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Microwave Heating of Heavy Oil and Bitumen

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***Abstract*—A theoretical study is presented for the feasibility of a microwave heating device that will raise the temperature of heavy oil and bitumen reservoir. The device is enclosed in a radome which is surrounded by a perforated metal pipe. Outside the pipe is occupied by a mixture of heavy oil and calcite. Various dielectric properties are assumed for the radome and the calcite region. Analytical and numerical results are presented for the temperature rise around the pipe.**

Key words— Microwave Heating, Heavy Oil, Bitumen

I. Introduction

High viscosity is a major problem in the recovery of oil from heavy oil and bitumen reservoirs. A common solution is to heat the region surrounding the oil pipe. Conventional heating methods such as hot steam or fluid injection, resistive heating, and explosions are not effective in many cases. Electromagnetic heating is a relatively new technique for use in enhanced oil recovery (EOR) methods. This method has many advantages over the conventional techniques. Heat transfer in different materials using microwave radiation has been studied extensively [1], [2]. Its application as an EOR is not adequately commercialised. Further study is needed to discover optimum design parameters for using microwave heating as a reliable heating method in the field.

This paper investigates the effect of microwave radiation on crude oil embedded in different rock formations. An infinite line source, a finite dipole antenna, and a horn antenna are used to model the radiation sources. Power absorbed and temperature rise due to microwave radiation is calculated using numerical and analytical tools.

II. Analytical Method

Figure 1 shows the model for a section of the pipe of height L used in this work. Here a and b respectively show the inner and outer radii of the radome which is a lossless dielectric of constant ϵ_2. The region $\rho > b$ is occupied by a mixture of calcite and heavy oil. This medium is characterised by a lossy dielectric of complex constant ϵ_3. The microwave radiator is enclosed in the region $\rho < a$ which is characterised by (ϵ_0, μ_0). For simplicity we assume no metal boundary at $\rho = a$.

As a first approximation we assume the microwave source to be an infinitely long electric current of amplitude I placed along the z-axis. The electric field produced by this current radiating in an unbounded medium (ϵ_0, μ_0) is given by [3]

$$E_z = -\frac{k_0^2 I}{4\omega\epsilon_0} H_0^{(2)}(k_0\rho) \qquad (1)$$

where k_0 is the wave number in the medium and $H_0^{(2)}$ is the Henkel function of type two and order zero. The total fields in the three regions of Fig. 1 are calculated by satisfying the boundary conditions at $\rho = a$ and $\rho = b$. The current I of the infinite antenna is fixed at 0.6431 Amperes so that, when the antenna radiates in an unbounded air medium, the net power radiated through a cylinder of height 1 m is 1000 Watts. The frequency is assumed to be 2.45 GHz, and the outer radius of radome is fixed at $b = 5$ cm.

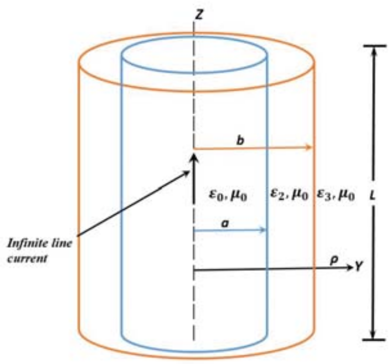

Fig. 1. An infinitely long electric current radiating inside a radome surrounded by infinite calcite medium.

Figure 2 shows power leaving a cylinder of height $L = 1$ m and radius ρ. The dielectric constant of the radome is fixed to be 2 [4], and that of the calcite region is assumed to be 6 with a loss tangent of 0.0003. Different thicknesses $d = b - a$

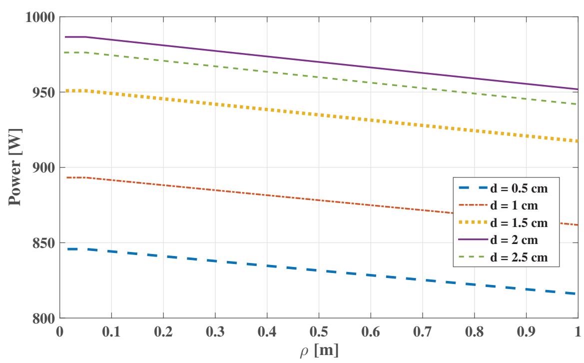

Fig. 2. Power leaving a cylinder of height 1 m and radius ρ, where d is the thickness of the radome.

of the radome are considered. It is seen from the above figure that for a fixed dielectric constant, the optimum radome is not necessarily a thin one. To transfer maximum power, the thickness and the dielectric constant of the radome can be chosen by using a "quarter wavelength anti-reflection coating". The result gives a thickness of 2 cm, and a dielectric constant of 2.45. Figure 3 shows that indeed the power transferred to the calcite region is actually 1000 Watts. We assume that temperature rise of 10°C will be sufficient.

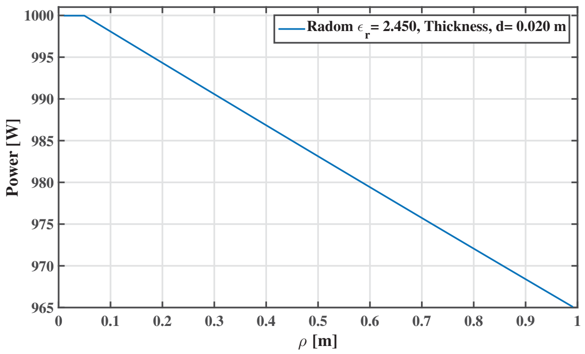

Fig. 3. Power leaving a cylinder of height 1 m and radius ρ. The thickness of the radome is 2 cm and its dielectric constant is 2.45.

Figure 4 shows the *pattern* of the temperature rise inside a cylindrical shell of thickness 10 cm and height $L = 1$ m in one hour in the calcite material. The assumed electrical properties for calcite are, $\epsilon_r = 2.4$ and $tan\delta = 0.001$. Its density is assumed to be 2710 [Kg/m^3] and specific heat capacity is 0.2 [Kcal/Kg-°C] [5]. The inner radius of the shell is at a distance $\rho + 5$ cm from the current source and the outer radius is at $\rho + 15$ cm. The radome is assumed to be absent.

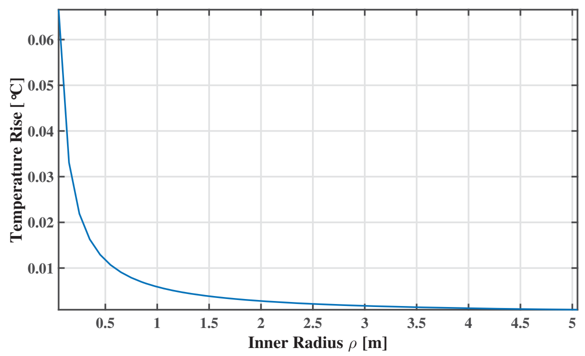

Fig. 4. Temperature rise in a shell of thickness 10 cm and height $L = 1$ [m].

III. Numerical Analysis

In this section a Finite Element Method (FEM) of computation is performed using the commercial software COMSOL. A Numerical Electromagnetic Computational model has been constructed. The preliminary experiment is as shown in Fig. 5. A centre-fed dipole antenna of diameter 2.75 mm, gap 0.5 mm, and length 5.5 cm is placed at the centre of an air cylinder and is oriented along the axis of the cylinder. The radome is assumed to be absent. The cylinder/antenna assembly is embedded in a lossy calcite sphere of radius 5 m. The sphere is surrounded by a Perfectly Matched Layer (PML).

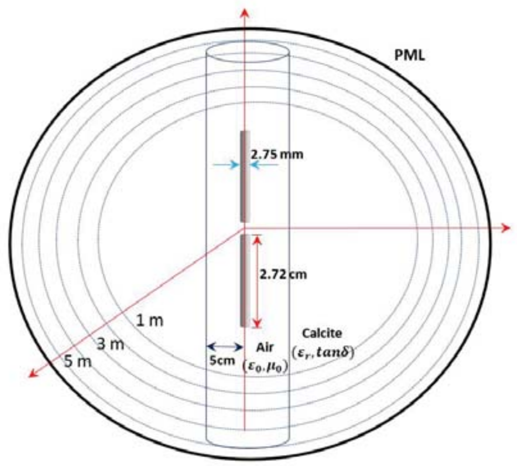

Fig. 5. The model used in COMSOL showing a dipole antenna and the 5 ficticious circles.

The antenna radiates approximately 1000 W. Net outward power flow is observed. To quantify this power flow, five fictitious spherical boundaries are defined. The boundaries share the same centre as the calcite sphere. They have radii ranging from 1 m to 5 m. The net power leaving each boundary in the radial direction is computed. This gives an indication of the power absorbed by the calcite as the energy flows outward. These values are plotted (dots) in Fig. 6. From the preceding analytical phase of the project an exponential expression was expected to model the decay in the power flow. The red curve in Fig. 6 corresponds to a best fit of the data to the expected exponential behaviour. The maximum radius of approximately 5 m was due to a limit in the available computing resources.

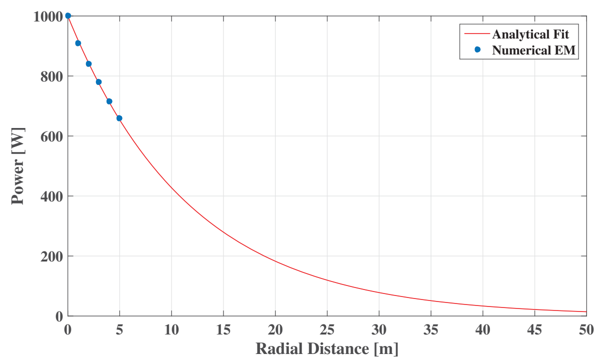

Fig. 6. Net radial power flow versus distance from origin. The dots are from Numerical EM, and the red curve is a fit of the dots to an exponential expression.

In the analytical method, the antenna was assumed to be an infinite line of constant current. The power radiated by such an antenna was the same regardless of the radome and/or calcite characteristics. We observed that for certain parameters of radome and calcite the total power entering the calcite could be equal to the radiated power if the thickness of the radome was properly chosen. In other words the "reflected" wave could be eliminated by the "quarter-wave coating" method.

In this section, we investigated the effect of the radome when the antenna is more realistic. Specifically we chose a half-wave dipole as the source of radiation. Both 2-D and 3-D analysis were performed. The excitation of this dipole was chosen so that the total power radiated was about 1000 Watts when the dipole was in free space. The presence of radome/calcite will change the current distribution on the antenna and therefore the power radiated will change. In other words, although the voltage applied to the antenna is kept constant, the input impedance of the antenna changes with the presence of the radome and/or calcite.

First, the mesh sizes were chosen small enough so that the computed results would not change when the mesh sizes were changed slightly. It was observed that the results converged when the mesh size was about $\lambda/50$ in 2-D simulations. For 3-D simulations we could not choose such a small mesh size because of computational limitations.

Table I below summarizes the power entering the calcite region computed by three different ways. The calcite is characterized by $\epsilon_r = 6$, $tan\delta = 0.0003$, and the radome has $\epsilon_r = 2$, $tan\delta = 0$. For the infinite antenna case the incident power (radiated by the infinite line through a cylinder of 1 m height) is 1000 Watts. The net power (incident-reflected) is obviously smaller than 1000 Watts. For the finite dipole considered in this section the incident power changes with the presence of the radome/calcite. However, we observe the same behaviour in all three cases. That is, as the thickness of the radome is increased from 0.5 cm to 2 cm, the net power entering the calcite region increases.

TABLE I
COMPARISON OF THREE METHODS FOR POWER ENTERING THE CALCITE REGION.

Radome	Power [W] entering the calcite region		
Thicknes [cm]	Infinite Antenna	Finite 2-D	Finite 3-D
0.5	845	798	805
1	893	829	853
1.5	950	884	910
2	986	943	942

The use of 1000 W sources in the simulations was chosen based on the availability of microwave sources. To explore the impact of multiple such sources, a three antenna version of the experiment was run. Three vertical dipoles, each transmitting 1000 W, were placed on the z-axis at the centre of the solution region. The temperature rise versus distance over a period of 6 months for this setup is shown in Fig. 7. As expected the temperature increase is nearly three times that of the single antenna. The temperature is not exactly three times that of the single antenna case, particularly close to the antennas, because the plotted temperature is on the XY plane. That is, the radiative contribution of the centre antenna is exactly like that of the single antenna case above. However the contributions of the other two antennas are diminished since the temperature measurement is not at the peak of the pattern for those antennas. It should be noted that constant heating for 6 months is impractical, therefore a feasible scheme of turning the sources on and off is required in real time scenarios.

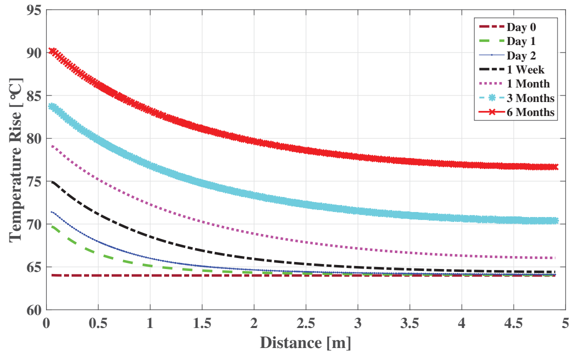

Fig. 7. Temperature variation in calcite (assumed values: $\epsilon_r = 4, tan\delta = 0.003$) with standard thermal conductivity 5.526 [W/(m-k)] and 6 months of constant heating using three 1000 W sources. The initial temperature is taken to be 64°C.

IV. Proposed Hardware

Figure 8 shows the structure of a section of a microwave heating system that could be used in an oil pipe. The complete system will include many vertically stacked up such sections. As shown in Fig. 8 each section consists of two compartments.

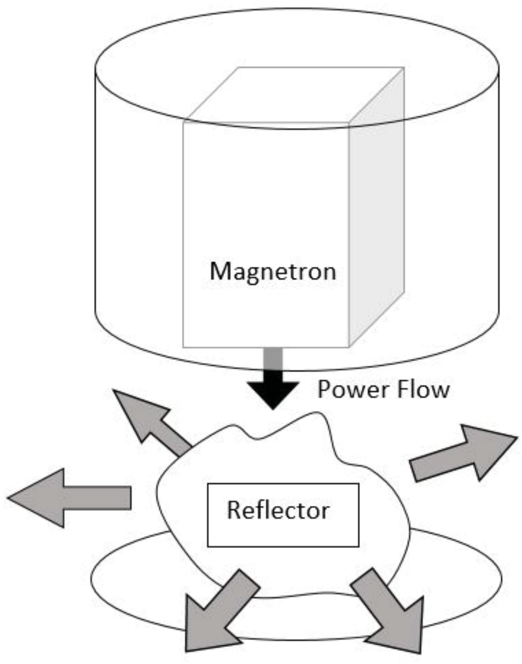

Fig. 8. A section of the microwave heating system where a Magnetron is radiating into an open cavity with a reflector.

One compartment includes the microwave source such as a magnetron which radiates into a lower section which scatters the power radially from the pipe. Figure 9 shows a scattering array in the lower section. This array consists of many

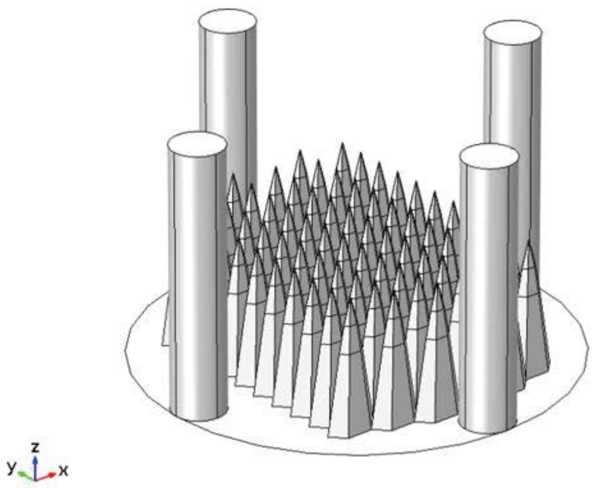

Fig. 9. A pyramidal reflector array designed in COMSOL to reflect power radially outwards.

pyramid-shaped metal spikes. The four columns are pipes which can be used for coolants and electrical connections to the lower sections. The radiated fields, and by inference, the heating pattern of the scattering array is shown in Fig. 10. As is clearly shown, the power radiated is almost completely radial. The heating will also be radial. Of course, the closest calcite will be heated the most, as expected. This will likely require cycling each individual heating compartment.

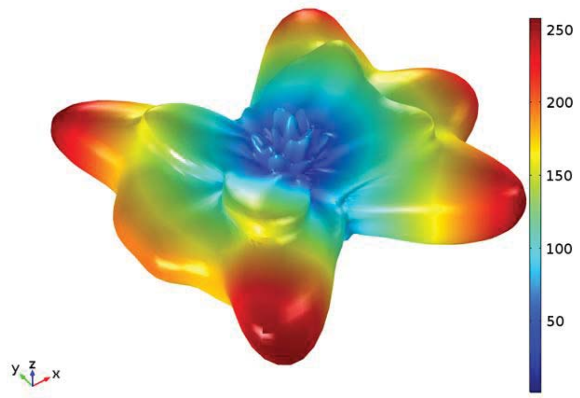

Fig. 10. Far-field pattern due to a radiating Magnetron over a pyramidal reflector array.

V. CONCLUSION

A simple microwave heating system is proposed for rising the temperature of heavy oil/bitumen around an oil pipe. Both analytical and numerical tools are used to study the feasibility of such a system. Some results are presented here and more will be presented during the conference. It is concluded that electromagnetic heating can be an effective tool for EOR. Further optimization is possible, though this particular design could be manufactured and tested as is.

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REFERENCES

[1] G. Malofeev, O. Mirsaetov, and I. Cholovskaya, "Injection of hot fluids for enhanced oil recovery and well stimulation," Regular and Chaotic Dynamics, Institute of Computer Science, RussiaIgevsk, Russia, 2008.
[2] A. Davletbaev and L. Kovaleva, "Combined RF EM/solvent treatment technique: heavy/extra-heavy oil production model case study," Proceedings of the 10th Annual International Conference Petroleum Phase Behavior and Fouling, Rio de Janeiro, Brazil, 2009.
[3] Roger F. Harrington, "Time Harmonic Electromagnetic Fields," McGraw Hill, 1961, p. 224.
[4] Paul Ehrlich, "Dielectric Properties of teflon from room temperature to 314° C and from frequencies of 10^2 to 10^5 c/s," Journal of Research of the National Bureau of Standards, Vol. 51, No. 4, October 1953.
[5] Joseph R. Smyth, Thomas J. Ahrens, "The crystal structure of calcite III," Geophysical Research Letters, Vol. 24, No. 13, Pages 1595-1598, July 1, 1997.