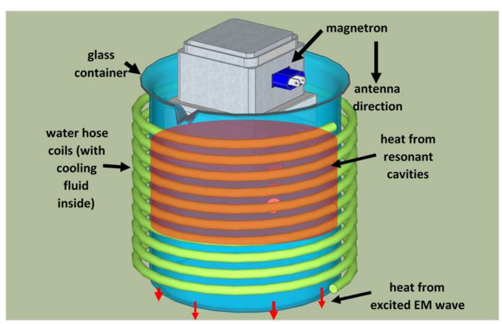

Figure 2 Heat exchanger system consisting of waterhose coils made from fiber-reinforced plastic (¼ in OD).

2.3 Material Selection

The waves generated by magnetrons are reflected by metal-based materials, hence It is suitable to utilize typical copper tubes in heat exchanger systems. Particularly, for the application of thermal stimulation in heavy oil reservoirs, microwave heating requires special oil well conditions that can only be applied to open-hole wells or non-metal liners [15].

The material used for the heat exchanger system's cooling tubes and the magnetron shield should be of high quality, work in a high-pressure and high-temperature environment, and be non-metal based and electrically conductive. However, using a high electrical conductivity material may cause a reduction of the heat absorbed by the reservoir components, which is contrary to the stimulation objective.

In order to determine the proper material for this cooling system, it is very important to calculate the energy change due to heating by electromagnetic waves and their absorption into the rocks. The amount of energy absorbed by the reservoir are influenced by the power density, $\Phi(r)$, [15]:

$$\frac{d\Phi(r)}{dr} = -\alpha\,\Phi(r) \tag{1}$$

The power absorption coefficient depends on the electric field absorption coefficient (α_e), with the following relation [15]:

$$\alpha = 0{,}02\,\alpha_e \tag{2}$$

with

$$\alpha_e^2 = \frac{\omega^2\mu\varepsilon}{2}\left\{\left(1+\left[\frac{\sigma}{\omega\varepsilon}\right]^2\right)^{1/2} - 1\right\} \tag{3}$$

The electrical value of this coefficient has not been found yet in oil reservoirs and requires further research. The power absorption coefficient in this paper was determined from the Abernethy equation regarding the relationship between power $P_{(r)}$ and distance (r) [15]:

$$P(r) = P_o e^{-\alpha(r-r_o)} \tag{4}$$

$$\text{where } P_o = P(r_o) \tag{5}$$

2.4 Cooling Fluids

Two types of cooling fluids were used in the experiment, i.e., water and a mixture of ethylene glycol and water. Both cooling fluids were chosen for their heat capacity. The heat capacity is a quantity that shows the amount of energy that can be stored in a material as heat. The higher the heat capacity, the more heat can be stored. Water has a very high specific heat capacity of 4.1814 J/(g. K) [16] at 25 ℃, while for a mixture of ethylene glycol and water it is 3.140 J/(g. K) [17]. Ethylene glycol needs to be mixed with water because of its toxic content. The mixture also has other benefits for coolant and antifreeze solutions [17], even though it reduces its specific heat capacity and thermal conductivity, as seen in Table 1.

Table 1 Heat transfer rate on a fiber hose in 270 seconds.

Cooling fluid	Thermal conductivity (K) W/m.K	Transfer rate (Q/t) Watt/s
Air (empty hose)	0.024*	1.43
Water	0.6*	19.43
Water + Ethylene glycol	0.3396**	12.17

Source: * [18]
** [19]

3 Result and Discussion

3.1 Maximum Electrical Conductivity Value

The power absorption coefficient was calculated based on the prior work to determine the maximum value of the electrical conductivity of the oil sample [2]. The analysis was obtained from a sand pack mixture with 22° API crude oil, 14 ppm nano ferrofluid, and microwave heating at a frequency of 2.45 GHz, with a variation of power usage. Based on the previous experiment, the reference for the minimum heating temperature needed for the oil sample density was 51 ℃ [10]. Figure 3 shows the heating design from the prior work, with the direction perpendicular to the test points.

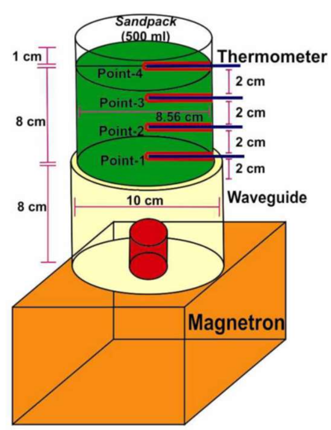

Figure 3 The microwave heating design [10].

There were four points of measurement that indicated the distance between the antenna and the depth of the sample. The first test point was located at a distance of 2 cm from the antenna, followed by another test point in the range of 2 cm.

The temperature changes in 100 seconds are presented in Figures 4 and 5. In Figure 4, the temperature of the sample rose along with the power usage. The most rapid change occurred at a distance of 2 cm, which was the point closest to the heating source. From this point, we also determined the relation of temperature vs. radius of penetration, which is presented in Figure 4. The power absorption coefficient and the electrical conductivity were obtained using the trendline approach in Figure 4 combined with Eq. (5). Here, we found an α value of 0.164 cm^{-1}. In a fixed sample medium, it was assumed that the electrical permissibility and permeability values were also fixed. Eq. (2) shows that the relationship between α and σ is directly proportional, hence for an α value of 0.164 cm^{-1}, a σ value of about 3.1389 S/m was obtained. This is the maximum value of electrical conductivity of a material that can be applied in magnetron cooling systems.

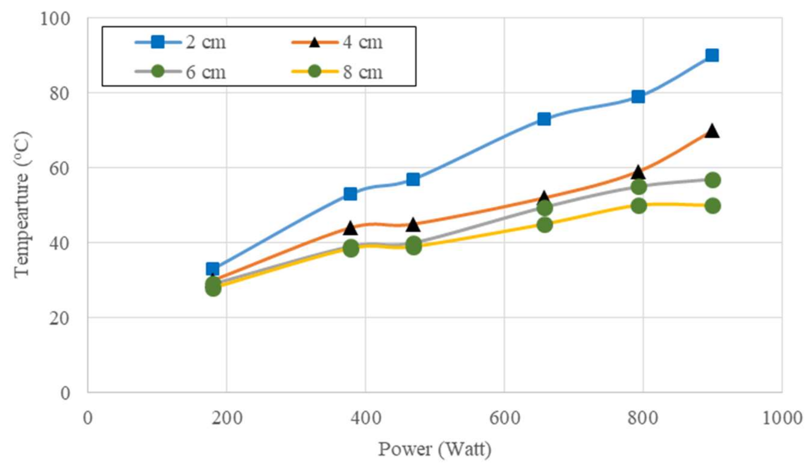

Figure 4 The temperature changes for each test point due to power usage of electromagnetic (microwave) heating in 100 seconds.

The relation between absorbed power and the radius of heat penetration is presented in Figure 5. The results describe that the absorbed power decreases with an increase in the radius. The decrease in power is the energy conversion from electricity to heat that is absorbed by the sample. A plot of the absorbed power vs. radius of heat penetration is presented in Figure 6.

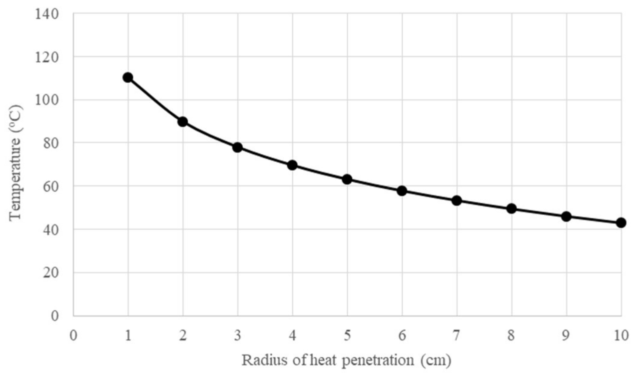

Figure 5 Temperature vs radius in microwave heating (power of 900 Watts).

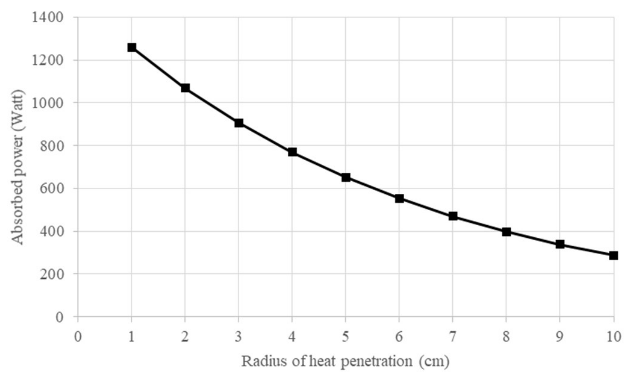

Figure 6 Absorbed power in microwave heating

3.2 Effectiveness of Cooling Fluids

We installed a thermometer inside and outside the glass of the HE design, as shown in Figure 2. . The inner thermometer (T1), 4 cm from the antenna, is used to monitor the temperature of the magnetron. Meanwhile, an external thermometer (T2), 6 cm from the antenna, is used to monitor the temperature after circulated coolant. The first experiment was carried out to see the heating speed using microwaves on the hose when it was empty or filled with air. This was done to see the actual speed of the microwave heating. The experiment was then continued with the hose filled with the two different coolants, i.e., water, and a mixture of ethylene glycol with water. The plot in Figure 7 is a comparison of the temperature rise due to microwave heating inside the glass (T1), which was directly exposed to heat, and outside the glass (T2), when coolant fluid had passed through the hose. The plot is a combination of the two different coolant samples previously mentioned.

The use of high frequency combined with high power produced very high temperatures in quickly. In Figure 7, we can see that the temperature rise at point T1 did not change, because of the constant treatment, while at point T2 there was a change in temperature due to the use of the cooling fluid. The temperature at point 2 dropped dramatically at the same point as in the first experiment. This shows that the fiber hose and the cooling fluid were able to absorb the heat. The heat transfer rate using the conduction formula that occurs in the hose is displayed in Table 1.

Contrary to expectations, the type of cooling fluid used did not significantly influence on its increasing trend. Point T2 in Figure 7 shows that the temperature of the thermometer after coolant going through the system appeared to overlap on the same plot. However, when enlarged, the difference between the two coolant is visible.

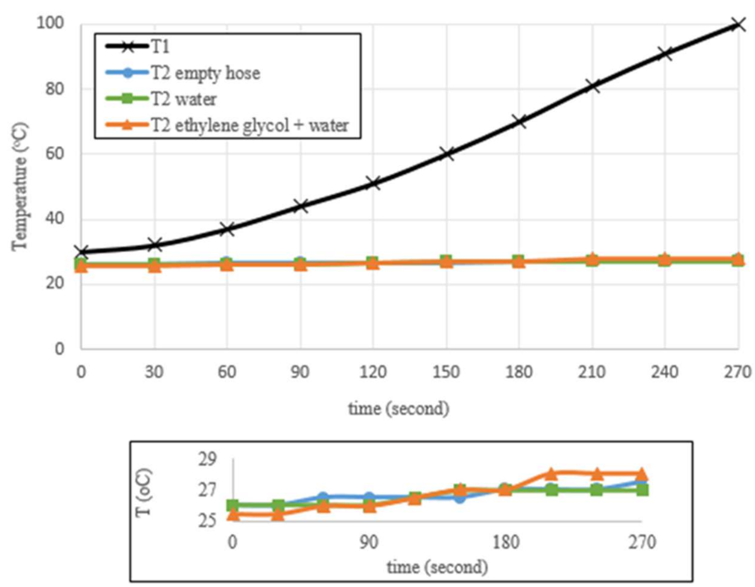

Figure 7 Comparison of the temperature rises due to microwave heating inside the glass (T1) and outside the glass (T2) due to the use of a coolant. (Box below: magnified image of the temperature rises at T2).

Compared with the heat transfer rate in Table 1, the cooling rate with water was the highest, so the final temperature was the lowest, followed by ethylene glycol mixed with water, and the empty hose. However, Figure 7 shows that the final temperature for ethylene glycol mixed with water was higher than for the empty hose. This indicates an imperfection in the experiment, such as the presence of air bubbles in the hose so that the cooling fluid did not entirely fill the hose. Further research needs to be done to see the cooling fluid's effectiveness in this system.

4 Conclusions

A heat exchanger system design was proposed as a magnetron cooling system in electromagnetic heating stimulation for heavy oil reservoirs. The system is intended for cooling and a shield to protect the magnetron from the reservoir fluids. The proposed design is based on wrapping a water hose instead of a copper tube around a magnetron container made of glass, which is then filled with cooling fluid. This design does not take up much space, and the cooling fluid was proven to reduce the temperature of the magnetron, although some breakdown may occur. To verify the effectiveness of the coolant, more variants will be tested in future work. Furthermore, the circulation system of the heat exchanger must be considered to improve the cooling system.

Nomenclature

r	=	position coordinate (cm)
P_o	=	total radiated power (watt)
$P_{(r)}$	=	power at r (watt)
$\Phi(r)$	=	power density (watt/cm)
α	=	power absorption coefficient (1/cm)
α_e	=	electric field absorption coefficient (1/cm)
ε	=	electric permittivity (F/m)
μ	=	electric permeability (H/m)
σ	=	electric conductivity (mho/m, S/m)
ω	=	angular frequency ($2\pi f$)

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