Autonomous Electrothermal Facility for Oil Recovery Intensification Fed by Wind Driven Power Unit

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Abstract. This paper describes the structure of autonomous facility fed by wind driven power unit for intensification of viscous and heavy crude oil recovery by means of heat impact on productive strata. Computer based service simulation of this facility was performed. Operational energy characteristics were obtained for various operational modes of facility. The optimal resistance of heating element of the downhole heater was determined for maximum operating efficiency of wind power unit.

1. Introduction

Global trend is in the decrease of light crude oil deposits, therefore exploitation of widely spread deposits of difficult to recover viscous and heavy crude oil becomes important. World reserves of such oil exceed reserves of light crude oil several times. Russia is on the third place in the world after Canada and Venezuela by deposits of heavy crude oil.

Naturally the recovery from the heavy crude oil well does not exceed 6–15%. Thermal impact on oil productive strata is one of most efficient ways to increase the recovery. Conventional methods such as injection of saturated superheated vapour, dissolvent, hot water or oil are not always successful and economically efficient. New approaches based on electrothermal impact of heating cable or downhole heater provide effective alternative to conventional methods [1, 2].

For the case of electrothermal facility the heating of oil stratum is provided by the downhole heater located directly in the well bottom zone inside of oilwell tubing. By means of thermal impact, an integral result in stimulation of oil recovery is achieved. The viscosity of oil is decreased and subsequently the recovery ratio is increased. On the other hand, paraffin blockage of tubing is reduced, therefore clear area of pipes is constant and oil recovery is not decreasing over time [3, 4].

Also the repair expenses on downhole equipment decrease leading to the increase of economic efficiency of oil well operation. This method of electrothermal treatment can be implemented for various recovery mechanisms, such as flush, gaslift and electromechanical.

Large scale implementation of electrothermal facilities for treating viscous and heavy crude oil and paraffin deposits are limited by electrical energy supply availability. Most of the active oil fields in Russia are located remotely from a centralized power supply system or suffer a power capacity shortage [5].

Nowadays major international oil companies develop energy efficient technologies of oil production intensification using renewable energy sources. Royal Dutch Shell, for example, uses solar energy to produce steam to be injected into the wellbore.
The given article is dedicated to addressing the oil and gas industry relevant issue of developing an energy efficient technology of electrical heating of oil wellbores with the use of renewable energy sources.

2. Autonomous electrothermal facility

Autonomous electrothermal facility fed by wind driven power unit provides thermal impact on oil strata by means of downhole heater in well bottom zone (see figure 1). As a result the viscosity of oil decreases and paraffin deposits melt and lift out by the oil flow.

All electric energy of the wind power unit is converted into heat inside the downhole heater. Wellbore heating temperature varies with the wind conditions. Thus the wellbore is heated periodically. Such an operating mode is acceptable and is also used when the facility is supplied by a centralized power system [6, 7].

In case of oil overheating, the electrothermal facility can be switched off by the signal of a temperature sensor located in the wellbore collar.

Heating element has several copper U-shaped tubes filled up with molten magnesium oxide. There are spirals of nichrome wire inside the tubes for conducting direct electric current. The source of direct electric current is a three-phase diode rectifier connected to the wind power unit generating three-phase alternative electric current.

![Figure 1. Electrothermal facility supplied by wind-driven power unit.](image)

The considered autonomous electrothermal facility comprises: 1 — wind-driven power unit; 2 — AC power cable; 3 — three-phase diode rectifier; 4 — DC power cable; 5 — control cabinet (optional); 6 — DC power wire-cable; 7 — cable from temperature sensor; 8 — sealing unit; 9 — above-ground wellbore valves; 10 — temperature sensor; 11 — piping; 12 — wellbore; 13 — downhole heater (see Figure 2).
Figure 2. The considered downhole heater comprises: 1 — DC power wire-cable; 2 — heater head; 3 — heat insulation; 4 — terminal chamber; 5 — heating tubes.

Such electrical heating approach has the following advantages:
• direct thermal impact on paraffin depositions without intermediate heat transfer mediums;
• no need for complicated control systems for the facility requiring highly qualified personnel;
• no costs for connection to centralized power systems;
• no energy costs;
• no need for modernization of existing power supply lines in case of insufficient transmission capacity.

The drawbacks are high capital expenditures including wind-driven power unit and installation costs.

3. Modeling

A. Computer modelling

A MATLAB Simulink model shown in Figure 3 was developed to obtain operating curves of the electrothermal facility for various load resistances.

The model consists of several main blocks: a permanent magnet synchronous generator, a three-phase diode rectifier, a load and a measuring complex.

The permanent magnet synchronous generator parameters obtained: stator phase resistance Rs (0.06 Ohms), armature inductance (5.2e-3 H), flux linkage established by magnets (0.19292 V.s.).
Uncontrolled rectifier parameters: snubber resistance $R_s$ (1e5 Ohms), $R_{on}$ (1e-3 Ohms). Load parameters varied through experiments.

Computer model parameters were verified based on a series of experiments with a simulation bench (see Figure 5).

Relationships of thermal power generated in the load (heating cable) in the whole windmill operating range from 50 to 500 rpm were obtained via computer modeling for various load resistances.

A windmill in the wind-driven power unit transforms wind energy into mechanical rotation energy according to the following equation [8]:

$$P_{WG} = \frac{1}{2} \pi r^2 3 \rho V^3 C_p$$

where $P_{WG}$ — windmill power (W); $r$ — windmill radius (m); $\rho$ — air density (kg/m$^3$); $V$ — wind speed (m/s); $C_p$ — wind energy utilization factor.

The wind energy utilization factor $C_p$ is determined by a windmill type and is not dependent on windmill dimensions. A typical aerodynamic characteristic of a three-blade windmill was used in the research [9].

A windmill speed (in rpm) with respect to its specific speed is determined as follows:

$$n = \frac{30 Z V}{\pi r}$$

where $Z$ — windmill specific speed; $r$ — windmill radius (m), $V$ — wind speed (m/s).

The above equations were used to process an input speed reference in the computer model, making it possible to correlate a windmill speed and a wind speed.

Thus, operating curves of the electrothermal facility supplied by the wind-driven power unit were obtained representing the thermal power dissipated in the downhole heater as a function of the wind speed (see Figure 4). The windmill radius is 2.5 m.

![Figure 4. Operating curves of the electrothermal facility supplied by the with wind-driven power unit obtained via computer modeling.](image-url)
B. Simulation modeling

In order to verify the data obtained via computer modeling, a simulation bench of the electrothermal facility supplied by the wind-driven power unit was developed, shown in Figure 5 [10]. Windmill operation was modeled with a three-phase asynchronous motor (1) (rated at 7.5 kW, 50 Hz, 380 V, 1450 rpm, 87.6%, 0.87). The motor (1) was controlled by a frequency converter (2) rated at 15 kW. In the simulation bench, just as in a real wind-driven power unit, a direct torque transmission from the motor (windmill) and a generator was used. A three-phase synchronous machine with permanent magnets (rated at 4 kW, 100 Hz, 400 rpm) was used as a generator (3). The bench comprises a three-phase diode rectifier (4) and a load unit consisting of active resistances (5) with dissipated thermal power up to 6 kW, as well as measuring instruments (6).

![Figure 5. Simulation bench of autonomous electrothermal facility supplied by wind-driven power unit.](image)

Repeatability of computer and simulation modeling accounted for at least 95%.

4. Energy Performance

In order to estimate the amount of energy produced by the wind-driven power unit as part of the electrothermal facility in one year for various resistance values, it is necessary to know wind conditions. According to the wind map annual average wind speed from 4 m/s to 9 m/s is optimal for Russia [11]. Weibull probability density function is used for the estimation:

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

(3)

where \( x \) — value for which a wind speed function is determined; \( \lambda \) — scale parameter; \( k \) — shape parameter.
The scale parameter is close to average wind speed and is equal to \( \lambda = 1.28 \cdot V_{av} \), where \( V_{av} \) — average wind speed (m/s).

A most common shape parameter \( k \) value for the Russian regions is 1.25 and 1.75 [9].

The operating speed range for most wind-driven power units is from 3 m/s to 25 m/s. Thus, the total amount of energy (MW·h) is equal to:

\[
W = \sum_{V=3m/s}^{V=25m/s} w
\]

where \( w \) — amount of energy produced at a specific wind speed (MW·h), \( w \) is estimated as follows:

\[
w = P \cdot t \cdot f(x; \lambda; k) \cdot 10^{-3}
\]

where \( P \) — power of the wind-driven power unit at a given speed (kW); \( t \) — number of hours in a year (h); \( f(x; \lambda; k) \) — Weibull probability density.

Wind power unit installed capability utilization factor \( K_p \) is calculated in accordance with formula (6) for two cases:

- with installation of the matching DC/DC convertor with the MPPT control algorithm after the rectifier;
- with direct connection of the power supply cable of the downhole heater to the rectifier.

\[
K_p = \sum_{V=3m/s}^{V=25m/s} w / (P \cdot 8760)
\]

![Figure 6.](image)

Application of the DC/DC convertor allows one to increase the amount of heat energy produced from 4 to 12% based on wind conditions (see figure 6.)

5. Conclusions

The article proposes a novel design of the autonomous electrothermal facility supplied by the wind-driven power unit. The proposed facility is particularly relevant for use in oil fields, remote from a centralized power system or suffering from a power capacity shortage.

The authors developed the computer model making it possible to estimate the wind-driven power unit operating efficiency for various load resistances, as well as with account for variation of wind conditions (annual average wind speed and wind speed distribution by scale). The computer model was validated with the laboratory simulation bench.
An optimal downhole heater resistance was obtained via modeling, the resistance ensuring maximal efficiency of the facility. Also, the amounts of energy produced by the wind-driven power unit in the case of a constant load resistance and in the case of a load resistance incremental control were compared through the DC/DC-converter.

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