Monitoring of energy efficiency of technological modes of gas transport using modern gas-turbine equipment

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Abstract. The paper presents calculations and an example of energy efficiency justification of the regimes of the equipment used. The engineering design of the gas pipeline in the part of monitoring the energy efficiency of a gas compressor unit (GCU) is considered. The results of the GCU characteristics and its components evaluation are described. The evaluation results of the energy efficiency indicators of the gas pipeline are presented. As an example of the result of the analysis, it is proposed to use gas compressor unit GCU-32 "Ladoga" because of its efficiency and cost effectiveness, in comparison with analogues.

1. Introduction
One of the priorities in the Energy Strategy of Russia recently is the development of resource-saving equipment, as well as a significant increase in the volume of gas exports and at the same time ensuring the technological independence of the gas industry, which means the use of domestic highly efficient gas transport technologies. In this field, the works of professors N.A. Malyushin, A.B. Shabarov, V.A. Shpilevoy, M.N. Chekardovsky, V.M. Pisarevsky, E.I. Krapivsky and other well-known authors are known.

2. Methodology
At the Transport of Hydrocarbon Resources Department of the Industrial University of Tyumen, complex studies are carried out to monitor the reliability, safety, and energy efficiency of complex process equipment for pipeline transport facilities of hydrocarbon raw materials at various stages of the life cycle. Monitoring the energy efficiency of gas pipeline modes is an important and complex multifactor complex task, both at the design stage and during the direct operation. For example, the existing methodology for the energy efficiency of PJSC Gazprom gas transmission facilities and systems evaluation [11] involves the calculation of indicators for various cases, including such indicators as indicators of efficiency coefficient, specific fuel gas consumption, specific electricity consumption for compression, etc.

The proposed methodological complex is presented in the form of numerous algorithms and mathematical- and software provided in the works of the authors and colleagues on various aspects of reliability, efficiency, and safety evaluation [2-10]. Production experience analysis has shown that at each stage of the life cycle of the facility there is a specific control, management and specific methodological aspects. As an example, the results of the analysis of the problematic field are presented to ensure the quality of managing the properties of objects at different stages (Table 1).

Table 1. Analysis of the problematic field regarding maintenance of the hydrocarbon transport system life cycle

Life Cycle Stage	Object and technical system properties and level maintenance factors		
	Reliability	Safety	Efficiency
Designing	Quality of methods for substantiating design solutions and their application in the field of materials and equipment selection, mode optimization		
	Quality of structural calculations and technological operations	Quality of the project and security solutions, protection against tie-ins, environmental monitoring	Quality of technological calculation, equipment selection, optimization solutions
Improvement at the design stage	Evaluation of design quality and development of reasoned technical solutions, justification methodologies improvement		
Construction	Control of the production process of construction and the design documentation adherence; quality control of work and testing	Control of the production process of construction and design solutions execution; quality control of works and testings	Production process monitoring, technological innovations, modern equipment
Improvement at the construction stage	Improvement of technology, quality control and testing		
Operation	Monitoring of object reliability with the use of proactive control systems, satellite and remote technologies	Security monitoring with the use of proactive control systems, satellite and remote technologies, security equipment	Monitoring of technological modes with the use of proactive control systems
Improvement at the operation stage	Development and modernization of expert systems		
	Making decisions on technical intervention, reconstruction	Making decisions on improving the effectiveness of the security system	Making decisions on technical re-equipment, modernization

At the design stage, taking into account the implementation of the import substitution program, a competent analysis of energy consumption options and the structure of operating costs is important. The general algorithm for implementing optimization solutions is shown in Fig. 1.

At the operational stage, the development of technology for monitoring the efficiency of operating modes of technological equipment for main oil and gas pipelines on-line is of particular importance. The structure of the information flow at the operational stage is shown in Fig.2.

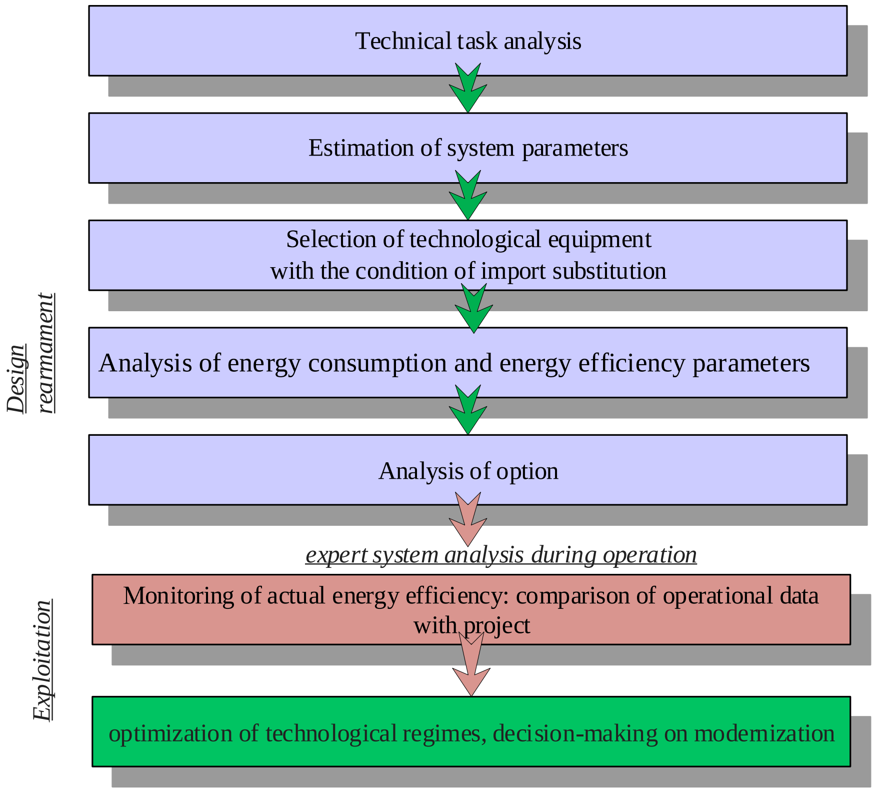

Figure 1. General algorithm for implementing optimization solutions for energy efficiency in the design

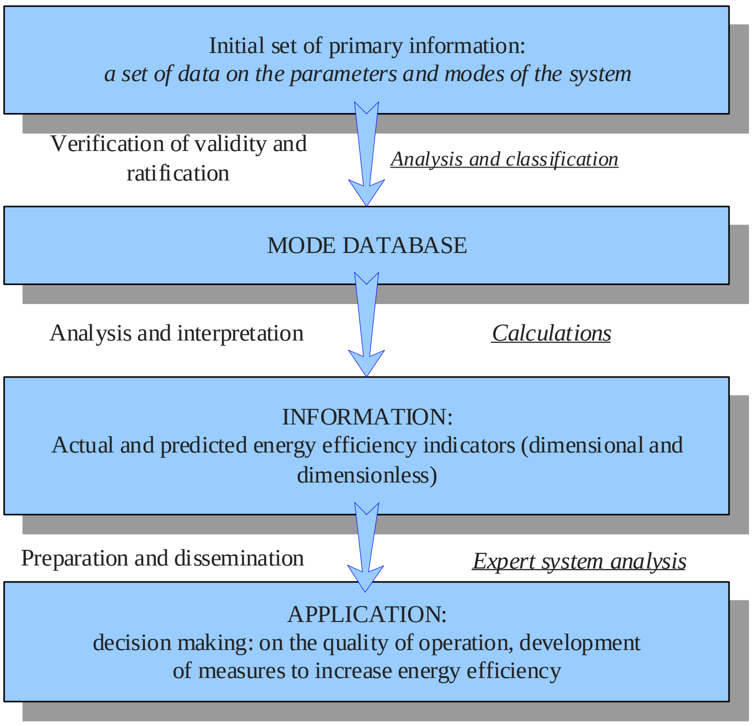

Figure 2. A structure of the information flow in the system for monitoring the energy efficiency of gas transport processes during the operation

IOP Conf. Series: Materials Science and Engineering **357** (2018) 012034 doi:10.1088/1757-899X/357/1/012034

3. Industrial testing on a technological project

Let us consider the option of using the algorithmic complex in terms of the "Power of Siberia-2" ("Altai") project, a gas pipeline between the gas fields of Western Siberia and the Xinjiang Uygur Autonomous Region in the west of China; the approximate length of the gas pipeline is about 6700 km, 2,700 km of which should pass on the territory of Russia.

The technological equipment of the "Altai" gas pipeline meets all modern requirements both from the point of view of the application of new domestic construction materials, and from the point of view of energy and resource saving. The newest gas compressor units are used, which ensure a high initial pressure in the pipeline and a high productivity when transporting gas. The "Altai" gas pipeline starts in the Urengoy field. The productivity of the pipeline with a diameter of 1420 mm, having a wall thickness of 32 mm, is 45 billion cubic meters of gas per year. Testing for strength and deformability is fully satisfied. Pipes of the gas pipeline "Altai" are electro-welded, longitudinal, with the factory insulating coating for the gas pipeline of the category III. The gas pipeline capacity is 133 million cubic meters per day [14].

When operating a gas pipeline, the criteria characterizing its efficiency and cost effectiveness are important, as well as the results of calculations in Table 2.

Table 2. Results of the analytical justification of the project

Name	Value
Throughput performance	61.639 $mln.m^3/day.$
Hydraulic resistance coefficient	0.0099099
Reynolds number	80465019
Pressure at the end of section	8.695 Mpa
Coefficient characterizing the intensity of the decrease in the gas temperature along the length of the section	0.002241
Average gas temperature	261K
Gas temperature at end of section	268.36K

Throughput performance:

$$Q_n = 1{,}33 \cdot 10^6 \frac{D^{2,5} \cdot \eta}{\Delta}; \tag{1}$$

where D - pipeline diameter, mm; η - dynamic viscosity of gas, Pa˙s; Δ - relative density by air.

Hydraulic resistance coefficient:

$$\lambda_{fr} = 0{,}067 \cdot \left(\frac{158}{Re} + \frac{2 \cdot k}{D_{vn}}\right)^{0,2}, \tag{2}$$

where k=0,03 – equivalent pipe roughness, mm; $D_{вн}$ – pipe inner diameter, mm; Re – Reynolds number.

Reynolds number:

$$Re = 17{,}75 \cdot 10^3 \cdot \frac{Q\Delta}{D\eta}\ . \tag{3}$$

Pressure at the end of section:

$$P_k = \sqrt{p_H^2 - \frac{\mathbf{Q}^2 \cdot \Delta \cdot \lambda \cdot Z \cdot T_{cp} \cdot L}{105{,}087^2 \cdot D_{vn}^5}}. \tag{4}$$

Coefficient characterizing the intensity of the decrease in the gas temperature along the length of the section:

$$a = \frac{k\pi d}{MC_p}. \tag{5}$$

Average gas temperature:

$$T_{av} = T_0 + \frac{T_H - T_0}{aL}\ 1 - e^{-aL}\ - Di\frac{P_H^2 - P_K^2}{2aLP_{sr}}\ 1 - \frac{1}{aL}\ 1 - e^{-aL}\ . \quad (6)$$

After carrying out calculations on this gas pipeline, it can be concluded that with the CS capacity Q_{ks}=133.76 mln.m^3/day, which is more than 15 mln.m^3/day, superchargers are more economical than GICC; therefore, in the centrifugal blowers they are used as a type of compressor machines.

Since there is a large capacity and gas is transported under high pressure, the GCU-32 Ladoga (2 working and 1 standby unit) is used.

GCU-32 Ladoga is a new, highly efficient unit developed for the Russian market based on the basic family of GCU MS5002, which is successfully operated at many compressor stations in Russia and has a total operating time of more than 16 million hours worldwide.

GCU-32 Ladoga includes elements specially designed for operation in difficult conditions of the Russian market: separate compartments of auxiliary equipment and gas turbines (to solve the problem of very low temperatures of the ventilation air), the use of special low-temperature steels for frames production, as well as the application of GOST (all-Union State Standard) standards and Russian certification.

The supercharger 400-21-1C is full-forcing and is designed for compression and transportation of natural gas through main gas pipelines. The type of the supercharger - centrifugal, two-stage with the system of end "dry" gas seals (DGS) and oleic supporting and resistant bearings.

The supercharger is equipped with two identical in design nodes of seals of the DGS developed by JSC "John-Crane-Iskra". Seals are designed to minimize gas losses. The supercharger is driven by a gas turbine MS5002E.

Table 3. Basic parameters of the supercharger 400-21-1C

Name	Value
Productivity, referred to 20°C and 0,1013 MPa, mln.nm/day	78.9
Volume productivity, referred to the initial conditions, m^3/min	505
Final, absolute pressure of the gas when exiting the discharge nozzle, MPa	11.86
Polytropic efficiency	0.85
Pressure ratio	1.4
Power consumed by the supercharger, MW	30.4
Initial gas pressure, at the inlet to the suction pipe of the supercharger, MPa	8.45
Initial gas temperature, at the inlet to the suction pipe of the supercharger, °C	5
The density of the gas, referred to 20°C and 0.1013 MPa, kg/m	0.689
Rotor speed, rpm	5550
Operating speed range, % out of nominal	70-105

"Nevsky Zavod" is manufacturing a gas turbine unit (GTU) MS5002E under license and in cooperation with GeneralElectricOil&Gas (NuovoPignoneS.p.A.).

The first batch of GTU MS5002E (Fig.3.4) is designed for operation on the gas trunk pipelines of OAO Gazprom as a drive of the natural gas blower 400-21-1C in the GCU-32 "Ladoga" made by "Nevsky Zavod" at the frequency of rotation of the power shaft equal to 5714 rpm. However, GTU MS5002E can work in the drive mode from the generator.

IOP Conf. Series: Materials Science and Engineering **357** (2018) 012034 doi:10.1088/1757-899X/357/1/012034

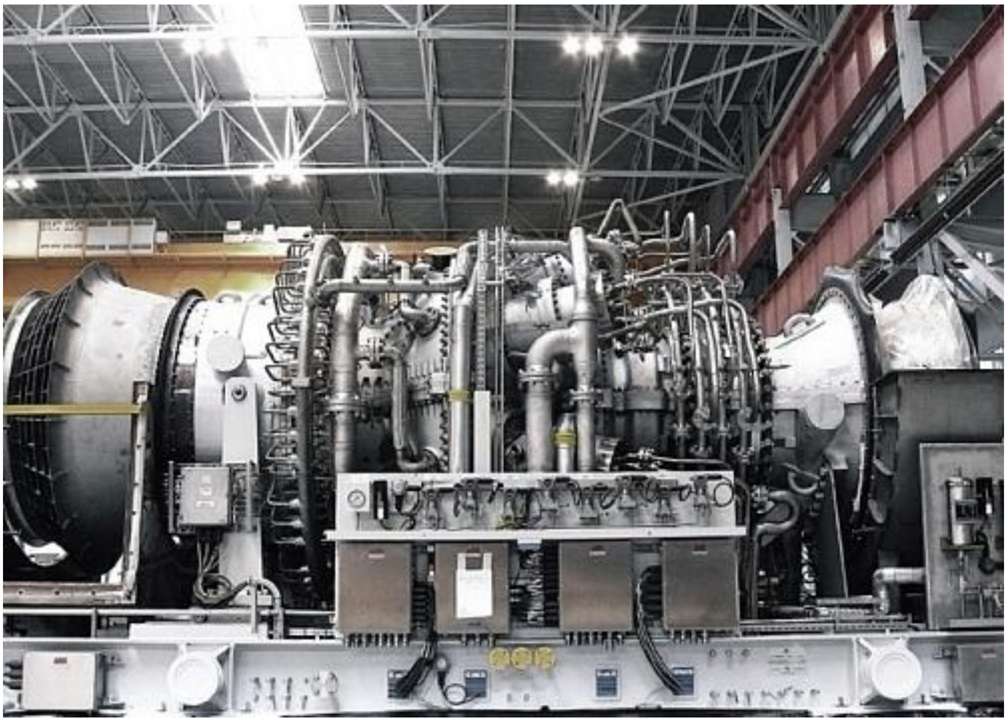

Figure 3. GTU MS5002E [12]

In the variant of using GTU MS5002E as a mechanical drive, it has a capacity of 32 MW and an efficiency of 36%, in the generator version - a capacity of 31.1 MW and an efficiency of 35%.

GTU is equipped with a low-emission combustion chamber and is extremely reliable in operation. Elements of the unit are designed by methods allowing to ensure its reliable operation in difficult climatic conditions and to provide all necessary volume of on-site service. GTU is installed in an easy-to-assemble hangar-shelter.

The 11-stage axial compressor provides a compression ratio of 17. It is designed on the basis of the axial compressor of the well-known GTU GE10 (more than 80 operating units, over 700,000 operating hours). The input guiding device and the guide blades of the first and second stages of the axial compressor are adjustable; their rotation is carried out by a hydraulic oil drive. Atmospheric air entering the inlet pipe of the compressor is pre-cleaned in an air filtering and conditioning system (AFCS).

The combustion chamber of type DLN2 is countercurrent and structurally made in the form of 6 separate flame tubes, evenly distributed (each in its housing) in the circumferential direction on the outlet housing of the axial compressor. Each of the six flame tubes has 5 burners designed to work on gaseous fuels.

A two-stage high-pressure turbine provides high efficiency in a wide range of operating modes. Both stages have a developed system of air cooling of convective and film types. For cooling, air drawn from the delivery pipe of the axial compressor is used.

The two-stage power turbine is based on the well-known PGT2S + turbine (over 80 operating units, over 500,000 operating hours). Turbine bearings are easily accessible for inspection.

Structurally GTU MS5002E is located on two separate frames (one is for turbo-block, the other is for the auxiliary equipment). On the auxiliary equipment frame, which is also an "oil tank", there are:

- oil supply system with pumps and filters;
- hydraulic oil system;
- starting system with a barring device and torque converter;
- fuel gas system, etc.

The body of the gas generator is made with a horizontal connector, the power turbine module does not have it.

Figure 4. GCU-32 "Ladoga" [13]

Both frames (of turbo-block and auxiliary equipment) are equipped with acoustic enclosure and heat insulation, which allows the maintenance of GTU in field. External cooling of the turbo-block and the equipment installed under the enclosures is carried out by supplying atmospheric air to the spaces under the enclosures with the help of blowers taking air from the atmosphere through separate sections of the AFCS.

The control system is based on the MARKVI control unit supplied by GeneralElectric.

Table 4. Technical specifications of GTU MS5002E

Parameters	Generator drive	Mechanical drive
Power on the turbine shaft, kW	31100	32000
GTU efficiency, %	35	36
Compression ratio in axial compressor	17	17
Exhaust gas flow rate behind the power turbine, kg/s	101	101
Exhaust gas temperature, ^{0}C	510	510

4. Conclusion

In this paper, the features of ensuring the energy efficiency of equipment for gas transportation at the design stage were shown. As an example, a variant of an algorithm implementation with preliminary calculation and selection of the latest gas pumping equipment is shown. Herewith, the construction stage of the cycle implies that construction and installation work must be carried out in full accordance with design decisions and regulatory documents such as SNiP, administrative regulations, technical conditions and equipment passports. Thus, compliance with the requirements of efficiency, reliability, safety at all stages and their qualitative monitoring will ensure the functioning of the gas transportation system at a high technological level. Analysis results and algorithms can be used by design and expert organizations.

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