Electro Steam Thermal Complex Powered by Wind-Driven Generator for the Treatment of the Oil Formation's Bottomhole Area

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Abstract. In this article authors propose application of the wind-driven power units as power source of bottomhole electric steam generator for the thermal high-viscosity oil reservoir stimulation. The structure of the electro steam thermal complex is proposed. An analysis of the wind energy potential in the areas where the largest high-viscosity oil deposits in Russia are located is carried out. As part of the complex under consideration, the type of the dependence of the bottomhole electric steam generator's power on the formation depth has been established. The calculation of the required installed capacity of wind power plants for placement as part of the electro steam thermal complex at the largest high-viscosity oil deposits in Russia has been performed.

1. Introduction

Due to the exhaustion of low-density oil deposits, heavy and high-viscosity oil (HVO) production increases in Russia, as well as around the world. For its efficient extraction, various thermal methods are used to increase oil recovery. For instance, technology of steam injection into the oil reservoir is particularly common.

In land-based steam generating plants, energy from the combustion of natural gas, oil-well gas, a portion of previously produced oil, or diesel fuel is consumed to produce water steam. Then, using pumps, steam is injected through heat-insulated oil well tubing (OWT) into the oil reservoir. Owing to the steam-heat stimulation, the viscosity of the oil decreases and its production is carried out. However, with an increase in the depth of the HVO formation, the heat losses in the OWT increase, as a result, the steam cools and condenses. It leads to a decrease in the efficiency of the steam-heat stimulation, and oil production becomes unprofitable. Therefore, this technology has a limit on the depth of the oil reservoir, usually not more than 1000 m [1–3].

More than half of the Russian HVO deposits are located in the Arctic region [4]. At the same time, the use of traditional technology of steam-heat stimulation of oil deposits using land-based steam generating plants can lead to thawing of permafrost rocks around the wells. As a result, the risk of deformation of the wellbore, subsidence of the wellhead and equipment damage increases [5–7].

It is possible to increase the efficiency of the thermal effect on the HVO, especially at a depth of more than 1000 m, by using electro steam thermal complex where thermal energy (steam) is generated directly in the bottomhole zone of the well. Owing to this, energy losses are reduced both at the stage of steam production and during its delivery to the formation. The use of bottomhole electro steam

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thermal complexes will also reduce the possibility of permafrost thawing as the main thermal processes take place below its depth. The bottomhole electric steam generators of various capacities have been developed [8, 9] at Saint Petersburg Mining University. It can be used for both HVO production and for controlling paraffin deposits in oil wells [10, 11]. However, a source of external power supply with a capacity of over 300–500 kW is required [12] for the implementation of this technology.

Most HVO deposits are located in regions that are either poorly covered by a centralized power supply system, or where the connection of power generating complexes is difficult due to the lack of a sufficient power reserve and transmission capacity of existing power lines. These circumstances impede the introduction of steam thermal complexes with bottomhole electric steam generator for efficient production of HVO.

The purpose of this research is to study issues related to determining the required installed capacity of a wind-driven generator (WDG) used as an autonomous power source for a steam-thermal complex with bottomhole electric steam generator.

2. The structure of the complex

A wind-driven generator is designed to power the bottomhole electric steam generator and auxiliary equipment (electric pump, control system, etc.). In the absence of wind, the steam generation process stops and then resumes when the wind speed exceeds the minimum operating value (usually 3 m/s).

The complex works as follows (Figure 1): WDG (1) produces a three-phase electric current of variable frequency and variable voltage level depending on the current wind speed. Further, through the rectifier (2), the current flows to the DC/DC converter (3), where the voltage level on the DC bus is stabilized. Single-phase autonomous inverter (4) with high-voltage (3–10 kV) single-phase power transformer (5) for supplying bottomhole electric steam generator (15) connects to a DC bus as well as a three-phase autonomous inverter (6) for powering a variable speed drive (7) of a pump (8) and auxiliary equipment, including a control system (9). When voltage is applied, the current from the power transformer (5) pass through the armored cable (10) through the input device (11) and then through the tubular insulated current lead (13) to the central electrode (14) of the bottomhole electric steam generator (15). Inside the steam generator, current flows from the central current lead through the perforated electrodes through the conductive fluid (18) to the housing electrodes, generating the required power. The automatic maintenance of the set technological parameters (boiler water consumption, pump speed) is provided by the control system (9).

The main structural parameters of the bottomhole electric steam generator (length, outer diameter) are determined by the diameter of the casing string and the productive formation thickness as well as the required thermal output [13, 14].

Electro steam thermal complex powered by wind-driven generator for the treatment of the oil formation's bottomhole area includes (Figure 1): 1 – wind-driven generator; 2 – three-phase rectifier; 3 – DC/DC converter with a DC bus; 4 – single-phase self-excited inverter; 5 – high-voltage (3…10 kV) single-phase supply transformer; 6 – three-phase self-excited inverter; 7 – adjustable speed drive; 8 – pump; 9 – control system; 10 – power cable; 11 – oil-filled input device; 12 – dielectric insert; 13 – tubular busduct; 14 – central current conductor; 15 – frame of the bottomhole electric steam generator; 16 – heat-resistant packer; 17 – water supply unit with a backpressure valve; 18 – formation fluid; 19 – casing string; 20 – boiler water; 21 – tubing.

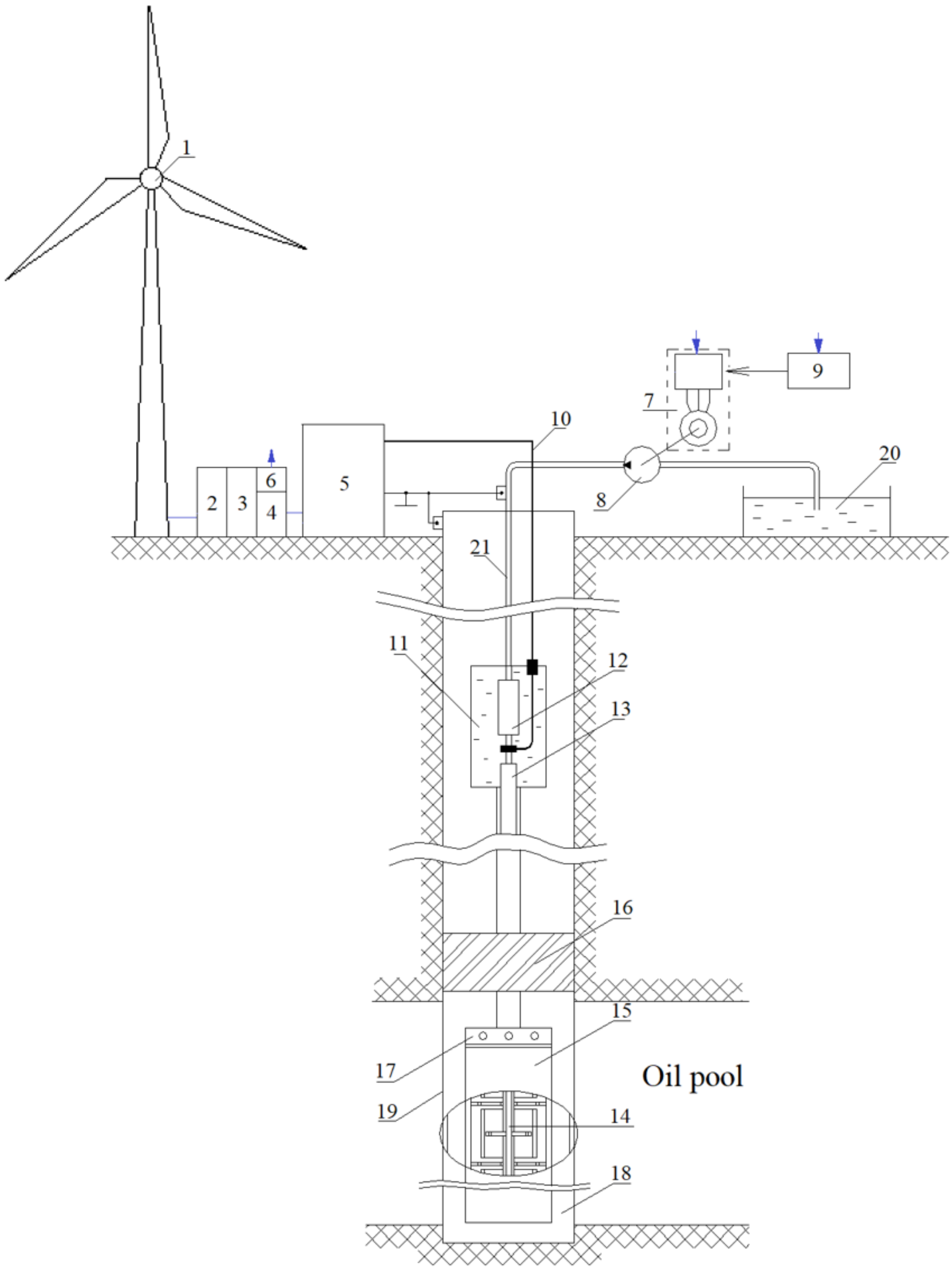

Figure 1. Electro steam thermal complex powered by WDG.

3. Analysis of the location of high-viscosity oil deposits

Russia ranks third in the world after Canada and Venezuela [15] in terms of discovered reserves of heavy and high-viscosity oil. In Russia, the bulk of the HVO is located in the field of the West Siberian, Volga-Ural and Timan-Pechora oil and gas provinces [4]. Data on the largest HVO deposits and average annual wind speeds at an altitude of 50 m for open areas are presented in Table 1.

Besides, there are a significant number of small deposits where ground-based steam generating complexes with extensive steam distribution systems are not profitable. However, autonomous complexes based on WDG could be effective in this case.

Table 1. The largest HVO deposits in Russia [4].

Deposit (region)	Occurrence depth (m)	The average annual wind speed (m/s)
West Siberian Petroleum Bearing Province		
Russkoe (Tazovsky District [a])	664	7.0
Severo-Komsomolskoe (Nadym and Purovsky Districts [a])	1056	6.5
Van-Yeganskoe (Nizhnevartovsk District [b])	893…1330	5.0
Tazovskoe (Tazovsky District [a])	1076	7.0
Novoportovskoe (Yamal District [a])	900	7.5
Zapadno-Messoyakhskoe (Tazovsky District [a])	834	7.0
Volga-Ural Petroleum Bearing Province		
Romashkinskoe (Almetyevsk District [c])	750	6.0
Novoelkhovskoe (Almetyevsk and Zainsky Districts [c])	760…1100	6.0
Akanskoe (Nurlat District [c])	1036	5.0
Nurlatskoe (Oktyabrsky District [c])	858…1940	6.0
Stepnoozerskoe (Nurlat District [c])	1345	5.0
Aksubaevo-Mokshinskoe (Aksubaevsky District [c])	927	5.5
Gremikhinskoe (Votkinsk District [d])	1110…1345	5.0
Chuboyskoe (Balezinsky District [d])	2025	6.0
Mishkinskoe (Votkinsk and Sharkan Districts [d])	1425…1490	5.5
Zimnitskoe (Cherdaklinsky District [e])	1325	5.0
Timan-Pechora Petroleum Bearing Province		
Usinskoe (Usinsky District [f])	1260	6.0
Yaregskoe (Ukhta District [f])	130…175	6.0
Srednemakarikhinskoe (Usinsky District [f])	1796	6.0
Naulskoe (Zapolyarny District [g])	850…890	7.0
Toraveiskoe (Zapolyarny District [g])	970…1515	7.0
Varandeyskoe (Zapolyarny District [g])	1290…1625	7.0
Labaganskoe (Zapolyarny District [g])	1400	7.0
Zapadno-Lekkeyyaginskoe (Zapolyarny District [g])	1364	7.0
Toboysko-Myadseyskoe (Zapolyarny District [g])	2750	7.0
Yuzhno Toraveiskoe (Pechora District [f])	1060	6.0

[a] Yamalo-Nenets Autonomous District
[b] Khanty-Mansiysk Autonomous District
[c] Republic of Tatarstan
[d] Republic of Udmurtia
[e] Ulyanovsk region
[f] Komi Republic
[g] Nenets Autonomous District

Most HVO deposits have a high wind energy potential (average annual wind speed of at least 6 m/s), with the exception of the Van-Yeganskoe, Akanskoe, Stepnoozerskoe, Gremikhinskoe, Zimnitskoe deposits (average annual wind speed about 5 m/s).

4. Heat calculation

The power allocated in the bottomhole electric steam generator is spent on heating the working fluid and its evaporation, taking into account the dependence of the environmental parameters and the properties of the working fluid on the depth at which the steam and thermal effect on the bottomhole zone of the oil reservoir is carried out:

$$W = Q \cdot \left(T_s\left(P(h)\right) - T_0\right) \cdot c_w\left(T(h), P(h)\right) \cdot \rho_w\left(T(h), P(h)\right) + Q \cdot r_w\left(T(h), P(h)\right) \cdot \rho_w\left(T(h), P(h)\right),$$

where Q – volumetric flow rate of the power fluid (m^3/s); P – steam pressure (Pa); T_s – boiling point (°C); T_0 – wellhead temperature (°C); c_w – specific heat capacitance of the power fluid (J/(kg·°C)); ρ_w – the power fluid density (kg/m^3); r_w – the power fluid heat of evaporation (J/kg).

The temperature at the wellhead (T_0) is taken equal to 20°C, the pressure during vaporization (P) formed by a liquid column (h) in the OWT. Boiler water is used as the power fluid, in which the specific heat, density and heat of evaporation depend on temperature and pressure and are determined taking into account the thermophysical properties of water and water vapor according to the reference data [16].

The result of calculating the dependence of the bottomhole electric steam generator power on the depth of the formation to produce 12 tons of steam per day (the minimum recommended daily volume of steam for thermal impact on the HVO) is shown in Figure 2.

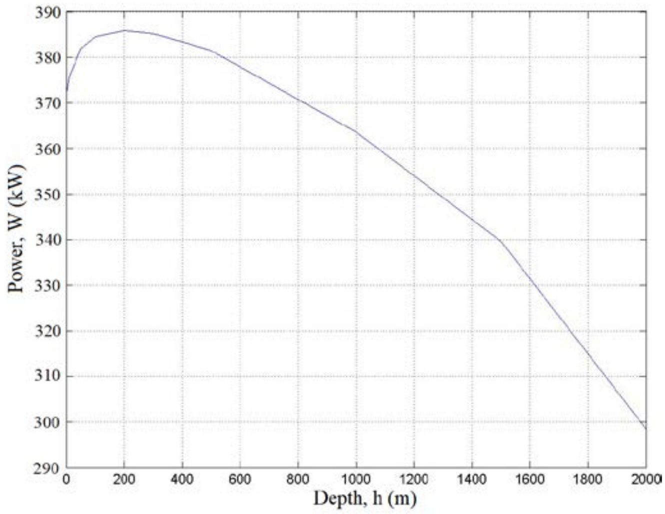

Figure 2. Dependence of bottomhole electric steam generator power (W) on the depth of the formation (h) for producing 12 tons of steam per day.

5. WDG power selection

For power supply of bottomhole electric steam generator it is supposed to use WPG with 200…400 kW nominal capacitance at a nominal wind speed of 12 m/s. The power of a wind wheel (rotational speed) is limiting by turning a blade; more than 50 m high mast is sectionalized and held by several levels of stretch marks, for example, WDG Vergnet GEV MP C 200–275 kW. This design of WDG allows installation work without the involvement of crane equipment. This is especially important for remote and hard to reach places.

Taking into account the above technical data of the wind turbine and the average annual wind speeds, the estimated variation range of the plant utilization factor (PUF) of WDG is presented in table 2 [17, 18].

Table 2. PUF of WDG.

Average annual wind speed (m/s)	PUF (%)	Average annual wind speed (m/s)	PUF (%)
5.0	19–26	6.5	33–35
5.5	24–29	7.0	34–39
6.0	29–31	7.5	40–43

To ensure an average level of steam generation of 12 tons per day, the required wind turbine power will be determined by the formula:

$$W_{WG} = 1.2 \cdot \frac{W(h)}{k} \cdot 100\%,$$

where W_{WG} – WDG installed capacitance (kW); W(h) – design capacitance of bottomhole electric steam generator to produce 12 tons of steam per day (kW); k – PUF of WDG (%); 1.2 – safety factor taking into account losses in cable lines, converting equipment and a transformer, as well as the own needs of the energy complex.

We will calculate the required installed capacitance of WDG (Figure 3) for power supply to the bottomhole electric steam generator with an average productivity of 12 tons of steam per day for the wells of the largest HVO deposits in Russia. In this case, we will use the average occurrence depth of oil formation for each field (table 1) and the average PUF for each average annual wind speed (table 2).

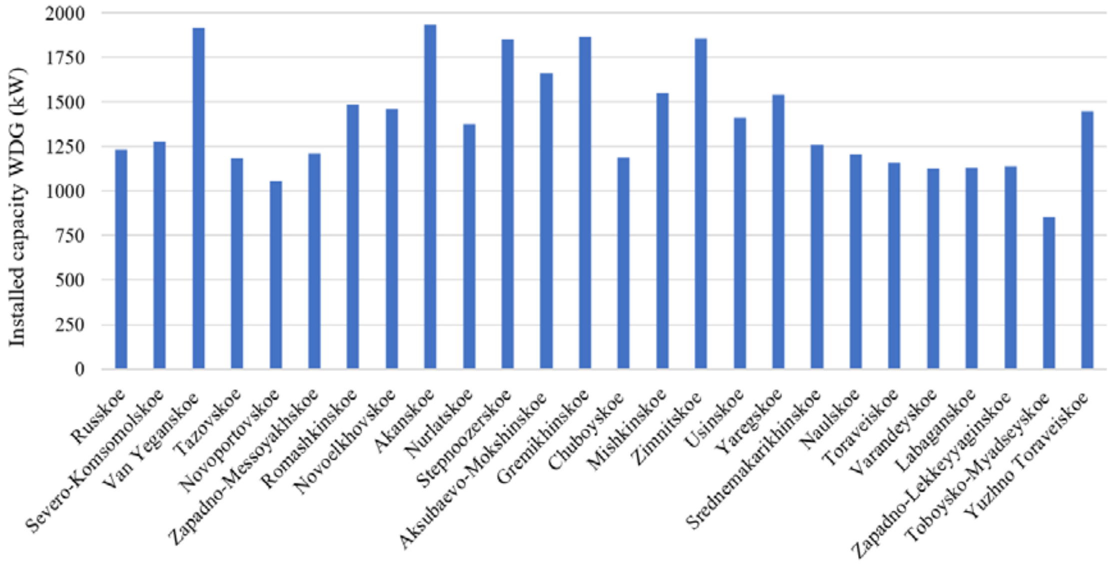

Figure 3. Required installed WDG capacity for powering the bottomhole electric steam generator with a capacity of 12 tons of steam per day.

6. Conclusion

It is most effective to use WDG to power the electro steam thermal complex to reduce oil viscosity in the following fields: Toboysko-Myadseyskoe, Varandeyskoe, Labaganskoe, Zapadno-Lekkeyyaginskoe in the Zapolyarny district of the Nenets Autonomous District; Novoportovskoye and Tazovsky in the Yamal and Tazovsky District of the Yamalo-Nenets Autonomous District; Chuboyskoe in the Balezinsky District of the Republic of Udmurtia.

For these fields, the installed capacity of wind turbines will not exceed 1200 kW to ensure an average daily volume of steam generation at the level of 12 tons.

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