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Full Length Article

Numerical simulation of RF heating heavy oil reservoir based on the coupling between electromagnetic and temperature field

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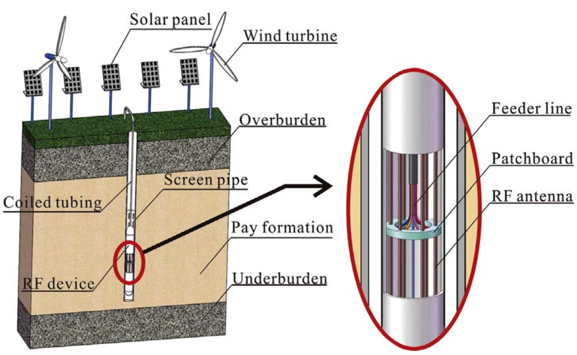
GRAPHICAL ABSTRACT



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ABSTRACT

At present, a technology of RF (radio frequency) heating is being investigated for enhanced heavy oil recovery, but continued high temperature appears near wellbore, which may destroy the wellbore integrity and RF apparatus. This paper first introduces a novel RF apparatus composed of antenna arrays for heating the heavy oil reservoir, and then the temperature distribution is calculated based on the coupling between electromagnetic and temperature field. To alleviate the high temperature in the vicinity of wellbore, two solutions are proposed: (1) a sleeve made of PTFE (polytetrafluoroethylene) is applied to the outside of the RF apparatus; (2) for improving accuracy of temperature calculation, thermos-physical parameters of reservoir, which are depended on the temperature, are considered specifically in the heat transfer equation and wave equation. Finally, the effect of properties of reservoir and the relative permittivity of sleeve on temperature distribution are investigated. Calculation results indicate that relative permittivity of sleeve has a tremendous influence on temperature distribution, and maximum temperature declines nearby the wellbore as the diminution of relative permittivity, moreover, the positions with highest temperature are moving far from the wellbore. When the parameters of specific heat and thermal conductivity are variable, the maximum temperature near the wellbore is lower than the temperature calculated by constant parameters. Variable relative permittivity of water can't decrease the temperature around the wellbore.

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Nomenclature

Parameter	Definition (Unit)
R_a	Radius of antenna array, mm
D_a	Diameter of signal antenna, mm
D_r	Diameter of reservoir, m
H_r	Height of reservoir, m
L_a	Length of antenna array, mm
D_s	Outer diameter of sleeve, mm
C_r	Specific heat of reservoir, J/(kg·K)
k_r	Thermal conductivity of reservoir, W/(m·K)
ε_{rw}	Relative permittivity of water, dimensionless
ε_r	Relative permittivity of reservoir, dimensionless
σ_r	Conductivity of reservoir, A/m^2
Φ	Porosity of reservoir,%
S_w	Water saturation,%
ε_{ro}	Relative permittivity of heavy oil, dimensionless
ε_{rr}	Relative permittivity of rock, dimensionless
μ_r	Relative permeability of reservoir, dimensionless
T_{const}	Initial reservoir temperature, K
ε_s	Relative permittivity of sleeve, dimensionless
σ_s	Conductivity of sleeve, A/m^2
ρ_r	Density of reservoir, kg/m^3
μ_s	Relative permeability of sleeve, dimensionless
ρ_s	Density of sleeve, kg/m^3
k_0	Wave number
j	Imaginary unit
ε_0	Permittivity of vacuum, F/m
μ_0	Permeability of vacuum, H/m
ω	Angular frequency, rad/s
c	Velocity of light, m/s
λ	Electromagnetic wavelength in reservoir, m
f	Frequency of electromagnetic wave, GHz
E_i	Electric field in medium, V/m i = 1,2
$\boldsymbol{n}$	Normal direction of interface
Q_i	Electromagnetic heat, W/m^3
S_{max}	Maximum grid element size, m

Subscripts

i	Medium
r	Reservoir
s	Sleeve
a	antenna

1. Introduction

In the situation of continuous low oil price worldwide, many petroleum corporations have no option but to interrupt the exploitation of heavy crude oil as a result of high mining cost and low profit. To solve the problem, a novel thermal recovery technology combined with electric power appears and is considered by some oil companies and scholars. The new technology is collectively referred to as "electric heating" and some literatures [1–6] have introduced the advantages of the technology, such as being environmentally friendly, highly heating efficiency, extracting resource in deep oil-bearing formation, avoiding extra heat loss and so on.

Currently, the electric heating technology can be classified as electrical resistive heating, inductive heating, RF heating and microwave heating [7,8]. Although the electrical resistive and inductive heating owns the advantages of the relative low cost of deployment, the heating processes are slow and the thermal penetration depth is limited. Besides, the microwave heating performs well in rapid heating, but the heat energy fails to be transferred to the further reservoir area owing to the shorter wavelength of the microwave. Instead, the RF (radio frequency) heating overcomes these shortcomings and presents a high heating efficiency. It owns the advantages of the higher frequency and enough greater output power. And, compared with steam recovery technology, the speed of RF heating is fast and additional heat loss is small, which will greatly enhance the oil production efficiency [9–11]. Therefore, the whole heating process is that the RF heating apparatus first radiates electromagnetic energy into oil-bearing formation, and then the energy is transferred by heat conduction. But, the process is so complex that the multi-physical fields must be taken into account.

A downhole configuration of the RF heating apparatus applied to the heavy oil reservoir is illustrated in Fig. 1. Electric power supply for the apparatus is mainly from industrial electricity, maybe wind energy and solar energy in the future. Feeder lines transmit high-frequency current to several antennas and then the electromagnetic wave come into being. Owing to the absorption of electromagnetic power by the reservoir, the heating transfer occurs during the process of electromagnetic wave propagating into the pay formation. In fact, the length of single-antenna is short and its radius is also small, what's more, the power of the signal antenna is so small that the heating coverage areas is limited and the reservoir temperature slightly increases. So, antenna array is designed to meet the high-power output and ensure a good performance of RF apparatus to sufficiently heat the oil-bearing formation.

In the early days, some scholars done a lot of theoretical research of electrical heating for improving oil recovery. In 1976, Abernethy [12] investigated the possibility of high frequency radiation heating by developing a mathematical model, which could evaluate the temperature distribution and some physical effects caused by the electromagnetic energy radiation. Pizarro and Trevisan (1990) developed a two-dimensional, two phase, mathematical model with the purpose of simulating the electrical resistive heating method for improving heavy oil recovery [13]. Vinsome et, al. (1994) modified reservoir simulator TETRAD by combining with the electrical heating equation. It was verified that the simulator was effective to conduct analytical calculation and field data [14]. Then Pu et, al. (2004) put forward a calculation model of electromagnetic heating-chemistry combination for improving heating and block removal efficiency [15]. Five years later, Mcgee and Donaldson [16] compared different electro-thermal heating methods by a mathematical model for calculating radial heat transfer.

There were some latest studies on the development of electromagnetic heating in recent years.

Davletbaev et al. (2011) built a 2D mathematical model of formation and RF electromagnetic radiation for heating heavy oil. The numerical calculations showed that the pressure in bottom wellbore and the electric power were important factors in improving heavy oil production [17]. Quintero and Quezada (2014) made an economic

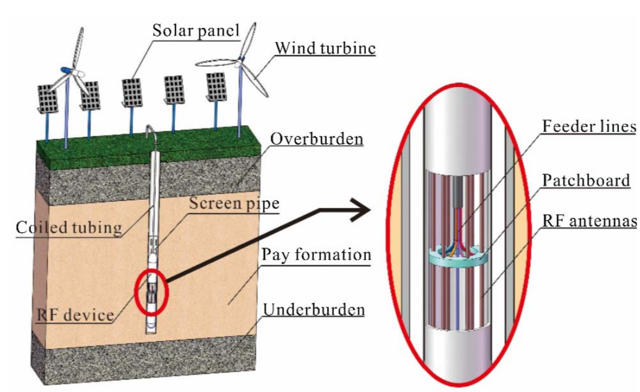

Fig. 1. Schematic diagram of RF apparatus configuration.