Thermal oil recovery method using self-contained wind-electric sets

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Abstract. The paper reviews challenges associated with questions of efficiency of thermal methods of impact on productive oil strata. The concept of using electrothermal complexes with WEG power supply for the indicated purposes was proposed and justified, their operating principles, main advantages and disadvantages, as well as a schematic technical solution for the implementation of the intensification of oil extraction, were considered. A mathematical model for finding the operating characteristics of WEG is presented and its main energy parameters are determined. The adequacy of the mathematical model is confirmed by laboratory simulation stand tests with nominal parameters.

1. Introduction

A reduction of high-gravity oil reserves is a worldwide trend. In the context of a decline in the production of high-gravity oil, the exploitation of widespread hard-to-recover high-viscosity oil is a highly important process [1]. World reserves of high-viscosity oil are several times higher than high-gravity oil. The Russian Federation occupies the third place after Canada and Venezuela in terms of hydrocarbon extraction.

In the natural mode of operation of wells with high-viscosity oil, the percentage recovery does not exceed 6-15%. Thermal methods of impact on productive strata are recognized as one of the most effective ways to improve oil recovery. Modern thermal technologies involve the combustion of a part of the extracted hydrocarbons (either due to their combustion, or on the surface in boilers to produce superheated steam or hot water) for their extraction with a positive balance. Despite the improvement of the methods, indicators such as the oil recovery factor, the environmental impact and the rational use of resources, cannot be considered as acceptable.

It is possible to increase the effectiveness of thermal effects by using of electrothermal complexes in which thermal energy is generated directly in the bottom-hole area, thereby reducing losses, both at the stage of its extraction and delivery. Electrothermal complexes, in comparison with traditional technology, have the following advantages: energy saving, low metal consumption and capital intensity, simplicity of design; environmental safety of technology [3, 6, 8].

A significant problem of increasing the high-viscosity oil extraction is the high cost of extracted hydrocarbons due to imperfections in the technology of extraction’s intensification. One of the problems which makes the extraction of oil more complicated, especially high-viscosity and paraffinic, is the formation of paraffin deposits (PD) on the walls of tubings, wellheads and pipelines. The accumulation of PD in the flowing part of the oilfield equipment and on the inner surface of the
pipes reduces their throughput diameter, reduces the system's productivity, leads to frequent stops for cleaning or even replacement of pipes and equipment, reduction of the repair interval, accidents and decrease in the efficiency of pumping units increasing the cost of production. Paraffin deposits are also a source of environmental pollution. The most intensive formation of PD occurs on the inner surface of the lifting pipes of the well. Similar complications are inherent in virtually for the entire oil extraction industry of Russia with some special features in terms of the predominant content of the PD at each deposit. Paraffin deposits increase the specific energy costs for missing the set oil flow rates, and also increase the hydraulic resistance of pipelines, reducing their productivity [9].

The distance between extraction sites and the centralized energy supply system complicates the task of efficient use of electrothermal heat treatment technologies to control the PD and increase the efficiency of extracting high-viscosity oil by using downhole electric heaters and electric steam heaters.

### 2. Circuit engineering design

There are several possible circuit-based solutions for the creation of electrothermal complexes for the thermal method of intensifying oil extraction using wind electric generators [2, 5, 7].

1. An electrothermal complex for the thermal treatment of the well bottom-hole area by an electric borehole heater (Fig. 1, a). This method is suitable for the extraction of heavy viscous oils or oils with a high content of paraffin and asphalt-resinous components. The operation principle is as follows: the generated by the wind electric generator set electric power through the rectifier goes to a downhole heater (its power is from 3 to 50 kW) located in the bottom-hole area. In order to control the heating process, it is proposed to use a temperature sensor mounted on a downhole heater.

   Advantages of this concept are [4]: the use of an autonomous power source in the form of a wind electric generator, connection to centralized electrical networks is not required, direct impact on the oil reservoir or PD in the composition of oil without the use of an intermediate coolant, absence of complicated and expensive systems of management. The disadvantage is uneven thermal impact on the productive stratum of heavy viscous oil, which can lead to significant fluctuations of well flow rate during the extraction.

2. A wind electric generator for heat treatment of the wellbore by an electric heating cable (Fig. 1, b). This method is also suitable for the extraction of oils with a high content of paraffin and asphalt-resinous components. The operation principle is as follows: the generated by the wind electric generator electric power through the rectifier goes to the heating cable (specific power from 40 to 80 W/m) which is located inside the well along its entire length. In order to control the heating process, it is proposed to use a temperature sensor installed at the wellhead.

   Advantages of this concept are [4]: use of an autonomous power source in the form of the wind electric generator, connection to a centralized electrical network is not required, direct impact on the PD in the composition of oil along the entire length of the well without the use of an intermediate coolant, absence of complicated and expensive systems of management. The disadvantage is the high cost of the heating cable.

3. A wind electric generator (Fig. 1, c) for the steam-thermal treatment of the well bottom-hole area. This method is suitable for the extraction of heavy high-viscosity oils. The operation principle is as follows: the generated by the wind electric generator electric power through the rectifier goes to the heating element (the power is from 100 kW) of the system of water preheating of a stationary terrestrial steam generator. In order to control the heating process, it is proposed to use a temperature sensor installed in the water preheating section of the steam generator.

   Advantages of this concept are: organic fuel (gas or fuel oil) saving during the production of steam, the lack of complicated and expensive systems of management. The disadvantage is the restriction on the depth of the oil reservoir occurrence (no more than 1300 m), the high cost of generation of thermal energy from the electric generator.

4. A perspective electrothermal complex for steam-thermal treatment of the well bottom-hole area (Fig. 1, d). This method is suitable for the extraction of heavy high-viscosity oils and gas hydrates.
The operation principle is as follows: the generated electric power by the wind electric generator through a rectifier goes to heating element (the power is from 300 kW) of the well bottom-hole electric steam generator. In order to control the heating process, it is proposed to use a temperature sensor installed on the steam generator.

Advantages of this concept are [4]: use of an autonomous power source in the form of a wind electric generator, connection to a centralized electrical network is not required, direct impact on the oil reservoir or gas hydrates, generation of steam directly in the well, no restrictions on the depth of occurrence of the oil reservoir. The disadvantage is the complexity of control systems.

All the generated electricity of the wind electric generator is expended on the production of thermal energy, while the degree of heating depends on the current wind conditions. This operating mode is applied in case of the control system maximum efficiency of the wind electric generator turbine operation in the given wind conditions operating mode [2]. In the case of oil overheating, by the signal from the temperature sensor, the installation is temporarily turned off.

**Figure 1.** Complexes for the thermal method of intensification of oil extraction with the use of wind electric generators: 1 - wind-driven power unit; 2 - AC power cable; 3 - three-phase diode rectifier; 4 - DC power cable; 5 - control cabinet; 6 - temperature sensor; 7 - cable from temperature sensor; 8 - above-ground wellbore valves; 9 - wellbore; 10 - piping; 11 - well downhole heater; 12 - heating cable; 13 - above ground steam generator; 14 - pre-heater system of water; 15 - packer; 16 - water pump; 17 - well bottom-hole electric steam generator.

3. **Modeling of the work of the wind electric generators in the composition of the electrothermal complex**

To find the working energy characteristics of the wind electric generator, as a function of the thermal
power of the heat released by heat element from the wind speed at various load resistances, a computer model was created in the Simulink MatLab System, shown in Fig. 2.

![Computer model by Simulink MatLab System](image)

**Figure 2.** Computer model by Simulink MatLab System

The model consists of several basic units: a synchronous generator with permanent magnets (SGPM), a three-phase diode rectifier (bridge), load, measurement complex. The determined parameters of SGPM are: armature inductance ($5.2 \times 10^{-3}$ H), stator phase resistance $R_s$ (0.06 Ohm), flux linkage established by magnets (0.19292 V.s.). Parameters of the power uncontrolled rectifier are: snubber resistance $R_s$ ($1 \times 10^5$ Ohms); $R_{on}$ ($1 \times 10^{-3}$ Ohms). The load parameters during the experiments were varied.

The parameters of the SGPM model were determined on the basis of the results of the series of experiments performed at the laboratory simulation stand (Fig. 3). Verification of the model parameters was carried out on the basis of additional series of experiments.

![Simulation stand](image)

**Figure 3.** Simulation stand
The operation of the wind wheel was modeled with a three-phase asynchronous motor (1) with rated parameters: 7.5 kW, 50 Hz, 380 V, 1450 r/min. The induction motor (1) was controlled by a frequency converter (2) with a rated output of 15 kW. In the simulation stand, as in the real wind electric generator, a direct torque transfer between the engine (wind wheel) and the generator is used. The generator (3) is a three-phase synchronous machine with permanent magnets with nominal parameters: 4 kW, 100 Hz, 400 r/min. The stand includes a three-phase diode rectifier (4) and a load block in the form of active resistances (5) with dissipated thermal power up to 6 kW, as well as measuring equipment (7).

During the experiments on the simulator, the dependencies of the heat output on the load in the entire operating range of the rotor speed from 50 to 500 r/min with different load resistances were obtained.

To calculate the amount of energy generated by the wind electric generator in the electrothermal complex, it is necessary to determine the wind conditions. For Russian Federation, according to the wind atlas, the range of average annual wind speeds from 4 m/s to 9 m/s is optimal. For calculations of Weibull probability density function, the following expression was used:

$$f(x; \lambda; k) = \begin{cases} \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{k-1} & x \geq 0, \\ 0 & x < 0. \end{cases}$$

where \(x\) - the value, for which the wind speed function is calculated; \(\lambda\) - scale parameter; \(k\) - form parameter.

The scale parameter is close in value to the average wind speed and is calculated as \(\lambda = 1.28 V_{mid}\), where \(V_{mid}\) - average wind speed (m/s). The most common value of the form parameter \(k\) for the regions of Russia is 1.25 and 1.75.

The operating range of wind speeds for most wind electric generators is in the range from 3 m/s to 25 m/s. The total amount of energy \(W\) is calculated as:

$$W = \sum_{v=3m/s}^{v=25m/s} w$$

where \(w\) - the amount of energy produced at a specific wind speed (kW·h).

To calculate \(w\), the following expression was used:

$$w = P \cdot t \cdot f(x; \lambda; k)$$

where \(P\) – the power of the wind electric generator at a given speed (kW); \(t\) - number of hours per year (h); \(f(x; \lambda; k)\) – Weibull probability density function.

Calculation of the coefficient of use of the installed capacity of the wind electric generator (\(K_p\)) was carried out according to formula (4) for two options: with a constant (optimal) resistance of the load element converting electricity into heat and when it is regulated. Calculations are made according to form parameter \(k\):

$$K_p = \sum_{v=3m/s}^{v=25m/s} \frac{w}{P \cdot 8760}.$$

When adjusting resistance, depending on the current wind speed, more energy is released than with a constant resistance, and at \(k=1.25\), an increase of 5-9% is observed depending on the average annual wind speed, at \(k=1.75\) the gain is 4-12 %. The values of the energies released per year are shown in Fig. 4.
Form parameter \( k \) (wind speed distribution by gradation) has a strong effect on the efficiency of the wind electric generator in the electrothermal complex at low (4-5 m/s) and high (7-9 m/s) average annual wind speeds. The difference between the obtained energy values for different parameters \( k \) reaches 20%.

![Figure 4](image)

**Figure 4.** The amount of electric power generated by the wind electric generator depending on the average annual speed for various parameters of form \( k \)

4. Conclusion
In the given paper, new circuit-based solutions for the creation of electrothermal complexes for the thermal method of intensifying oil extraction using wind electric generators are suggested. The use of the proposed complexes is especially important for deposits, which are remote from the centralized power system or in case of electrical power shortage.

A computer model that makes it possible to evaluate the efficiency of the operation of wind electric generators at various load resistances, taking into account variations in wind conditions (average annual wind speed and wind speed distribution by gradation), is developed by authors. The adequacy of the computer model is verified on a laboratory simulation stand. A comparison is made between the amount of generated electric power and the constant resistance of the load and its stepwise regulation.

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