

Thermoacoustic inductor for heavy oil extraction

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Abstract. The problem of enhancing heavy oil reservoir performance is a matter of relevance for many years. Among the technologies aimed at solving this problem, the technology of the bottom-hole and well casing heating is the most interesting. This is a real possibility to transform thickened hydrocarbon into a recoverable state, as well as to solve the tasks of cleaning the borehole from asphaltenes, resins, and paraffin sediments. In both cases, the borehole area is generally warmed up and the product is then pumped out by the known techniques. The type of the equipment, the way of the well operation, the stage of reservoir development, physical and chemical properties of paraffin sediments, etc. are taken into consideration. In the article, basing on the electromagnetic induction method and the Joule effect, the advantages of induction heating compared to the traditional resistive and steam methods are presented. It is shown that under the induction exposure, the heat is not focused on the apparatus, but on heating the oily product. Basing on the method, a thermoacoustic inductor with unique technical characteristics has been developed.

1. Introduction

In the context of depletion of low-viscosity oil reservoirs of the Volga-Ural oil-and gas bearing province, significant reserves of oil production are the high-viscosity heavy oil deposits.

However, the traditional development methods used in the low-viscosity oil fields are inapplicable because of the low oil mobility and, consequently, lead to low wells productivity, a low level of reserves production and a high cost of the extracted product. The use of the most proven and widely used oil production technologies, as well as formation and the bottom-hole zone treatment techniques [1-11], does not always lead to achieving the desired result. These approaches can be used, at best, only in the case of a substantial in-situ oil viscosity reduction, particularly in the bottom-hole formation zone, where on top of it the asphalt-resin and paraffin sedimentation takes place (ARPS). Asphalt-resin and paraffin sediments are also observed alongside the well-bore, resulting in a significant tubing capacity reduction. This entails a reservoir depression reduction, which plays a primary role in the process of high viscosity hydrocarbons production.

Several technologies for the asphalt-resin and paraffin sedimentation protection and sediments removal are used at the depths of 200-1500 m, but the most common methods are the use of scrapers and hot liquid (steam) flushing [12-18]. The main virtue of these methods is a small cost of work. At the same time, resistive technologies have a significant temperature effect on the power supply cable, poor paraffin sedimentation control, low-quality pipes cleaning and, as a result, the high risk of a bull plug or paraffin crystallization. The latter leads to faster formation of new crystals and a rapid



thickening of sediment. Heating appliances using tubular heating element technology of resistance type are of extremely low efficiency and have a high cost of power. Due to the effects of high temperatures, their application may cause insoluble substances formation. For example, in heaters of 1M type, heat release happens in the process of current flow through the electrolyte. Because of this, the temperature is created only directly on the body of the apparatus and, in the case of a large paraffin amount, its recrystallization at the top part is possible, which in turn may result in the geophysical cable sticking. In the automatic induction heating equipment ITV-210 U, ITV-520, the heat evolution takes place not inside the heater, but in the casing, which is directly in contact with the bottom-hole formation zone of the well. These instruments use the principle of pipes controlled induction heating by high-frequency current and the subsequent release of detached sediments by the flow of the recovered product [7]. In general, the induction equipment of the types in question has been stripped of the above-mentioned deficiencies and has been doing a pretty good job of asphalt-resin and paraffin sediments cleaning. However, its resource is severely constrained by the possible appearance of an internal resonance effect, and it is poorly adapted for the hard to recover reserves production. Still, it is the induction heating that seems to be the most rational method for two tasks solving: a well from asphalt-resin and paraffin sediments cleaning and the bottom-hole formation zone heating.

2. Materials and methods

The essence of the induction heating method is in the electromagnetic energy transmitting from the source to the object to be heated without any contact between them (e.g. when the inductor was placed on the metal wall of the pipeline through the thermal insulation layer or when the inductor is isolated from the casing by the oil containing borehole liquid).

The energy source is the semiconductor frequency converter, which generates current pulses of the specified power in the inductor.

Due to electromagnetic induction, eddy currents cause the metal heating appear in the heated object. Therefore, the heat goes directly from the surface of the metal to the heated environment, allowing high efficiency of the heating system. The process of the induced current flowing on the metal surface is shown in Figure 1. The heating is caused by the electromagnetic waves penetration into the volume of the metal. The interchangeable current contour is located near the metal specimen. As a result of the electromagnetic field penetration into the metal specimen, eddy currents appear in the metal which, due to the scattering of electrons at the lattice sites, transfers some of their energy to them. As a result, the metal is heated (Joule's heat is released).

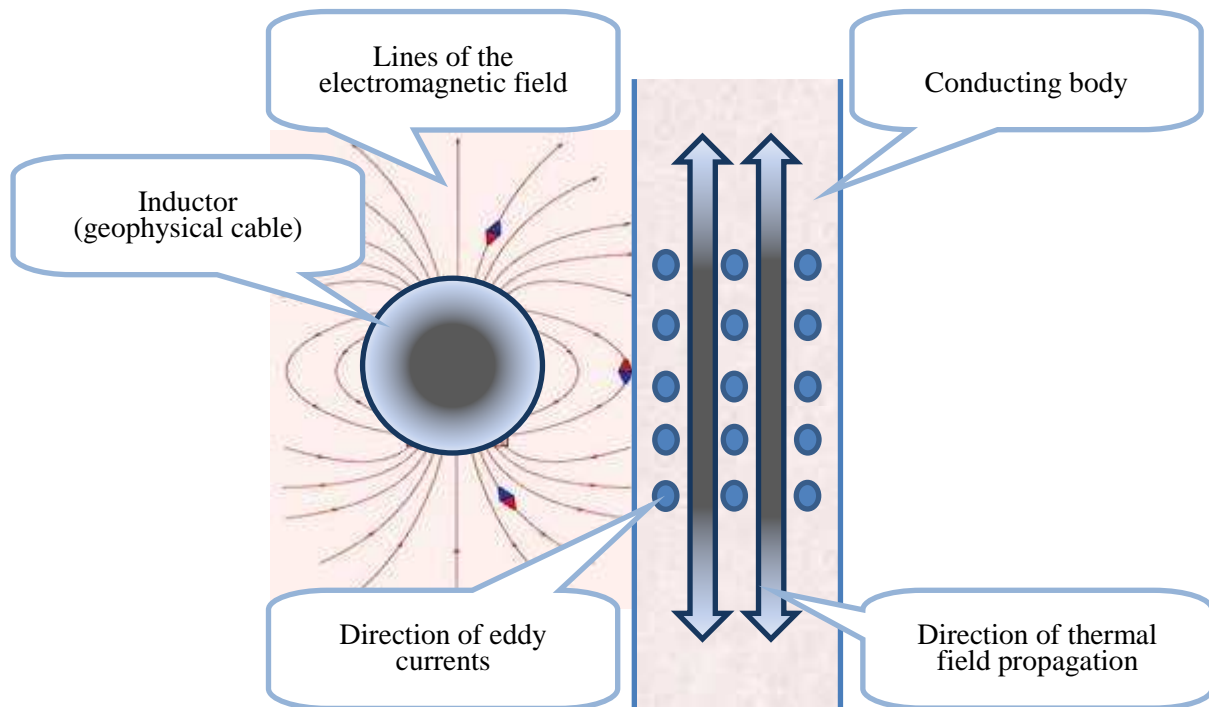


Figure 1. The formation of induced current on the metal surface.

In this way, the heating is done without direct contact of the induction coil with the metal and ensures a high efficiency of electrical energy into heat converting.

The depth of the heated layer depends on the electromagnetic field frequency, which is in the ranges from a few dozen kHz to a few MHz. The field is provided by a special generator. Using the experimental and calculating methods, the authors selected a range of 10 to 40 kHz with a priority of 22 kHz. At medium and high working frequencies, the depth of the heated layer is small because of the skin effect, and leveling the thermal field in the sample is provided only by the heat conductivity processes.

At lower working frequencies, the electromagnetic waves penetration rate increases, but the homogeneous heating is still achieved through the heat-conductivity mechanisms.

The working frequency reduction allows maximizing the heated part area. It should be noted that the warm-up rate is highly dependent on the heated metal magnetic characteristics. Thus, the electromagnetic heating of the metal is based on the three physical phenomena: the energy transfer from the inductor to the heated mass by means of the electromagnetic field, the electricity into heat conversion in accordance with the Joule effect and the heat through metal transmission as a result of thermal conductivity.

Let us consider the effects of the electromagnetic and acoustic fields on productive layers. It is known [19] that in saturated porous media, which may be dielectrics, the electromagnetic field contributes significantly to the heat transfer intensification. In this case, as a rule, it is assumed that a plane, a monochromatic electromagnetic wave is superimposed on a semi-infinite wave. Since a saturated porous medium is a heterogeneous, multi-component system, the Maxwell, thermal conductivity and piezoconductivity equations systems are usually solved to determine the electromagnetic field temperature and pressure parameters. As a rule, the time to equalize the pore oil temperatures is much shorter than the warm-up period, where consequently $x \leq l(\tau)$ and $x > l(\tau)$, is presented as:

$$\begin{aligned} \frac{\partial}{\partial x}(\lambda_1 \times \frac{\partial T_1}{\partial x} - m \times c_1 \times \rho_1 \times v_1 \times T_1) &= a_1 \times \frac{\partial T_1}{\partial \tau} - \beta_1 \times E_0^2 / z_1 \times \exp(-2 \times \beta_1 \times x), \\ \alpha_{11} \times \frac{\partial T_2^2}{\partial x^2} &= \frac{\partial T_2}{\partial \tau} - \beta_2 \times E_0^2 / z_2 / a_2 \times \exp(-2 \times \beta_2 \times x), \end{aligned}$$

where λ is heat conductivity W/(m×K); $\lambda_I = \lambda_0(1-m) + \lambda_1 \times m$, $\alpha_I = \beta_0 \times c_0(1-m) + \rho_1 c_1 m$; $\lambda_{II} = \lambda_0(1-m) + \lambda_2 m$, $\alpha_{II} = \beta_0 \times c_0(1-m) + \rho_2 \times c_2 \times m$, $\alpha_{II} = \lambda_{II}/\alpha_I$, ρ – density, kg/m³; c – heat-absorption capacity, J/(kg×K); m – porosity; β – electromagnetic wave attenuation factor 1/m; E_0 – electric field intensity amplitude $x=0$, V/m; index “0” means the skeleton, “1” is a liquid, and “2” is a solid phase of oil.

The temperature required to melt the bitumen oil is defined as:

$$t = z/(\beta \times E_0^2) \times [\beta_2 L_2 + \alpha_{II} (T_\phi - T_0)],$$

where z is the medium resistance, Ohm; L_2 – latent heat of melting of the bitumen of the solid phase, J/kg; T_ϕ – melting point, K; T_0 – initial temperature, K.

The depth of electromagnetic field penetration is:

$$h_3 = 1/(\omega_3 \times \text{tg} \delta) \times 1/(\epsilon \times \mu_0)^{1/2},$$

where ω_3 is the cyclic frequency of an electromagnetic field, $\text{tg} \delta$ is a dissipation factor of a dielectric, ϵ – dielectric permittivity of the medium; μ_0 – magnetic permeability of a nonmagnetic dielectric, equal to the magnetic permeability of vacuum, g/m.

Let us consider the acoustic field impact. In [19], it has been proved that when the acoustic field is distributed with a frequency more than characteristic, each elementary volume of the saturating environment and of the reservoir skeleton makes vibrational movements relative to each other near the equilibrium position. This often results in periodic changes in densities and pressures.

The acoustic effects on beds characteristic frequency are defined as follows:

$$\omega_x = \pi \times \mu / (16 \times \rho \times r_0^2),$$

where $\mu = 50 \times 10^{-3}$ (Pa×s), r_0 is the size of pore channels in meters, ρ – the oil density (kg/m³).

Results of the experiments conducted in cases when $\rho = 50 \times 10^{-3}$ Pa×s and $\rho = 800$ kg/m³, which is the characteristic of dense sand, has shown, that the frequencies in the range of 3-22 kHz correspond to pore channels from $6,4 \times 10^{-5}$ m to $1,4 \times 10^{-5}$ m. This allows us to conclude that the saturating medium motion relative to the collector skeleton in the indicated frequency ranges occurs only in pore channels with a diameter less than $(6,4 - 1,4) \times 10^{-5}$ m. For pore channels and large cracks, the saturating medium movement do not occur and therefore need to be matched with other frequencies.

Let us consider a mechanism forming thermal field directly in a conductive body (for example, in a metal pipe wall).

Total volumetric heat sources in the medium under the influence of the acoustic and electromagnetic field are:

$$q_{a3} = q_a + q_3.$$

When an acoustic field influences a reservoir, thermal sources have the form:

$$q_a = (\alpha_a \times \beta_a \times N_{a0}) / (\pi \times r_0 \times h) \times |H_0^{(2)}(\dot{k}_a \times r)|^2 / (\text{Re}\{j \times \dot{k}_a^* \times H_0^{(2)}(\dot{k}_a \times r_0) \times H_1^{(2)*}(\dot{k}_a^* \times r_0)\}),$$

where α_a and β_a – attenuation coefficient and phases of acoustic waves; N_{a0} – acoustic waves radiant power; h is the emitter cylinder height; r is the emitter cylinder radius; r_0 is the excitation point radius; \dot{k}_a is magnetic constant; $H_0^{(2)}(\dot{k}_a \times r)$ is the zero order Hankel function of the second type; Re is the real part of the complex quantity. The index «*» means a complex-mating value; j is a unit imaginary number; $H_1^{(2)*}(\dot{k}_a^* \times r_0)$ is the first order Hankel function of the second type.

When the electromagnetic field influences the reservoir, the thermal sources are:

$$q_3 = (\alpha_3 \times \beta_3 \times N_{30}) / (\pi \times r_0 \times h) \times |H_0^{(2)}(\dot{k}_3 \times r)|^2 / (\text{Re}\{j \times \dot{k}_3^* \times H_0^{(2)}(\dot{k}_3 \times r_0) \times H_0^{(2)*}(\dot{k}_3^* \times r_0)\}),$$

where α_3 and β_3 are the factors of damping and the electromagnetic waves phases; N_{30} is the electromagnetic wave emitters power; \dot{k}_3 is vacuum permeability; $H_0^{(2)}(\dot{k}_3 \times r)$ is the zero-order Hankel function of the second type.

The conductivity coefficient depends on the acoustic field intensity:

$$\lambda_a = \lambda_0 + A I(r), \text{ if } I(r) \geq I_{kp}, \text{ or } \lambda_a = \lambda_0, \text{ if } I(r) < I_{kp},$$

where λ_0 is the conductivity coefficient in the absence of an acoustic field; A is an experimentally defined small parameter; $I(r)$ is the acoustic field intensity; I_{kp} is the acoustic field intensity required to increase efficient conductivity (e.g. for sandstone $I_{kp} = 700-900$ W/m²):

$$I(r) = (N_{a0} / (2 \times \pi \times r_0 \times h)) \times (\text{Re}\{j \times \dot{k}_a^* \times H_0^{(2)}(\dot{k}_a \times r_0) \times H_1^{(2)*}(\dot{k}_a^* \times r_0)\} / (\text{Re}\{j \times \dot{k}_a^* \times H_0^{(2)}(\dot{k}_a \times r_0) \times H_1^{(2)*}(\dot{k}_a^* \times r_0)\})).$$

In the light of the above-mentioned and relying on the experience gained as a result of pilot industrial tests, it can be concluded that the induction system has a number of advantages over the normal resistance (on the basis of thermal electric heaters of tubular heating elements or a heating cable) and steam heating, which is consistent with the conclusions in [20-21]. These are cost-effectiveness, speed, and depth of warming, safety, durability, and reliability.

3. Thermo-acoustic inductor device design

The authors took part in a project to create thermostat inductor ISS-120 for the transmission of electromagnetic and acoustic energy to the heated facility. The device is an electrical conductor with an insulating material that meets the requirements of heat resistance in the specified modes of heating the housing. Its shape thus repeats the shape of the heated object. The temperature of the inductor is close to the ambient temperature and practically does not depend on the heated object temperature (with the calculated thermal insulation from the heated object). The device (Fig. 2) is intended for the hydrocarbons production (oil, bitumen, etc.) with higher than average viscosity and for cleaning the well from the asphalt-resin and paraffin sediments. It is executed in the form of a module. Depending on the design of a well and formation thickness, one or more modules, connected in series, can be used.

The thermoacoustic inductor converts high-frequency currents into a thermal and acoustic field. The thermal field is generated by shielding a high-frequency electromagnetic field produced by current-conducting veins by the armor of the cable. The acoustic field is formed due to the magnetic-striction effect, based on the linear dimensions of the material change under the electromagnetic field influence. This effect is formed in the armor of the cable under the electromagnetic high-frequency pulses influence. The linear dimensions of cable changing (7) drive flange (3), deforming springs (5) and thus compensates for the increase in the linear dimensions of the cable during the heating process. The surface of flange (3) emits an acoustic field that propagates into the oil reservoir. Under the influence of an elevated temperature and under the acoustic pulses influence, the hydrocarbons filling the reservoir reduce viscosity and increase their own mobility. This increases the oil recovery. The device is delivered and installed in the formation interval by means of the tubing string or using cable by geophysical crews.

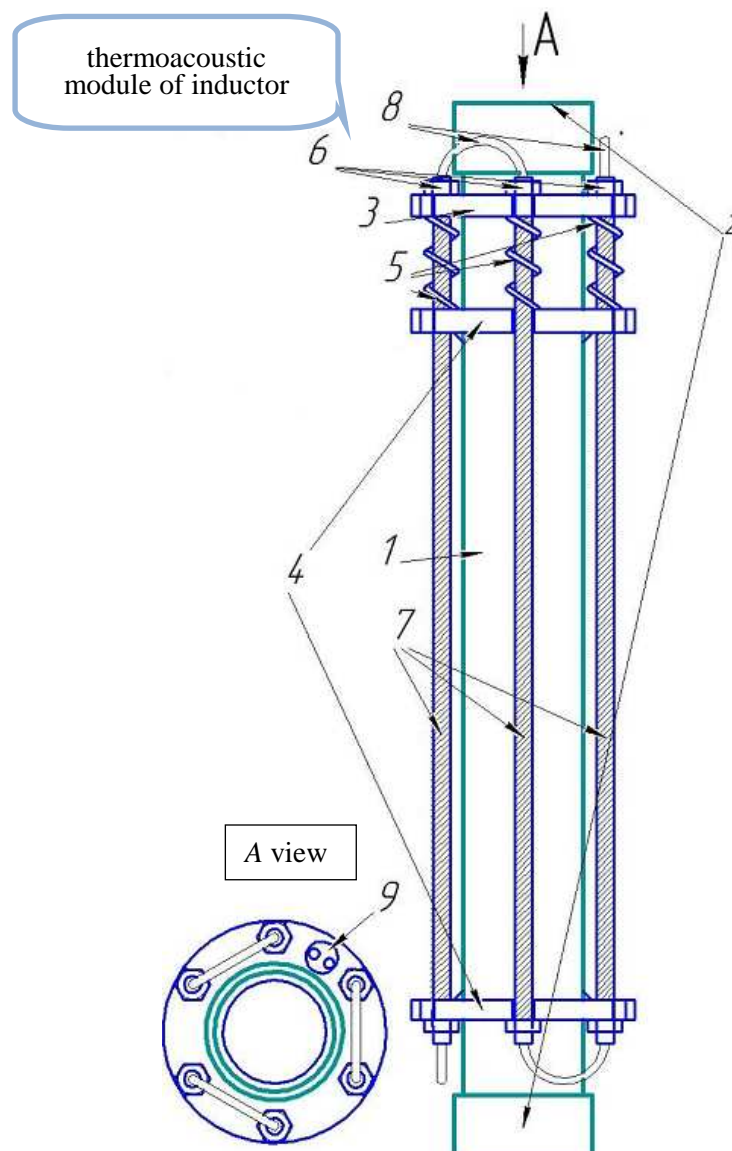


Figure 2. Thermoacoustic inductor design:

1 – metal pipe with a diameter of 3 or 2.5 inches; 2 – couplings for fastening to the tubing and to another module; 3 – movable flange sliding on pipe 1; 4 – flanges fixed on tube 1; 5 – springs; 6 – nuts to adjust cable-to-cable tension 7 by compressing spring 5; 7 – double armored multicore logging cable; 8 – connecting wires (conductive cores of the cable); 9 – connector to connect to the power cable.

The device is operated by a high-frequency current generator on the surface.
High-frequency currents are transmitted via a power cable to slot (9).

Table 1. Technical characteristics of thermoacoustic inductor

Product Name	Oil-well string inductor (ISS-120)
Induction heating cabinet type	UINS-50
Maximum converter frequency, kHz	22.0
Maximum power, kW	200.0

Voltage at exit inverter, V	530.0
Secondary-winding voltage, V	5000.0
Continuous heating time, days	3-10
Cable outer diameter	12.30
KG7×0,75-75-90 (-150, -200, -260), mm	

When high frequency is applied to the strings, the vaporization process and subsequent collapse of vapor bubbles in the liquid flow occur, accompanied by noise and hydraulic shocks, thereby causing a cavitation-acoustic effect on the oil reservoir, increasing oil inflow.

4. Conclusion

A study of the distribution theory of electromagnetic and acoustic waves showed that:

- for the best impact on the reservoir, it is necessary to calculate the optimum power and frequency values of wave emitters;
- the acoustic field is more efficient for the thermal well treatment than the high-frequency electromagnetic field in the near-by zone;
- absorption of the acoustic waves occurs in the vicinity of wells due to the large absorption factor in the saturated porous medium, and this means that the thermal sources are located mostly near the well, thus causing the rapid heating of the wells;
- with a greater initial production rate, the rise in temperature at the bottom is slowed down, as along with the extracted oil, the heat released by the acoustic and electromagnetic waves absorption is also carried away.

Comparison of the thermoacoustic inductor characteristics with the existing resistive and steam technologies has shown that the developed device has the following advantages:

- the capital costs for the installation of induction heating systems and their operation are lower than those of resistive systems and heat tracers;
- the starting capacity does not exceed the working power capacity;
- the cost of the inductor cable consumables is a few times lower than the corresponding cost of the heating cable per 1 meter;
- high efficiency coefficient provides low operating costs;
- durability due to the fact that the cable itself does not contact the heated surface and is not a source of high temperature;
- the induction heating system control cabinet is made using modern technologies and allows remote control and heating control, as well as combining its operation with distributed control and emergency protection systems.

5. Acknowledgments

The results of the studies were confirmed by experimental-industrial tests certificates of the ISS-120 thermoacoustic inductor at the JSC Tatoylgaz facilities in 2017. After the thermoacoustic treatment, the well was commissioned with a production rate of 90 tons per day. Then the production rate dropped first to 60 tons per day, and then - to 30 tons per day. On some days, the flow rate increased to 70 tons per day, which gave grounds for assumptions about incomplete well development after treatment. As a result of thermoacoustic treatment, more than 2 thousand tons of oil was additionally recovered on the well.

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