A Mathematical Model of Gas-Turbine Pump Complex

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Abstract. The articles analyzes the state of an extensive network of main oil pipelines of Tyumen region on the basis of statistical data, and also suggest ways of improving the efficiency of energy-saving policy on the main transport oil. Various types of main oil pipelines pump drives were examined. It was determined that now there is no strict analytical dependence between main operating properties of the power turbine of gas turbine engine. At the same time it is necessary to determine the operating parameters using a turbine at GTPU, interconnection between power and speed frequency, as well as the feasibility of using a particular mode. Analysis of foreign experience, the state of domestic enterprises supplying the country with gas turbines, features of the further development of transport of hydrocarbon resources allows us to conclude the feasibility of supplying the oil transportation industry of our country with pumping units based on gas turbine drive.

1. Introduction

Issues related to energy consumption economy more and more often become the center of world attention. Relevance of energy saving is caused by the fact that traditional sources of energy are limited, while the main transportation of oil is one of the largest consumers of fuel and energy resources (FER) in the Russian Federation. [1] Mainline pumping units, in turn, are energy-intensive machines, so their effective operation is a very important task of operating organizations.

The main part of energy for domestic consumption in the pipeline transportation of oil is electricity. GOST (All Union State standard) for oil transfer pumping units, developed in the USSR, provided the main electric drive of main pumps, which was due to the progressive policies of the vast country in the field of development of the unified system of power supply. Russian standard technical documentation of oil transport companies, also does not leave choice to a project engineer concerning the main drive units.

The existing system of oil and gas pipelines in the Russian Federation has developed in the 60s-80s of the last century, and the greatest development of structures occurred due to the need to transport large volumes of oil and gas from Western Siberia to the central regions of the country and for export.

The state policy of Russian export gas pipelines determined the need for the creation of two new destinations:
- northern: from the fields in Western Siberia (beginning in the area of Surgut) and the Timan-Pechora oil and gas province to the Barents Sea coast and further export of oil by sea to the countries of North-West Europe and North America;
- eastern: with the prospects of developing the resources of Eastern Siberia and the Far East and organization of oil exports to China, Japan and other countries in the Asia-Pacific region.

Since a large part of the routes of both projects is planned in the northern latitudes, as well as in Siberia, there is experience in design and construction of such pipeline systems in appropriate climatic conditions in Russia and it can be complemented by foreign expertise in some aspects.

Mainline pumping units are powerful energy consumers, so their efficient and economical operation is a very important challenge for operating companies.
2. Methods

One of the conditions for the dynamic development of the mainline oil transport is to reduce the cost of pumping, an important component of which is energy costs. There are various ways of reducing energy consumption:

- Optimization of oil pumping conditions applying modern methods of pipeline capacity control;
- Reduction of energy losses in operating equipment, transmission lines, distribution networks;
- Introduction of modern methods of reducing the hydraulic resistance of the pipeline;
- Optimization of techniques for selecting the pump units drive, as the electric main pump has no alternative at the stage of drawing up the specifications and technical documentation;

With the developed system of gas supply, oil pumping units with gas turbine drives can compete with existing one. Their use is especially important in areas where there is no unified power supply system. The choice of the type of OPS drive is affected by a number of fundamental factors. In the first place, it is the existence of powerful sources of energy, as well as technical, energy and economic aspects.

During the initial period of the national oil transportation development a choice of the type of OPS driving pumps was not difficult. In many cases, there was only one source of energy - the energy of combustion of the pumped product. This ensured a reliable and uninterrupted autonomous power supply. This solution is widely used at present for gas turbine driving of compressor stations of main gas pipelines where the source of energy is the energy of the pumped gas combustion, and the automatic control and regulation system ensures perfect operation of all main gas pipelines.

Energy consumption on the oil transportation can be significantly reduced by choosing the optimal type of pump stations drive both in the construction and renovation of the existing oil pipelines, as the electric drive of main pump has no alternative at the stage of drawing up the specifications and technical documentation already. [3]

Analysis of foreign experience, the state of domestic enterprises supplying the country with gas turbines, features of the further development of transport of hydrocarbon resources allows us to conclude the feasibility of supplying the oil transportation industry of our country with pumping units based on gas turbine drive. [2]

Today there is no strict analytical dependence between main performance properties of the power turbine of gas turbine engine (GTE). At the same time there is necessity to determine the operating parameters when using a turbine at gas turbine pumping unit (GTPU), interconnection between power and speed rate, as well as the feasibility of using this or that mode. [4]

In order to determine the dependence between major operating parameters characteristics of various gas turbine engines were examined, as well as experimental data [5], in relative terms, which are ratio of current parameters to nominal ones:

\[
N = \frac{N_{tp}}{N_{nom, tp}}; \quad n = \frac{n_{tp}}{n_{nom, tp}}; \quad G_t = \frac{G_t}{G_{t,nom}},
\]  \hspace{1cm} (1.1)

where \( N \) – work turbine power;
\( n \) – work turbine revolutions frequency;
\( G_t \) – fuel consumption.

Analysis of GTE parameters [8] showed that for each power value there exist the most appropriate values of the number of turbine revolutions. [6] As a result of the analysis of turbine revolutions at the height of powers, the optimal modes curve was obtained (Figure 1).
Considering the efficiency of work turbine of gas turbine engines [7], the optimum engine usage area was determined. In approximating optima curve in the software package «Advanced grapher», the dependence of power turbine rotor revolutions frequency from power under optimal conditions when \( R^2 = 0.99965 \) was obtained:

\[
n = 6.8713N^2 - 9.9611N + 4.1184
\]  

(1.2)

Taking into account the above, we can conclude that the use of work turbine as a drive of the main pumps can compete with the electric motor in conditions of an uneven supply of oil, and the resulting optimum of mode would save fuel gas at maximum engine power.

A mathematical model of the system, "gas generator, power turbine-pump oil pipeline" as part of the gas-turbine pumping complex (GTPC) was composed (Figure 2).

![Figure 1. Area of optimal modes of using work turbine.](image)

**Figure 1. Area of optimal modes of using work turbine.**

The model is made in the form of system of equations, identifying the state of GTPC system:

where:

- \( n \) — work turbine revolutions frequency;
- \( N \) — work turbine power;
- \( \psi \) — generalized parameter of the pump head;
- \( \psi_c \) — pump head rate at zero flow;
\( k \) - number of pumping units;

\( \Phi \) - generalized parameter of pump flow;

\( \beta \) – volume expansion coefficient;

\( L \) – length of pipeline;

\( \nu \) – kinematic viscosity of liquid;

\( d \) – pipeline diameter;

\( Z \) – the difference in geodesic marks.

The use of gas turbine pumps drive enables the regulation of transfer mode by changing the pump rotor rotating frequencies and introduces an additional option in the management of the pipeline. In this connection, pipeline management is inconceivable without the widespread introduction of automated control systems, requiring developed algorithms, which should be based on the principles of mathematical modeling and system identification oil pipeline - pump - gas turbine drive as a unified energy complex.

Using the model for various tasks will enable taking more effective management decisions and quickly affect the modes of joint work of a pipeline, a pump and a gas turbine drive.

The model is based on the principle of energy conservation. The thermal energy of fuel (Input parameters: \( G_{a} \) - air flow rate; \( G_{fg} \) - fuel gas consumption, \( G_{mix} \) - combustible mixture consumption, \( T \) - temperature) is converted into mechanical work at the drive shaft (Input parameters: \( N_{gtu} \) - engine power, \( N_{red} \) - power transmitted to reducer) of the main pump. Then it is converted into hydraulic energy in the pump (Input parameters: \( Q \)- pump output, \( N \)-pump head) and finally into energy of oil product motion through the pipeline. Nominal parameters of GTPC system are revolution frequency (\( n_{nom} \)), power (\( N_{nom} \)) gear reduction rate (\( i \)), pressure head (\( H_{nom} \)) and supply (\( Q_{nom} \)) in pump, dimeter (\( d \)), the length (\( l \)), performance (\( Q \)) of the pipeline, as well as density (\( \rho \)) and viscosity (\( \nu \)) of oil product.

One of the main elements of the block diagram characterizing feature of indicated model is a gas turbine drive which can be decomposed into a gas generator and power turbine. The efficiency of the GTE depends on the factors affecting the state of the object.

The aim of the problem solution at optimizing the drive operating mode in an installation is to provide such a ratio between the power and rotation frequency for pump and oil pipeline data, that will minimize fuel consumption. This can be achieved by establishing a certain ratio between \( n_{a} \) and the required pumping capacity, matching rotation frequency of the free turbine rotor and the rotor of the pump by means of a reducer, which is highlighted as a separate element in Fig. 2.

3. Conclusion

The advanced model will enable carrying out a research of modes of interworking of oil pipeline, pump, power turbine and a gas generator, carrying out a rational choice of equipment frame sizes and determining interconnected constructive parameters of the installation and of the pipeline. Such a model will become the basis for solving all kinds of technological problems in engineering and operation of the facility in order to optimize its operation. Depending on the question posed, the solution sequence and its realization program will be modified, and the boundary conditions should reflect the specifics of the problem and minimize the number of possible solutions.

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