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Thermal analysis of high frequency electromagnetic heating of lossy porous media

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HIGHLIGHTS

- Analytical solutions are presented for electromagnetic heating of lossy media.
- The solutions can be used as forward models in design of experimental studies.
- The solutions allow estimation of electromagnetic absorption coefficient.
- The solutions allow estimation of electromagnetic power loss.

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ABSTRACT

Industrial applications of the electromagnetic wave as a source of energy have been increasing in recent years. One of the growing areas of application of electromagnetic heating (EMH), especially using high frequency waves, is the heating of geological media for extraction of hydrocarbons. In this work, electromagnetic field propagation in a lossy, electrically isotropic, and homogenous medium was studied to determine the effectiveness of EMH for heavy oil recovery. The electromagnetic heat source is modeled using Beer-Lambert's law coupled with heat conduction. New analytical solutions are developed to find temperature distribution in linear and radial geometries subject to various boundary conditions. The effect of electromagnetic heat generation on thermal penetration depth is examined. One of the challenges in electromagnetic heating of geomaterials has been reflection of the incident wave due to impedance mismatch and thus loss of the applied power. The analytical solutions developed allow determination of absorbed power by the geological media and thus can be used as a tool to predict efficiency of electromagnetic heating. In addition, the aforementioned solutions can be used as forward model for design of experiments and to estimate the electromagnetic absorption coefficient of geomaterials.

1. Introduction

Electromagnetic heating (EMH) is a generic term for thermally stimulating materials with electrical energy. It can be divided into four main distinct groups; (i) direct resistance heating (DRH); (ii) induction heating (IH) for heating highly conductive materials; (iii) radiofrequency heating (RFH); and (iv) microwave heating (MWH) for relatively low-conductivity materials. At low frequencies (<100 Hz) resistance heating or so called Joule or Ohmic heating controls the process. At high frequencies between radio frequency (between 10 and 100 MHz) and microwave frequency (between 100 MHz and 100 GHz) dielectric heating dominates (Basak and Ayappa, 1997). A household microwave oven operates at 2.45 GHz.

Dipole polarization is the mechanism by which high frequency electromagnetic waves heat poor conductors or dielectrics. When employing high frequency EM energy, polar molecules, such as water molecules having an electrical dipole moment, generate heat as a result of molecular rotations caused by oscillations. Therefore, the heat source of high frequency heating is volumetrically distributed and located in situ and thus is more easily conveyed as compared to the conduction or convection based heating methods, wherein the heating source is applied at the boundaries of the medium (Hassanzadeh and Harding, 2016).

The determination of electromagnetic heating efficiency of geomaterials needs solution of coupled energy and wave equations. Maxwell's equations are generally used to describe the wave

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Nomenclature

Roman letters

$\underset{\rightarrow}{A}$	cross sectional area (m^2)
$\underset{\rightarrow}{a}$	unit vector (–)
$\underset{\rightarrow}{B}$	magnetic flux density (Wb/m^2)
$\underset{\rightarrow}{D}$	electric flux density (C/m^2)
E	electric field intensity (V/m)
$\underset{\rightarrow}{E_0}$	magnitude of electric field intensity at inlet (V/m)
H	magnetic field intensity (A/m)
H_0	magnitude of electric field intensity at inlet (A/m)
H_0^1	Hankel's Bessel function of the first kind (–)
$\underset{\rightarrow}{h}$	thickness (radial) (m)
J	electric current density (A/m^3)
j	complex index (–)
k_T	effective thermal conductivity (W/m K)
$\underset{\rightarrow}{L}$	length (linear) (m)
M	magnetization of the material (A/m)
M_t	volumetric heat capacity (J/m^3 K)
$\underset{\rightarrow}{N}$	Stark Number (–)
P	dielectric polarization of the material (C/m^2)
P_0	power (W)
$\dot{q}_{em}$	volumetric heat generation (W/m^3)
r	r-direction (Radial) (m)
r_w	inner radius (m)
r_e	outer radius (m)
T	temperature (K)
t	time (s)
V	volume (m^3)
x	x-direction (Cartesian) (m)
y	y-direction (Cartesian) (m)
z	z-direction (m)

Greek letters

α_{em}	attenuation factor (or absorption coefficient) (1/m)
β_{em}	phase constant (or wavenumber) (1/m)
ε_0	electric permittivity of the vacuum (F/m)
ε	electric permittivity of the medium (F/m)
η	intrinsic impedance of the media (Ω)
ϕ	azimuthal angle direction (Radial) (–)
γ_{em}	propagation constant (1/m)
μ_0	magnetic permeability of the vacuum (H/m)
μ	magnetic permeability of the medium (H/m)
ω	angular frequency (rad/s)
$\underset{\rightarrow}{\wp}$	Poynting vector (W/m^2)
ρ_v	volume charge density (C/m^3)
σ	medium conductivity (S/m)
θ_η	impedance phase (degree)
τ	period (s)
χ	electric susceptibility of the medium (–)

Subscripts

D	dimensionless parameter (–)
em	electromagnetic (–)
s	phasor form (–)

propagation (Sadiku, 2014). They can be simplified to Beer-Lambert's law (Hippel, 1954) using several assumptions. Beer-Lambert's law states that the power and field intensity decreases exponentially as the wave propagates through the medium. The law is appropriate for semi-infinite media (Ayappa et al., 1991a,b).

EMH has applications in many industries including the polymer and wood manufacturing industries, the food industry, biotechnology and medical fields, and in oil extraction. The food industry is the main user of microwave heating for fast food preparation and rapid heating of the foods. While highly effective and ubiquitous, microwave heating still suffers from the existence of hot/cold spots or uneven heat distribution. There is no such deficiency for radio frequency heating (Hossan and Dutta, 2012). Several studies have been conducted for modeling of the EM heating process of food. Ayappa et al. (1991a,b) compared the Beer-Lambert power formulation with the numerical solution of Maxwell's equations. They found that there is a critical slab thickness above which the Beer-Lambert law limit is valid. Yang and Gunasekaran (2004) used pulsed and continuous microwave energy to heat cylindrical gelatinous substances. Their analysis showed that the Beer-Lambert law resulted in comparable accuracy to Maxwell's equations.

Short processing time and quick start-up of electromagnetic heating led to significant popularity in material synthesis processes. Bhattacharya et al. (2013) optimized the heating process by using four different electromagnetic source configurations. They showed that heating pattern is critical to homogenize the reactor dynamic and reduce the reaction time. Electromagnetic heating can also be applied in fabrication processes, especially in bonding polymer-based devices by heating a highly dielectric thin material sandwiched between two layers (Lei et al., 2004; Rahbar et al., 2010). In biotechnology, the pros and cons of applying electromagnetics have been investigated in recent years. The health risks due to near-field (wireless communication center) exposure was the main focus of some studies (Keangin et al., 2011). Also, extensive numerical and experimental studies have been done on the microwave ablation (MWA) process, which has been used for neutralizing cancer cells (Rattanadecho and Keangin, 2013). In the wood manufacturing industry, microwave irradiation has been used for thawing frozen wood, drying or killing microorganisms and insects (Erchiqui, 2013).

In heavy oil recovery, the use of EMH in conjunction with solvent injection to dilute the bitumen is increasing due to the high energy intensity of the current thermal recovery methods and the associated environmental footprint. Abernethy (1976) developed an elegant analytical model based on the Beer-Lambert power formulation to find the temperature distributions from the radiation of electromagnetic energy in a radial system. However, the full coupling of heat conduction and the Beer-Lambert power formulation was not possible. Steady-state flow performance of a vertical well was compared to an unheated case. In another modeling effort, an algorithm was developed by Fanchi (1990) for estimating the temperature increase associated with reservoir electromagnetic heating. An asymptotic solution to Maxwell's equations was presented and it was shown that for an axially symmetric wave, which is propagating radially, the power attenuation follows the Beer-Lambert law. Carrizales et al. (2008) developed analytical solutions for single-phase and steady-state countercurrent flow where the source antenna is placed in the production well and for the case of co-current flow where the flow is taking place in the same direction as the electromagnetic wave propagation.

In this study, our focus is on the EMH of heavy oil reservoirs by installation of an electromagnetic antenna in the SAGD-style wellpairs. At the beginning of the SAGD-type processes, the fluid around the wellbores is immobile and thus preheating is required to establish the fluid communication between the two wells. In this stage, the dominant mechanisms of heating are conduction