

## Improvement of Efficiency of Steam-Thermal Treatment of High-Viscous Oil Formations Using Downhole Electric Steam Generators

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### ABSTRACT

The presented work investigates a method for developing hard-to-recover hydrocarbon reserves based on a downhole electrothermal steam generator, which is distinguished by energy efficiency, resource conservation and environmental safety. The paper presents an overview of downhole electro-thermal equipment that improves the quality of thermal treatment of the bottom-hole zone of high-viscous oil formations by separating steam in an electric steam generator and increasing its dryness, wherein thermal energy in the oil-formation medium affects all its components and completely changes ties and filtration conditions. This is expressed in a decrease in the viscosity of oil, its increased mobility, weakening of structural-mechanical properties, improvement of the conditions for capillary imbibition, and, as a result, an increase in the displacement factor and the final oil recovery. A simulation of the reservoir temperature field was performed by setting the heat flow in the ANSYS software package to understand the thermal processes in the steam generator and to more accurately determine the necessary heating parameters for a given water flow rate. The temperature field of the reservoir simulation after the heat treatment of the bottom-hole zone was conducted in the software package Femlab 3.5. The proposed simulation models can help in the development of the physical model and further research. This technology is environmentally friendly and does not emit emissions into the atmosphere.

**Keywords:** high-viscous oil, steam generator, oil recovery, thermal treatment, environmental safety.

### INTRODUCTION

The demand of the modern world for energy is constantly growing, which entails environmental problems associated with a decrease in natural resources (Litvinenko 2020; Oberle et al. 2019; Makhovikov et al. 2019; Zuev et al. 2019; Rogachev 2019). At present, the rational development of widespread useful high-viscosity oils is of particular importance, the explored reserves reach 700 billion tons (Alekseev et al. 2017). International experts have recognized thermal methods of influencing productive strata of high-viscosity oil as non-alternative methods of oil recovery (Pang et al. 2019; Zyrin et al. 2016;). That is why there is an increased interest of the scientific community in methods of enhanced oil

recovery of oil reservoirs as the most energy efficient and resource-saving.

The disadvantages of modern thermal methods for high-viscous oil recovery include high material and capital intensity of heat-power equipment, waste of thermal energy in the distribution pipeline system and in the well, as well as a decrease in the process efficiency due to the combustion of part of the produced oil or gas in steam generators and significant environmental degradation in oil production areas (Gilmanov et al. 2017; Kadyrbekova et al 2015; Suchkov 2007; Antoniadi, et al. 2000; Khisamov et al. 2014).

One of the promising directions for the development of thermal methods for oil recovery is the development of down-hole electric steam generators (ESG), which differ in that they do

not emit harmful substances into the atmosphere, in contrast to traditional technologies (Zagrivnyi et al. 2011; Litvinenko et al. 2006; Kopteva et al. 2018). The developed downhole electrothermal properties have relatively low metal and capital capacity. An electrothermal complex based on a downhole electrode heater, designed for thermal impact on a productive formation of high-viscosity oil, which allows performing technological operations on steam-thermal, pulse-dosed thermal plastic and thermohydrodynamic impact on the bottomhole impact zone. The mode of thermal steam treatment is implemented at a given consumption of thermal energy and boiler water, which provide a certain amount of steam in the zone of the productive formation. The mode of impulse-thermal exposure is provided by alternating impulses of steam-thermal exposure and the supply of boiler water with increased hourly costs.

The main mode of operation for such devices is a long-term mode (10–20 days) of operation with a heat flux providing boiling of the reservoir fluid at a pressure of the heat carrier injection into the reservoir under the following modes:

- without supplying water from the surface (heating the reservoir fluid);
- with supplying water from the surface in the mode, which is equivalent by power consumption to steam injection at the set parameters (for example, when the ESG operates with electrical and thermal capacities of 1 MW and water is supplied from the surface with an hourly flow rate of 3 tons, which is equivalent to injecting 3 tons of steam with a dryness of 0.8 );
- pulse-dosed and thermo-hydrodynamic thermal treatment of the bottom-hole zone of the well.

Since the duration of entering into the operating mode is negligible compared to the steady-state mode, the steady-state mode of the ESG operation is subjected to further consideration.

The previously proposed methods for thermal treatment of reservoir using downhole ESG have a number of disadvantages in terms of efficiency, since they failed to improve the quality of the produced steam (dryness), which resulted in the reduced efficiency of thermodynamic treatment of producing reservoirs and an increase of its water flooding (Belsky et al. 2020; Kopteva et al. 2018; Pang et al. 2019).

## MATERIALS AND METHODS

The design of the device for thermal treatment of the bottom-hole zone of the well, located in the zone of the producing reservoir inside the production casing 1, includes a downhole electric steam generator-separator (Figure 1), which is mounted at the end of the tubing string 18. The ESG consists of a metal housing 2, made in the form of a cylinder and being a zero electrode 14. The central current lead 3, having a heat-resistant insulating shell 4, is fixed in the upper part of the housing 2 through the bushing 19; condensate collectors 5 in the form of steel rings are located on the inner surface of the housing. Inside the housing 2, on the current lead 3, phase electrodes 6, spaced evenly one above the other, separated by tubular heat-resistant insulators 4, are mounted height along; each phase electrode is made in the form of a multiple-thread screw with a blade attack angle of 30°-35°, wherein the blades are used for swirling the flow around the axis in order to obtain the tangential component of velocity and steam separation.

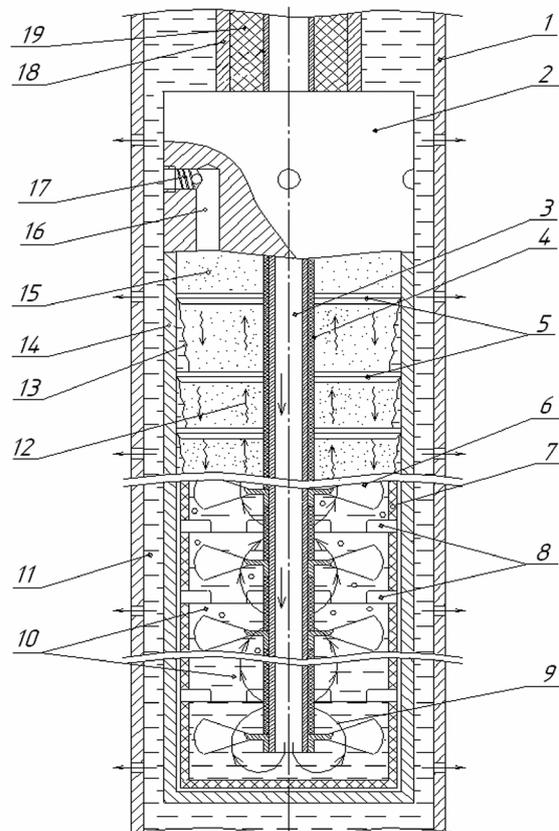
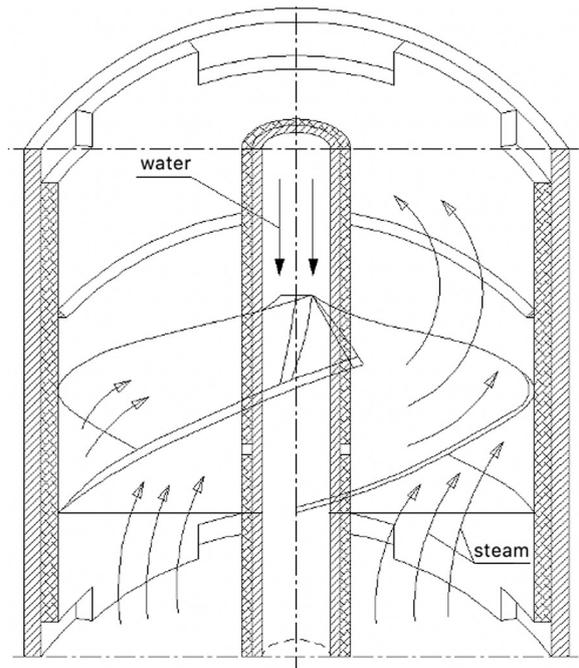


Figure 1. The design of the electric steam generator-separator

The electrode spacing is determined by power of the device, the supply voltage, the surface current density and the specific resistance of the current conductive fluid (Kuchin et al. 2020). Each phase electrode is placed in a fluoroplastic ceramic cup having a sidewall 7 and current conductive windows 8. The upper part of the housing, free of phase electrodes and forming the steam zone 15 of the electric steam generator, comprises a steam outlet channel 16 with a valve 17.

Due to the flow of electric current between phase electrodes and the housing, the working fluid is heated with subsequent boiling and the formation of steam 12, which in the process of vertical motion acquires the tangential component of velocity, which results to swirling of the steam-water mixture, via phase electrodes 6, around the central axis of the electric steam generator, separation of steam and its discharge through the steam outlet channels 16 with the valve 17 into the zone 11, filled with downhole fluid, wherein the condensate 13, arising as a result of condensation and separation of the steam-air mixture and precipitating on the inner surface of the housing 2 of the ESG, is delayed by the condensate collectors 5. Boiling and steam generation results to heat exchange between the wall 14 of the housing 2 of the electric steam generator and downhole fluid 15. Feeding with boiler fluid is performed through the central current lead 3.

Due to the fact that phase electrodes are made in the form of a multiple-thread screw with a blade attack angle of about  $30^\circ$ , the leaving steam-water mixture is swirled around the flow axis (Figure 2). This results to the separation of the mixture along the radial component. The central steam zone will have a greater dryness  $\gamma$  (Figure 3) than the peripheral zone, since due to the tangential component of velocity, the suspended, larger micro-drops will be carried to the periphery, where they condense, are delayed by steel rings of condensate collectors and flow back to the boiling zone. The curves in Figure 3 show the nature of the change in the dryness of steam as it moves from the boundary with the heating zone (line 1), in the central part of the steaming zone (curve 2) and at the outlet of the ESG (curve 3). The condensate collectors, fixed on the inner surface of the electric steam generator, hang over the outer edges of phase electrodes and serve as impact resistant louvers. When steam flows through the curved channels of such louvers, centrifugal accelerations occur.



**Figure 2.** The nature of the steam-water mixture motion in the upper part of the ESG

The value of these accelerations can be quite great, which to a certain extent determines the operating efficiency of the louvered separators. In particular, with a radius of curvature of the condensate trap  $r = 1$  cm, a steam velocity of  $v = 5$  m/s, which corresponds to the field conditions of the ESG operation, the particle acceleration makes about  $2500 \text{ m}^2/\text{s}$ .

As of the steam volume of the ESG, the known law of fluid resistance that acts on balls that are moving through a fluid can be used with a reasonable degree of accuracy (Figure 4). According to this law, the force necessary for moving particles of water with a diameter of  $d$ , at a uniform radial velocity of the particle  $v_r$ , is expressed by the dependence:

$$F_c = 3\pi\mu_s v_r d \quad (1)$$

where:  $\mu_s$  is the dynamic viscosity of steam.

Equating the force  $F_c$  to the effect of the centrifugal force on the moving particle of water and making the appropriate transformations, we find the time needed to separate the particles of water, the farthest removed from the separator wall, and taking into account that over the specified time period the particles are raised up with a certain average axial lifting velocity  $v$  to a height of  $H_c$ , we obtain the final expression for assessing the height of the separation zone of the ESG:

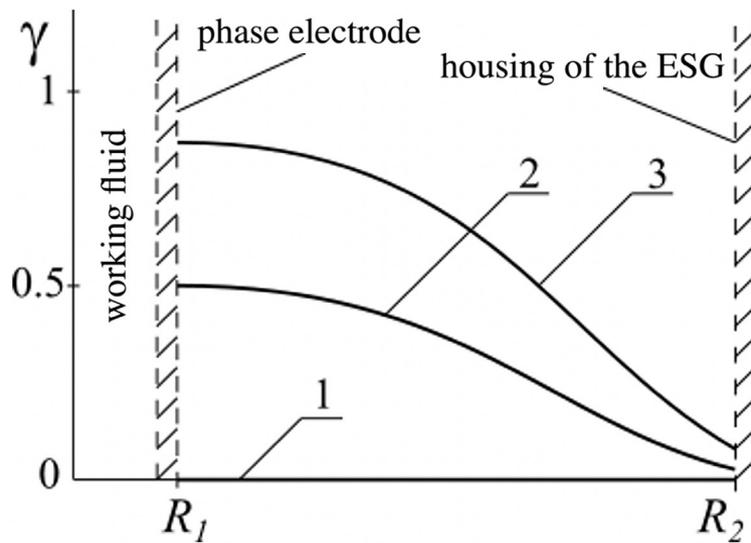


Figure 3. The dependence of steam dryness over the ESG cross-section in the separation zone

$$H_c = \frac{18g\mu_s v \ln\left(\frac{R_2}{R_1}\right)}{(\rho_w - \rho_s)d^2\omega^2} \quad (2)$$

where:  $\rho_w$  and  $\rho_s$  are the densities of water and steam;

$\omega$  – the angular velocity of a particle,

$R_1$  is the outer radius of the insulating shell of the tubular current lead,

$R_2$  is the inner radius of the housing of the electric steam generator.

## RESULTS AND DISCUSSION

Under actual operating conditions of the Usinsk deposit (Usinsk, Russia), when the electrode spacing in the separation zone is 0.2 m,  $H_c$  makes about 2 m. Taking into account the heating zone, the total length  $H$  of the ESG should be at

least 5 m. Having conducted the studies, it was found that the dryness of the steam at the outlet of the ESG reaches 0.8–0.9.

When operating this kind of electro-thermal devices, it is necessary to consider the thickness of a producing reservoir of high-viscous oil, which can reach 20 m or more. In this case, in order to improve the efficiency of bottom-hole zone heating, it is permissible to increase the length of the ESG by several meters, which makes it possible to produce steam of higher quality by introducing additional phase electrodes in the separation zone. To remove saline deposits formed on the inner surfaces of the ESG, it is necessary to “blow-off” the ESG from the inside with hot water once a day for a minute, while reducing the power supply by means of the current controller.

Thus, the main advantage of the proposed electric steam generator-separator is an increase in dryness of the produced steam, wherein thermal

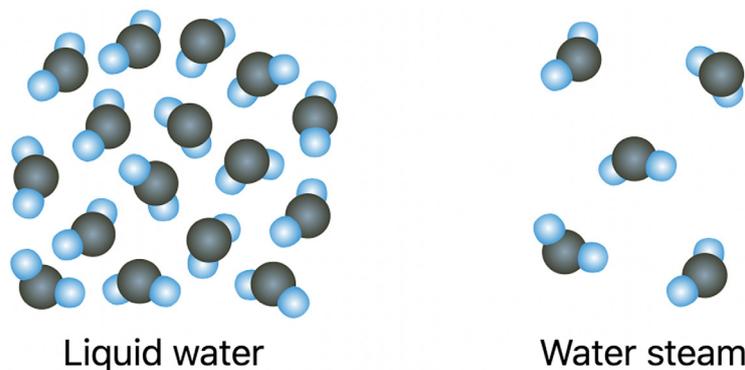


Figure 4. Arrangement of water molecules in liquid (water) and gaseous states

energy in the oil-formation medium affects all its components and completely changes ties and filtration conditions, which is expressed in a decrease in the viscosity of oil, its increased mobility, weakening of structural-mechanical properties, improvement of the conditions for capillary imbibition, and, as a result, an increase in the displacement factor and the final oil recovery. Owing to the design features of phase electrodes, as a result of the separation of the steam-water mixture, steam with a higher degree of dryness and, accordingly, of higher quality enters the reservoir, thereby increasing the efficiency of thermal treatment of wells.

A simulation of the reservoir temperature field was performed by setting the heat flow in the ANSYS software package (Figure 5) to understand the thermal processes in the steam generator and to more accurately determine the necessary heating parameters for a given water flow rate. Dependence of heat flux on material conductivity is:

$$q_v(T) = \frac{U^2}{R_i(T)} \cdot \frac{1}{V_i} = \frac{2S_{ef} \cdot U^2}{\rho(T) \cdot l} \cdot \frac{1}{S \cdot \gamma \cdot G} \quad (3)$$

where:  $U$  is the voltage;  
 $l$  is the phase electrodes length;  
 $S$  is the the phase electrodes cross-section area;  
 $T$  is the temperature;  
 $S_{eff}$  is the effective cross-sectional area of the conductive part of the working fluid in the interelectrode gap with electrical resistance  $\rho(T)$ ;  
 $\gamma$  is water density;  
 $G$  is the volumetric flow rate.

You can notice a decrease in temperature at the water-steam boundary due to conductivity decreasing in the steam zone. Experimental studies of the dependence of the resistance of the working fluid  $\rho(T)$  on various concentrations  $C$  of an aqueous solution of NaCl, which are well approximated by the following formula:

$$\rho(T) = A \cdot e^{-BT} \quad (4)$$

where the coefficients  $A$  and  $B$  are given in Table 1.

Based on the simulation results, the optimal value of the thermal power was obtained which amounted to 2 MW for generating steam with a calculated quality of wet vapor was 0.8.

The temperature field of the reservoir simulation after the heat treatment of the bottom-hole zone was conducted in the software package Femlab 3.5 (Figure 6). It is proposed to enter a horizontal heating well with a downhole steam generator to the existing complex of bottom-hole zone treatment of the extractive horizontal well with steam to increase the crude production by reducing oil viscosity (Figure7).

The mathematical model of the reservoir is based on boundary conditions and the following system of equations:

$$\begin{cases} \lambda_f \cdot \frac{\partial^2 T}{\partial z^2} - u \cdot \rho_c \cdot \lambda_c \frac{\partial T}{\partial r} = \rho_f \cdot c_f \cdot \frac{\partial T}{\partial t}; \\ \omega_0 = -\frac{k \cdot k_0}{\mu_0} \cdot \frac{dp_0}{dr} . \end{cases} \quad (5)$$

where:  $\lambda_f$  is the field heat conductivity;

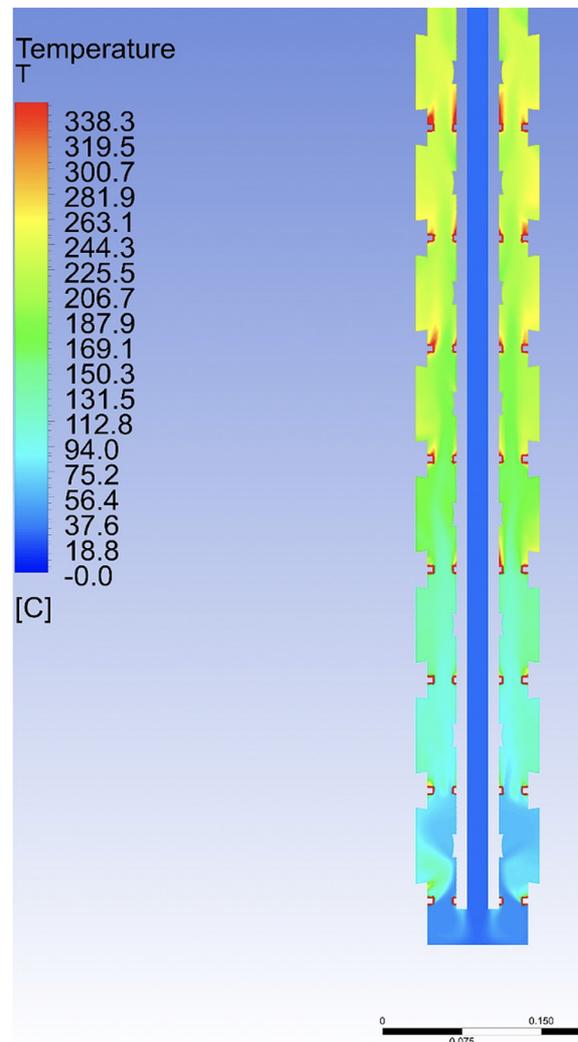


Figure 5. Modelling the reservoir temperature field in the ANSYS software package

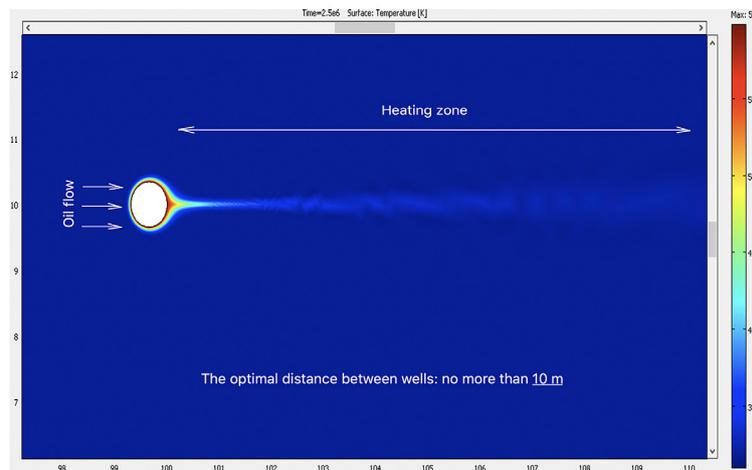
$\rho_f$  is the density of the of reservoir rocks;  
 $c_f$  is the heat capacity of reservoir rocks;  
 $u$  is the filtration rate of fluid (oil) in a field;  
 $k$  is the absolute permeability;

$k_o$  are relative phase permeability of oil and water;  
 $\mu_o$  is viscosity of oil and water in reservoir conditions;  
 $p_o$  is pressure in the oil and water phases.

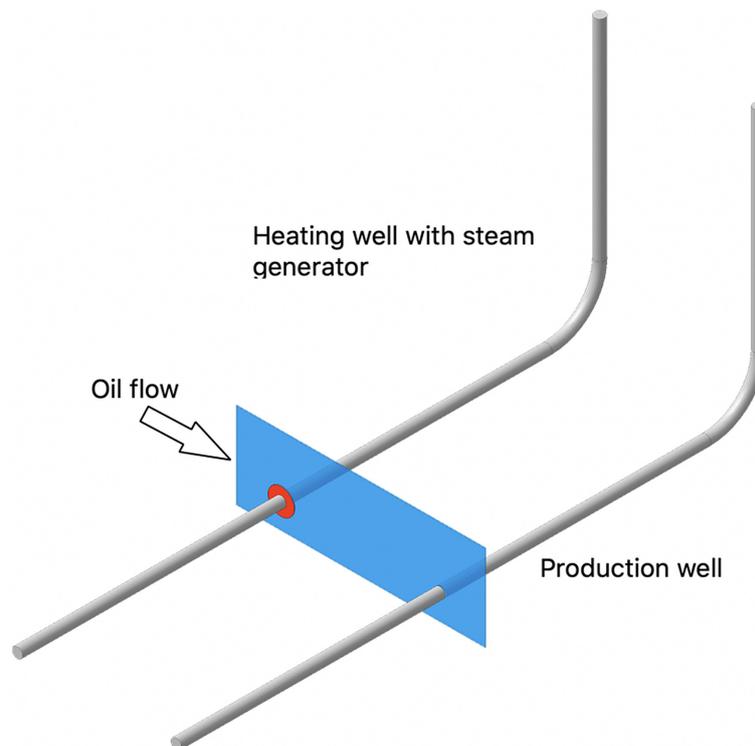
**Table 1.** The coefficients A and B

C, %	A, Ohm·m	B, 1/K
6	0.898	0.012
10	0.602	0.012
12	0.45	0.01

Based on the results of reservoir modeling, the optimal distance between wells was determined, which is less than 10 meters (Figure 8). This distance accounts for half of the reservoir depression (the pressure at which the fluid moves from the reservoir to the wellbore).



**Figure 6.** Modelling the temperature field of the reservoir in the Femlab 3.5 software package



**Figure 7.** The proposed complex of treatment of the bottomhole zone of a production horizontal well with an additional horizontal heating well with a steam generator

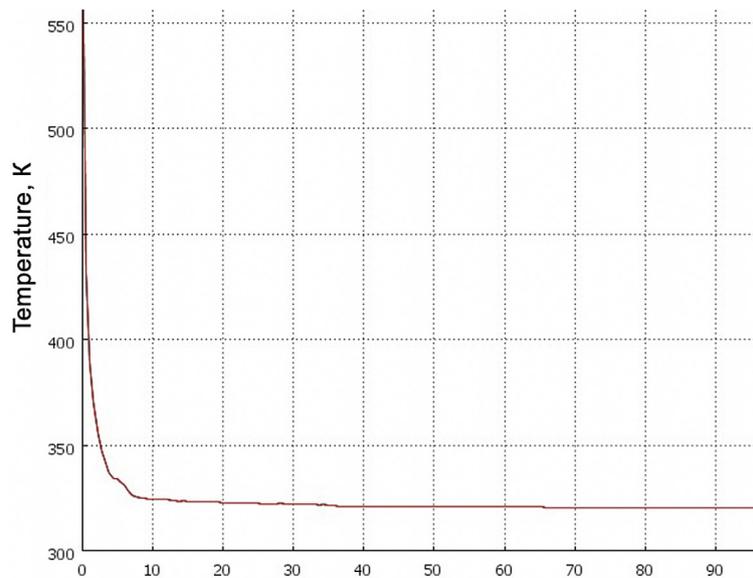


Figure 8. The temperature dependence on the distance between wells

## CONCLUSION

The use of thermal methods is directly related to fuel and energy costs. Combustion of oil, used in the traditional method, results in atmospheric pollution. The use of electrothermal equipment can solve this problem. The well development process becomes environmentally friendly and less costly. Automation of the process greatly simplifies the work.

The proposed design of the electric steam generator allows to increase the oil recovery of the reservoir, and also provides an additional positive effect after thermal treatments. The electric steam generator has some other advantages, such as: mobility, working with minimum water conditioning and oil pool development located in nature-protected areas that are difficult to access. Down-hole ESG with a supply voltage of 6 kV and a frequency of 50 Hz makes it possible to obtain thermal capacity up to 1 MW and, due to better steam-thermal treatment, ensures the restoration of hydraulic connection between the reservoir and the well, increased oil recovery of high-viscous oil and production rate of wells, as well as restoring the operation of unprofitable wells for oil, natural gas, fresh, mineral and thermal waters.

The proposed simulation models can help in the development of the physical model and further research.

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