Study of the Possibility of Creating Autonomous Low-Power Thermal Power Plants Using Alternative Energy Sources

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Abstract. The areas of use of low-capacity power plants are very wide: industrial enterprises, medical institutions, residential cottages, business centers and other objects of large cities; main gas pipelines, gas distribution stations, oil pipelines that need energy supply for normal operation; enterprises for processing household waste; developing areas of the country where there are currently no energy sources and power lines; energy-deficient areas of the Far North, Far East, and some Non-Chernozem regions; small towns, cottage settlements and villages, in many of them the issue of centralized heat supply; large livestock farms, enterprises for processing agricultural products, enterprises of the logging industry, etc.

In this study, an important problem for oil fields is considered - utilization of associated petroleum gas. Low-power power plants are considered as a combustion engine. It is important to note that high-quality fuel treatment is required for internal combustion engines or gas turbines. The proposed scheme of associated gas utilization based on a small power plant is not fuel-intensive. Studies of compressor and turbine matching are presented, resulting in an optimal range of operating areas. These results allow us to determine the limitations for the operation of the power plant.

1. Introduction

The diversity of energy consumers, different requirements for the type and quality of energy supply, makes us take a fresh look at the role of low-power power plants (from tens kilowatts to several megawatts) in the overall structure of the energy industry [1-3].

Serious attention is paid to the construction of relatively cheap low-power autonomous power plants for various purposes, which can be financed both from local budgets and through investments. In principle, thermal power plants can use various engines produced by industry: internal combustion engines, steam and gas turbines, or their combinations [4-6].

These features of the operation of autonomous installations, severe climatic conditions, sometimes insufficient qualification of the service personnel, require high reliability of products, ease of installation, repair, as well as a high degree of automation, including computer control.

Some of the energy consumers are independent small oil companies operating in fields remote from the infrastructure.
The most acute problem nowadays is the problem of utilization of associated petroleum gas, which is faced by all oil companies, not just small ones. For oil companies, transportation and processing of associated petroleum gas into fuel for further use is unprofitable, since the cost of such fuel is higher than the market price. At the moment, associated petroleum gas is being flared in huge quantities. The establishment of autonomous installations using associated petroleum gas in the energy sector will solve the problem of heat and electricity supply not only to oil companies, but also to nearby settlements. Given the high energy consumption of oil production, there is a practice of using associated petroleum gas, including for generating electricity for field needs, creating energy-saving technologies based on autonomous low-power installations.

2. Analysis of power plants of low power
It is known to use a gas-piston power plant for utilization of associated petroleum gas [7-10]. For example, PJSC "Tatneft" has put into trial operation a gas-piston power plant with a capacity of 200 kW, partially utilizing the existing volume of associated petroleum gas. Another type of power plants suitable for utilization of associated petroleum gas are gas generators of turbojet engines, auxiliary power plants, and a turbocharger (figure 1).

![Figure 1. Longitudinal sections of the turbofan engine (a) and turbocharger (b).](image)

The world leader in the production of micro turbine power plants is Capstone [11-13]. Capstone turbine units distinguish by a high level of technical solutions: the presence of air bearings in a high-speed turbo-generator rotor; the use of a compact heat recovery unit, the design of which ensured the small dimensions of the entire installation; the use of a highly efficient combustion chamber that provides minimal emission of nitrogen oxides NOx [13-16].

Public company "Special Design Bureau of Turbochargers" (PLC “SDBT”) is developing a turbine unit based on a supercharged turbocharger, designed for the utilization of used motor oils and wood waste (sawdust, wood chips, sleepers), generating electric and thermal energy.

The installation provides generation and output to the external network of three-phase current with a voltage of 380V±1.5%, hot water with a temperature of 90°C (figure 2).

The characteristics of power plants with a turbocharger determine the areas of their application in practice. These include:
- mobile steam generator sets for heating equipment and steam-thermal effects on oil reservoirs, including high-viscosity bitumen in the oil and gas industry;
- energy sources for farms and individual settlements, especially in the Far North, mountainous areas, and other remote regions;
- local boiler houses with decentralized power supply in housing and communal services and in production.
When designing a turbocharger, the main task is to obtain gas-dynamic characteristics of the working fluid flow that ensure satisfactory operation of the turbocharger together with the engine over the entire operating range of the latter with a sufficiently high efficiency.

The disadvantage of the known micro turbine power plants, in our opinion, is the high level of fuel requirements [17-20].

This circumstance requires the introduction of an expensive preliminary preparation of associated petroleum gas into the technology for use as a fuel (filtration, separation, drying, compression), which prevents the transition from a pilot plant to the industrial development of this technology.

Flaring of associated petroleum gas is mainly due to its high content of heavy hydrocarbons and sulfur-containing impurities, which makes it impossible to use such gas as fuel for gas piston power plants and gas turbine power plants [21,22].

There is a known technical solution for the method of utilization of associated petroleum gas and an energy machine for its implementation, which can be considered as one of the possible solutions for creating a low-power power plant with minimal fuel requirements (figure 3).

The machine (figure 3) contains: a body 1, shovel machines 4, 12 connections to payload units 5, 13, a burner 6 and elements for supplying atmospheric air 2, associated petroleum gas 1. The body is made in the form of an exhaust pipe, the inlet of which is hermetically connected to the body of a jet pump 8. The exhaust pipe outlet is connected to the atmosphere.
3. Autonomous power plant based on turbochargers for supercharging internal combustion engines, turbojet engine and gas turbine and high-speed electric generators

From the analysis of known technical solutions, it follows that a new innovative solution is possible, which allows creating an autonomous power plant based on turbochargers for supercharging internal combustion engines, turbojet engine and gas turbine and high-speed electric generators. This power plant is focused on a wide range of fuels: liquid, gaseous, forest and agricultural waste, biogas, household waste processing products, products of underground or industrial gasification of solid fuels, oil production and refining waste.

A schematic diagram of a power plant based on a supercharged turbocharger is shown in figure 4.

Figure 4 contains: 1 – power generator; 2 – turbocharger; 3 – shroud; 4 – combustion chamber – heat exchanger; 5 – injectors; 6 – Compressed air; 7 – hot compressed air; 8 – associated gas.

In fact, this turbine heat engine. The plant works as follows. Atmospheric air enters the compressor inlet, where it is compressed and enters the combustion chamber – heat exchanger. Then the hot compressed air enters the turbocharger turbine and expands, performing work, part of which goes to the compressor drive, and the excess to the electric generator drive.

The heated exhaust air in the turbine goes back to the combustion chamber-heat exchanger. Associated gas flow through its main line through injectors under an excess pressure equal to $P = 0.04 – 0.2$ MPa, and fed into the combustion chamber-heat exchanger.

The quantity of turbochargers in the plant is determined by the value of the second flow rate of the working fluid, their characteristics, possibly high parameters of optimal combustion of associated gas, depending on the excess air coefficient.

Thus, a new design solution of the plant is proposed, which consists in the fact that, from a fuel composition consisting of an oxidizer (air) and fuel (crude associated petroleum gas, wood waste in the form of sawdust, wood chips), they provide a process without soot combustion of fuel at low pressure, the process of recapturing the heat of the solid body surface and removing the remaining heat of combustion products through an exhaust pipe to the atmosphere. The characteristics of a high-speed turbocharger unit are influenced by the complex processes of the gas generator unit through the heat transfer process, which is practically stationary, between two carriers – one of which is cold.
compressed air up to a pressure determined by the compression ratio $\pi_k^*$ in the compressor, and the other is a high-temperature flow of low-pressure combustion products equal to $P = 0.12$ MPa (absolute pressure).

The fuel composition, with the value of the heat content in the initial state, is equal to $I = 0.96585$ kJ/kg, combustion receives a high temperature working fluid with temperature, approximately $T = 1030$ °K, determined by the value of the complete combustion $\eta_c = 0.98$, in gas-generator block when the ratio of the components is equal to $\alpha = 3.5$, it transfers heat to the compressed air through the dividing wall. The wall material is 12X18H10T steel, which has a thermal conductivity coefficient $k = 21$ W/m·K. The heat exchange coefficient was chosen to be $h = 50$ W/m²·K, and the heat exchange area, for the temperature of heated compressed air at the turbine inlet equal to $T = 700^\circ$C, was approximately equal to $S = 140$m². The wall thickness was assumed to be $\delta = 0.0001$ m [5].

Accomplishment of the minimum fuel requirements is ensured by the fact that in the power plant only one component is compressed in the compressor – the oxidizer, which does not require any preparatory operations with air during the operation of the turbocharger. The operation of the gas generator is carried out at low pressure and high temperature combustion products are involved only in the process of heat transfer when they move at low speed through the flow channel into the atmosphere, while providing a fairly low emission of incomplete combustion components, including NOx (the molar fraction of NO in the combustion products is of the order of $r_{NO} = 0.000014$).

The issues of coordinating the operation of the compressor and the turbine are given as a result of the computational study. The heat exchange process is carried out on serial units produced by the industry, for example, the FP31 heat exchanger from Funke GmbH has a geometry of 0.5x0.6x1.332mp with an area of exchange equal to $S = 150$ m².

4. Estimated calculations of the operation of autonomous power plant

The issues of coordinating the operation of the compressor and the turbine are given as a result of the computational study. The heat exchange process is carried out on serial installations produced by industry, for example, the FP31 heat exchanger from Funke GmbH has a geometry of 0.5x0.6 x1.332m with a heat exchange area of $S = 150$m².

Figure 5 and 6 shows estimated calculations of the operation of such plant.

The calculations were carried out according to the following dependencies taken in the operation [6]:

Compression work

$$L_c = \frac{k}{k - 1} \cdot R \cdot T_i^* \cdot \left(\frac{\pi_k^{(k-1)/k}}{\pi_m^{(k-1)/k}} - 1\right) / \eta_c^*,$$

Expansion work

$$L_e = \frac{k}{k - 1} \cdot R \cdot T_j^* \cdot \left(1 - \pi_m^{(k-1)/k}\right) \cdot \eta_m^*,$$

where: $R = 0.287$ kJ/kg·K – gas constant; $k = 1.4$ – ratio of specific heats; $\pi_k^*$ – the degree of pressure rise in the compressor; $\pi_m^*$ – the degree of pressure reduction in the turbine; $\eta_c^*$, $\eta_m^*$ – adiabatic efficiency of compressor and turbine; $T_i^*$ = 288.15 K – compressor inlet air temperature; $T_j^*$ – air temperature at the turbine inlet after the heating process in the heat exchanger; $L_c$ – compression operation kJ; $L_e$ – extension operation kJ.

Figure 5 shows the dependence of the degree of pressure decrease in the turbine on the degree of pressure increase in the compressor. In the figure 6 shows the difference between the expansion work ($L_e$) and the compression work ($L_c$) depending on the temperature of the hot air at the turbine inlet for
the possible use of turbochargers - mass production (a) and the possible use of turbojet gas generators - large-scale production (b).

Figure 5. Dependence of the degree of pressure decrease in the turbine ($\pi_T^*$) on the degree of pressure increase in the compressor ($\pi_k^*$).

Figure 6. The difference between the expansion work ($L_g$) and the compression work ($L_c$) depending on the temperature of the hot air at the turbine inlet for the possible use of turbochargers - mass production (a) and the possible use of turbojet gas generators - large-scale production (b).
Figure 6 allows for an estimated thermal calculation under various limitations of the machine parameters.

Example:
Let \( G_\text{sec} = 1.5 \text{ kg/s} \); \( \pi_k^* = 1.5 \); \( T_{ul}^* = 750 \text{ K} \).

From the (figure 6) we find: \( L_c - L_c = 22.86 \text{ kJ/kg} \).

Then:
The machine power capacity \( N_m = (L_c - L_c) \cdot G_\text{sec} = 22.86 \cdot 1.5 = 34.29 \text{ kW} \).

The power of the power machine for different temperatures of hot air at the turbine inlet is shown in figure 7 example for \( G_\text{sec} = 2.5 \text{ kg/s} \); and an example for \( G_\text{sec} = 6.5 \text{ kg/s} \) in figure 8 for the possible use of turbochargers - mass production (a) and the possible use of turbojet gas generators - large-scale production (b).

![Figure 7](image)

**Figure 7.** Power of the power machine for different temperatures of hot air at the turbine inlet at \( G_\text{sec} = 3.5 \text{ kg/s} \) for the possible use of turbochargers - mass production (a) and the possible use of turbojet gas generators - large-scale production (b).
Figure 8. Power of the power machine for different temperatures of hot air at the turbine inlet at $G_{\text{sec}} = 6.5 \text{ kg/s}$ for the possible use of turbochargers - mass production (a) and the possible use of turbojet gas generators - large-scale production (b).

5. Conclusion
The paper is devoted to the current topic of associated petroleum gas utilization. A schematic diagram of a low-power installation with minimal fuel requirements is presented. As a result of the study, the optimal heat content $I = 0.96585 \text{ kJ/kg}$ was determined, during combustion, a high-temperature working fluid with a temperature of $T = 1030 \text{ °K}$ is obtained, with the value of the combustion completeness equal to 0.98.

Studies of the coordination of the compressor and turbine were carried out. The research results are presented in the form of dependencies. The obtained data on the coordination of work allow us to determine the optimal power of the installation, knowing at the same time the gas flow rate, the required temperature, the compression ratio of the compressor and the degree of expansion of the turbine.

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