NEW APPROACH TO INCREASING THE ENERGY EFFICIENCY OF A LARGE-SCALE GAS TRANSPORTATION SYSTEM

GEORGY FOKIN

GAZPROM TRANSGAZ SAINT PETERSBURG, LLC

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FOREWORD

As humankind develops, there is constant increase in energy production, both in gross terms and per capita. The most common form of energy used by humans is electricity, given that it has a number of advantages: an established base of production, convenient delivery to end-user, universality, and convenience and ease in converting it to other types of energy.

Hydroelectric, nuclear and thermal power plants are the backbone of modern energetics. The structure of electricity production, however, varies substantially from country to country. So, for example, in France more than 75% of the electricity is generated by nuclear power plants (NPP), in Norway almost 90% is generated by hydroelectric power plants (HPP), and in Russia the production of electricity is mainly concentrated in thermal power plants (TPP) - at more than 67%. The breakdown of electricity production worldwide is: TPPs provide 63% of production, HPPs - 20%, and NPPs- 17%.

At present, the annual production of electricity worldwide exceeds 20 trillion kW/hour (20,000 million kW h), an increase of more than 4 times over the last 30 years. According to data from FY 2010, most of the electricity is produced (in kW h) by: the USA (4.33 T), China (4.21 T), Japan (1.15 T) and Russia (1.04 T).

Thus, the bulk of electricity is generated at thermal power plants, the main source of energy being fossil fuels, that is, solid (mainly coal), liquid (petroleum products) and gaseous (natural gas). However, there is an increased tendency to utilize natural gas at power stations as this reduces the amount of air pollutants.

Global energy consumption from 2008 to 2035 will grow by 53%, and approximately half of this expected growth will fall to China and India, as said by the Bloomberg agency, referring to a U.S. Department of Energy report. In order to meet the demand for fuel, global extraction of natural gas will increase during this period by 52% - up to 4.79 T cubic meters.

According to other estimates, by 2040 the volume of electric energy consumption will increase by 32% worldwide as a result of population growth, causing an increased demand in industry, transportation and the private sector, as mentioned in Exxon Mobil Corporation's annual forecast. Natural gas consumption for generating electricity will rise by 62%, thereby moving into second place in electric energy production, after petroleum, and squeezing out coal.

An analysis of the present situation and forecast of the developments in energetics indicate both an increase in the share of natural gas used in energy production and a substantial increase in its extraction.

In order to supply natural gas to power stations and other industrial and domestic facilities, a network of main gas pipelines including delivery pipes with compressor stations (CS) has been formed. To facilitate gas transportation, gas inside the CS is burned, but this creates an additional source of harmful chemical and thermal pollution.

As the production of electrical and fuel energy rises and, along with this, the demand for natural gas increases, everything grows at an increasingly high rate, including the impact on the environment, which comes in various forms of pollution: biological, mechanical, chemical, thermal, light, noise, electromagnetic, and radioactive. The scale of this phenomenon is becoming global and affects various aspects of life just about anywhere on the planet.

In order to solve the contradiction between the demand for increased energy production and the desire to avoid pollution of the environment, it is necessary to focus on increasing the efficiency of fuel energy utilization obtained in burning fossil fuels. This report is devoted to the above subject, with regard to large-scale gas transportation systems.

GOALS

The work presented here is devoted to increasing the efficiency of organic sources of thermal energy and, specifically, natural gas. This is a challenge posed by life which is reflected in the legislation of the Russian Federation, including federal law No. 261-ФЗ, dated Nov. 23, 2009, "On Energy Conservation and Energy Efficiency, and on Amending Certain Legislative Acts of the Russian Federation."

The technology used for natural gas extraction and transportation requires cross-country gas pipelines to deliver gas to the end-user. In order to increase throughput capacity of the pipeline, gas should be compressed to high pressure values (5-10 MPa and more), but to compensate for hydraulic losses additional energy must be periodically conveyed to gas. This is carried out at compressor stations located every 100 to 150 km in cross-country gas pipelines.

There are three aspects to increasing the energy efficiency of a gas transportation system:

1. The mechanical energy required to create the energy to pressurize gas and compensate for hydraulic losses is mainly produced by gas turbine units. In order to obtain this energy, 0.2-0.3% of the natural gas flow pumped through a compressor station (CS) is burned in turbine combustion chambers at every CS. Thus, during gas transportation from recovery fields (for example in West Siberia) to the end-user (European Community countries), as much as 6-7% of the total volume of pumped gas is burned in combustion chambers. So, only a part of the heat energy is conveyed in the form of pressurized natural gas, about 70% of this energy being emitted into the environment with escaping gases, causing heat pollution as well as nitrogen and carbon oxide pollution. This has become more and more noticeable in recent years and is increasingly attracting the attention of ecologists. If this escaping energy could be put to use it would be a huge contribution to energy conservation and ecology.
2. Between compressor stations the pressure of fuel gas in cross-country pipelines is throttled (reduced) from 5.4-9.8 MPa to 2-3.6 MPa. Thus, the energy received from burning fuel gas at previous stations is completely lost. Moreover, when natural gas is delivered to the end-user, whether it be household or industrial, gas pressure at gas distribution stations (GDS) must be lowered; that is, gas pressure coming through cross-country pipelines must be reduced to the end-user's pressure (0.3-1.2 MPa). When this occurs, as it does with the existing technology, the gas pressure energy received at the previous CS is completely lost.
3. In order to increase the throughput capacity of gas pipelines and to increase gas reserves in the pipeline, gas should be cooled after every compressor station. This is done by gas air cooling units (ACU) using atmospheric air gas blasting. Although electric energy to drive the ACU fan motors must be expended, the fuel gas saved at compressor stations makes up for this expenditure. However, the balance

between power supply expenditures and gas flow gains in pipelines with multiple compressor stations remains unresolved.

The analysis of the above three problems and, more importantly, their solutions are presented in this work.

METHODS AND RESULTS

In 2005, the proportion of fossil fuels consumed in Russia was 70.3%, (175.2 million tons of standard fuel), the proportion of coal was 26.4% (65.9 million tons of standard fuel), and fuel oil made up 2.7% (6.6 million tons of standard fuel). Other fuel types consumed in 2005 made up 0.6% (1.6 million tons of standard fuel). For the same year, Russian thermal power stations were supplied with unprocessed fuels comprising 117.8 million tons of coal, 151.8 billion cubic meters of gas, 4.7 million tons of fossil fuels and 1.3 million tons of peat. The consumption rate remains approximately the same today.

Natural gas is an indispensable resource. It can be pumped out of the ground, easily and economically transported through pipelines over a great distance, and supplied to remote localities. Natural gas can be very efficient (up to 90%, not including transportation losses). The specific heat from burned gas is about as high as that of oil. Gas can be converted fairly simply into liquid for shipping by sea or land and is the method used for delivering gas to Japan and Korea. Gas is, however, a valuable chemical raw material used in the production of miscellaneous goods; this means that large-scale usage of gas fuel for producing electricity, where other methods are available, can lead to serious problems. Our grandchildren may later resent us for not having the wisdom to limit global gas usage in time and leave them with at least some gas fuel. Moreover, it is highly likely that the exclusive role of natural gas as an energy producing fuel will lead to an increase in its cost in the future, in which case it will be less competitive in the production of energy.

According to gas industry experts, energy consumption of gas transmitted through Russian pipelines is 50-70% higher than in the USA and countries of Europe. In 2010 the price of gas in European countries reached 400 USD per 1000 cubic meters.
The development of new gas fields requires serious investments. Therefore, the struggle to save energy and increase efficiency in gas transportation, and to reduce gas flow at compressor stations becomes more and more significant.

Russia is the worldwide leader in natural gas extraction.

Table 1. Leading world gas extractors

Country	2010	2006	
	Extraction, In billions of m^3	Extraction, In billions of m^3	World Market Share (%)
Russian Federation	647	673.46	18
United States of America	619	667	18
Canada	158		
Iran	152	170	5
Norway	110	143	4
China	98		
Netherlands	89	77.67	2.1
Indonesia	82	88.1	2.4
Saudi Arabia	77	85.7	2.3
Algeria	68	171.3	5
Uzbekistan	65		
Turkmenistan		66.2	1.8

Egypt	63		
Great Britain	60		
Malaysia	59	69.9	1.9
India	53		
United Arab Emirates	52		
Mexico	50		
Azerbaijan		41	1.1
Other countries		1440.17	38.4
World gas production		3646	100

The Russian open joint-stock company Gazprom OJSC (OAO GAZPROM) operates the longest ranging gas-transportation system in the world (Fig. 1) of more than 155 thousand km of cross-country gas pipelines, and this number increases every year .

Fig. 1 Unified gas supply system

More than 85% of gas compressor units have actuators from gas compressor stations with an efficiency rate of 23-35% (Fig. 2) and weighted average efficiency rate of 31.2%. This means that about 1.2-1.3 million GJ of heat per year are released into the atmosphere with gas emissions from compressor plants. Harnessing this heat would generate about 5000 MW of electricity.

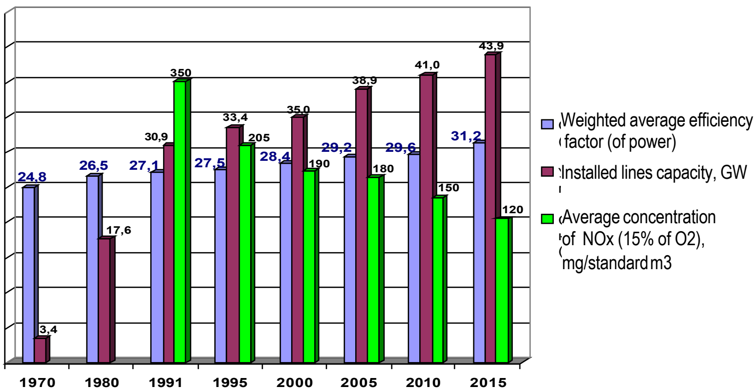


Figure 2. Characteristics of all gas compressor units

More than 4000 gas compressor units with a total capacity of 44.2 GW provide gas transportation in Russia. Annually, these units pump about 700 billion cubic meters of natural gas.

One of the largest gas transport enterprises in Russia, Gazprom transgaz Saint Petersburg LLC, a 100% subsidiary of Gazprom OJSC, operates more than 10 thousand kilometres of gas lines (Fig. 3), 28 compressor plants with 175 gas compressor units and total power of more than 1300 MW, of these 1000 MW are derived by gas turbine drives.

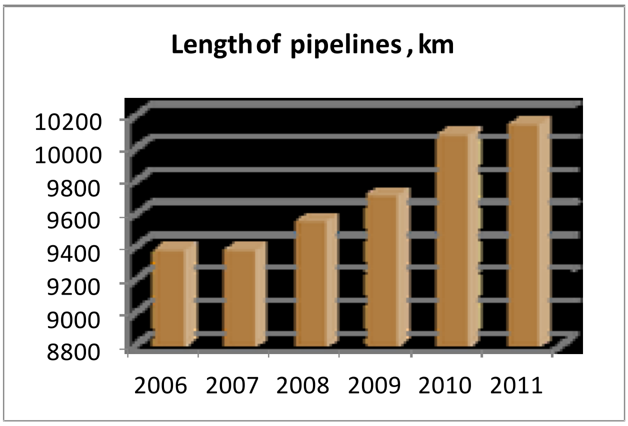


Fig. 3 Length of Gas Transportation System pipelines

The average annual volume of transported gas exceeds 100 billion cubic meters, Fig. 4, of that more than 70% of the transported gas is exported to international customers, and a large part of this gas is pumped through gas compressor units with gas turbine drives.

Transportation volumes, in billions of cubic m.

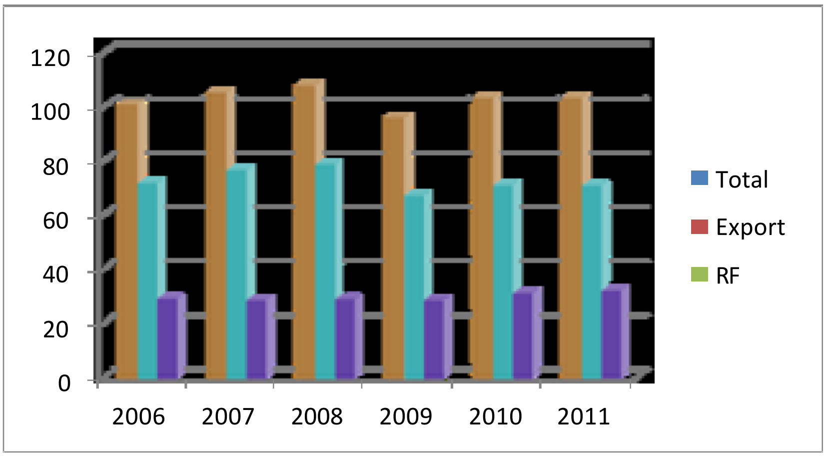


Fig.4. Gas transportation volumes

The amount of potential thermal energy transported via cross-country gas pipelines is enormous. One example of this type of pipeline is the Yamal-Europe gas pipeline, which transports natural gas from Russia across the Republic of Belarus to European countries. Its estimated capacity equals 33 billion cubic meters of gas per year. If we take the average calorific value of gas to be 38,500 kJ/cubic meters, we obtain a potential gas flow capacity in the main pipeline of 40,290 MW, exceeding the total capacity of all large hydro power stations operating in Russia (Table 2), or about 10 times the power of one of the largest nuclear power plants in Russia – The Leningrad NPP. And this is just for a single gas line.

Table 2.

Description	Installed capacity, MW
Sajano-Shushenskaja HPS	6400
Krasnojarskaja HPS	6000
Bratskaja HPS	4500
Ust-Ilimskaja HPS	3840
Volgogradskaja HPS	2541
VOGES HPS	2300
Cheboksarskaja HPS	1370
Saratovskaja HPS	1360
Zejskaja HPS	1330
Nizhnekamskaja HPS	1205
Zagorskaja HPS	1200
Votkinskaja HPS	1020
Chirkejskaja HPS	1000
Total capacity	**34066**

If we use the same reasoning for GTS total gas flow (more than 100 billion cubic meters), then the potential power is 126,250 MW. And since the first line of the North European Gas Pipeline (Nord Stream), projected capacity of 27.5 billion cubic meters per year, was launched in 2011 and a second line of the same capacity will be launched in the near future, then the total power potential of gas transported through GPS equals about 200,000 MW. This is quite a large amount, and an improvement of energy efficiency in gas transportation will result in a large economic benefit.

At the same time, the energy from gas burned in combustion chambers of gas compressor units is used only for building up pressure in the mains, but then is completely lost, as is the pressure energy of compressed gas.

A considerable part of this energy could be put to good use.

Let us, then, consider ways to meet the goals mentioned above.

1. **Thermal potential** of exhaust gases is fairly substantial. Let us analyze it in terms of the aforementioned Yamal-Europe gas pipeline, Fig. 5.

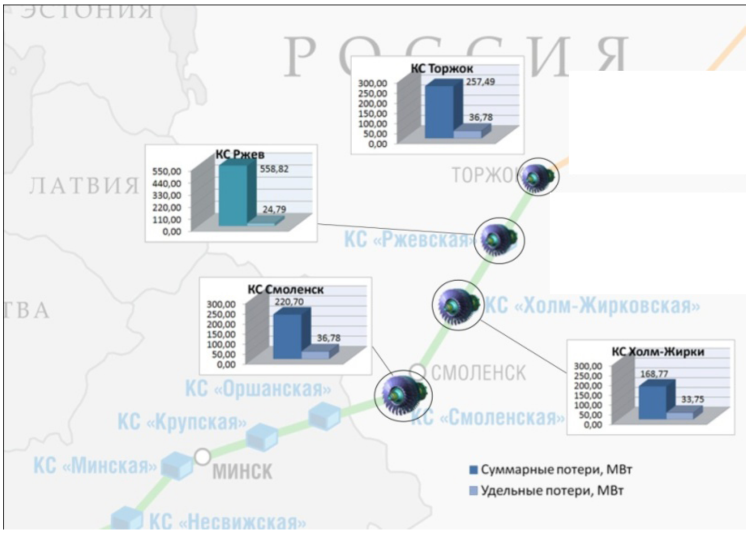


Figure 5. Yamal-Europe gas pipeline, Russian side.

Thermal energy specific loss along the Yamal-Europe gas pipeline is 22.5 to 36.78 MW. This lost thermal power could provide from 3 to 5.5 MW of electric power, while increasing the overall efficiency of fuel gas thermal energy use. Therefore, this strategy is particularly attractive, since, in addition to raising energy efficiency, we can simultaneously solve the ecological problem because, when retaining emissions (carbon and nitrogen oxides) during fuel gas burning, useful energy generation increases and thermal environmental stress decreases.

At present, natural gas blowers are generally driven by gas turbines, and the efficiency for the heat combustion of fuel gas is no more than 23-35%. So, 3/4 to 2/3 of thermal energy is injected into the atmosphere. In-house electric power needs at compressor stations are met either by purchasing electric power or by producing electricity at captive power plants with additional fuel consumption, which, in a world where prices for hydrocarbons are continuously rising, reduces the energy efficiency of gas supply via cross-country pipelines and decreases competitive strength of gas transportation companies. At the same time, compressor stations annually emit thermal energy with exhaust gases at an amount of 1.2-1.3 million GJ, which could be used to generate additional power, including electrical, up to 5,000 MW. We propose to use combined steam-and-gas units, including combustion-steam turbines, to generate additional in-house electrical power, using the same burned fuel gas, which will raise heat use efficiency up to 38-52%.

The solution is to install steam-turbine (not necessarily water-steam) heat-utilization units; that is, install these in waste-heat exchangers at compressor stations, where all, or part of, hot turbine exhaust gases are directed, and install one or several steam-turbines as actuators for natural gas blowers or generators.

About 10 heat-utilization units at compressor stations are currently operating in Italy, Germany, Switzerland, the USA and Russia. Since 2011, Gazprom transgaz Saint Petersburg LLC has been carrying out research-and-development activities to design a pilot model of a combined steam-and-gas utilization unit that will generate electric power for in-house needs of compressor stations. The unit includes a gas turbine that operates at a compressor station and a newly designed utilization steam-turbine unit that uses a turbo-generator with choked-flow, low flow-rate turbine and high-speed synchronous electric generator with permanent magnet excitation. This approach makes it possible to design power generating units with unique size and weight parameters.

One of the most important initial-stage items is to select a working medium for a utilization steam turbine. During an analysis of the thermal efficiency of various vapors, the following substances were examined: ammonia, water, butane, isobutane, pentane, isopentane, Freons R114 and R245fa.

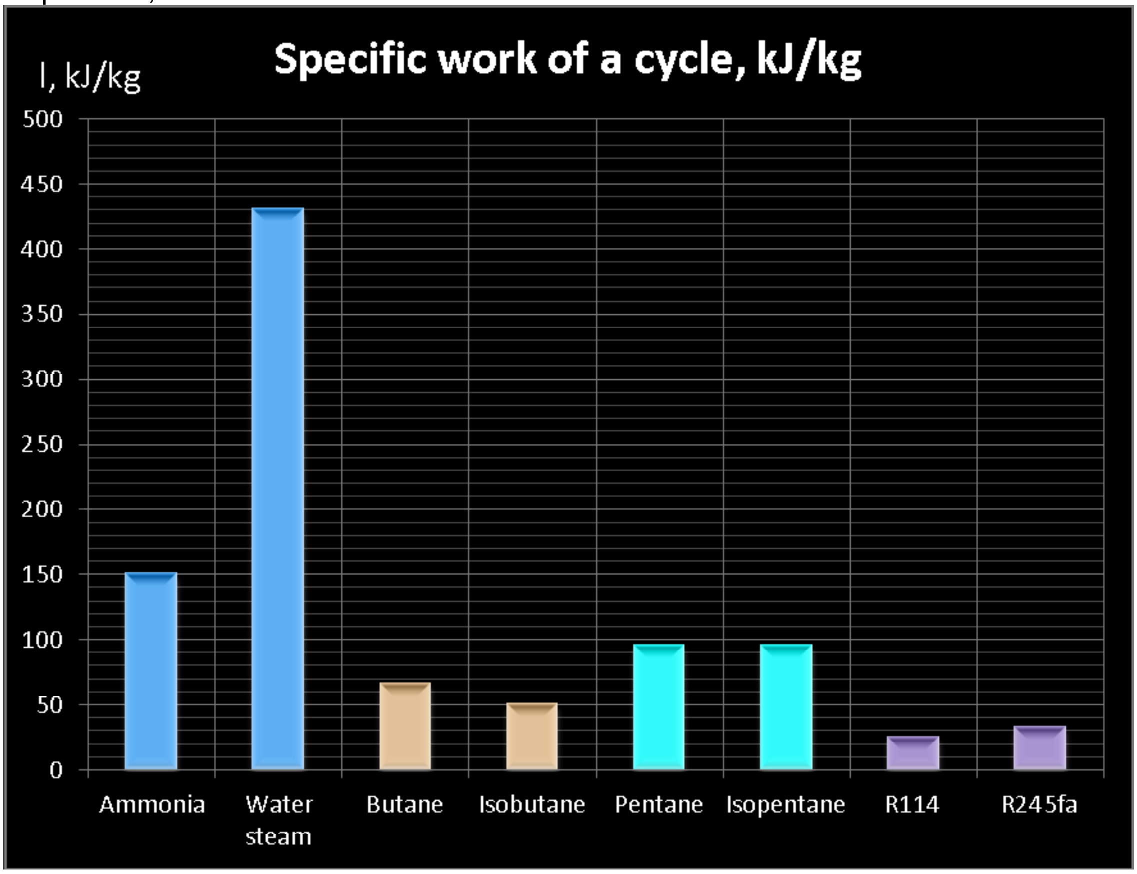


Fig. 6. Specific work of vapor cycles.

The substances compared show similar results with respect to thermal efficiency, but in terms of specific work, water vapor has significant advantages, Fig. 6, making it the favorite for utilization steam turbine design.

The use of Freon (khladon) R245fa is also being considered as it is ecologically clean, explosion proof, non-combustible, ozone safe, nontoxic, with maximum boiling temperatures from 20 to 40^{O}C, and frostproof. Furthermore, using Freon makes it possible to apply low-grade thermal energy usefully, which considerably expands the applicability of the designed units.

At the first stage of work, the following was completed:

- calculations for thermodynamic cycle of steam-turbine unit using various substances;
- gas dynamic, thermodynamic and strength calculations for the steam turbine flow part, optimization of gas dynamic, thermodynamic and geometric parameters based on a target function analysis;
- electromagnetic, heat and strength calculations and optimization of high-speed synchronous electrical generator with permanent magnets;
- calculations for operation modes of a turbo-generator that uses a steam turbine and a high-speed electrical generator.

Electric power generated by a utilization unit can be used for compressor station in-house needs, such as:

- lighting the compressor station site;

- heating buildings and facilities at the site;
- supplying power for communication systems, telemechanics stations, electrochemical protection systems;
- supplying power to external users, by transferring power to external electricity networks while maintaining stable operation modes in the utilization turbo-generator units;
- actuator for electric motors in gas ACUs;
- actuator for electric motors in compressor station equipment – pumps, fans, air blowers, etc.
- actuator for the main technological equipment at compressor stations – natural gas blowers.

The work will be completed in 2013 in the form of a working prototype.

It is important to note that such heat-utilization independent power units can also be used at other facilities where there is low potential exhaust gas heat – electric power stations, boiler houses and other thermal facilities.

2.1. Fuel gas of gas compressor units

To increase the efficiency of compressor stations, it is necessary to use the energy from the pressure produced during fuel gas reduction before its transfer to combustion chambers of GDUs. A facility having three GDUs with a capacity of 16 MW each, consumes about 450 thousand cubic meters of fuel gas per day. In addition, up to 300 kW of electric power can be generated, which fulfills most of the basic in-house needs of a compressor station. The efficiency output for converting fuel gas pressure energy into electricity is 71% to 82%. It is important to note that electricity is generated without additional fuel combustion, and without additional gas consumption; and that the power generation process fits seamlessly into the basic technological process and equipment design of the compressor station. In summary, we propose to use turbo-electric generators based on an extension turbine to generate in-house CS electrical power needs that will increase the energy efficiency of the natural gas supply. At this time, the scientific and technical substantiation has been completed. In the coming years we plan to begin implementation of this project.

2.2. Natural gas at gas distributing stations GDS

Gas in cross-country pipelines is throttled at gas distribution stations (GDS) before it reaches the end-user. Thus, in the gas transmission system described here, out of an annual 100 billion cubic meters of transferred gas, only about 30% (i.e. 28.7-29.1 billion cubic meters) was supplied to Russian consumers. Hourly gas consumption came to a total of 3.31 million cubic meters. Meanwhile, a microturboexpander generator МДГ-20, with electric power of 20 kW, created by Gazprom transgaz Saint Petersburg LLC, consumes just 1200 cubic meters per hour. Therefore, the total power generation potential of a GDS adds up to more than 55 MW.

Research on how to use the energy from reducible gas at GDSs was carried out by Gazprom transgaz Saint Petersburg LLC in 2007-08. This work was directed at selecting the type and parameters for a microturboexpander generator with an expansive low-consumption turbine developed at Saint-Petersburg Polytechnic University (SPbSPU) and high RPM electric generator with permanent magnets developed by Microturbinnye Tekhnologii LLC RDS. In 2010-11 a prototype of a microturboexpander generator was designed and then assembled at Sertolovo GDS. The main features of this state-of-the-art equipment is high quality electric power, high efficiency and absence of an oil system.

The most up-to date scientific achievements were employed in the development of the Microturboexpander generator МДГ-20 design, making it a world-class unit:

a) Low flow-rate extension turbine

This turbine represents a new class of turbines, Fig. 7, characterized by the following main features:

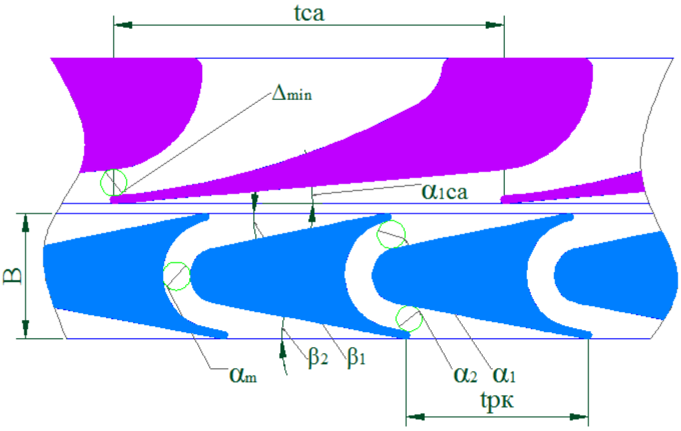


Fig. 7 Flow part of the low flow-rate turbine

- small angles of outlet from the nozzle block (NB), α_{1r} =3…9°;
- wide angles of flow rotation in the impeller wheel (IW),θ_2 =160…170°;
- small angles of inlet into IW, β_{1r} = 6…14 °;
- small amount of nozzle blades and rotating blades (z_{nb} ≥ 2) and (z_{iw} ≥ 6…8) as compared to conventional turbines;
- high relative pitch $\bar{t}$ of nozzle blades (t/b ≥ 1.0) and rotating blades (t/b ≥ 1.2);
- small volume flow rates of the working medium;
- possibility of considerable enthalpy drops with comparatively high economical efficiency;
- transonic and supersonic flows in NB and in IW;
- increased erosion resistance of nozzle and working screens.

b) High-speed synchronous generator with permanent magnets

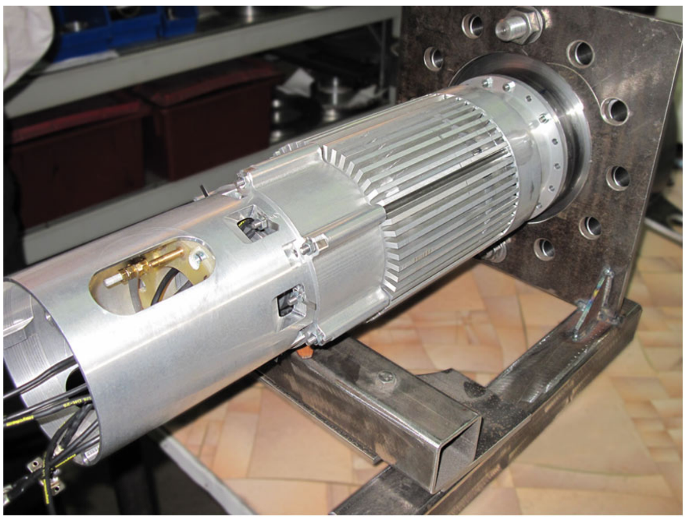


Fig. 8. Synchronous generator

- synchronous generator, Fig. 8, is made with permanent super strong magnet excitation;
- is distinguished by high reliability;
- has a substantial advantage - simplicity of design and maintenance – is an important factor for the facilities of autonomous and small-scale power generation;
- has a higher performance factor;
- provides a reliable excitement;
- has improved output, size, weight and noise characteristics;
- has a simple cooling system.

c) **Spade gas dynamic bearings (SGDB), Fig. 9**

SGDBs have several advantages:

- SGDBs ensure operational integrity over a wide range of temperatures and therefore have all the advantages pertaining to gas-lubricated bearings;
- provide high rotational speed of supported shaft;
- are ecologically clean because they use ambient air or other working gases, such as natural gas, as a lubricant;
- eliminate the need for the delivery of special lubricants, which is particularly important when working in distant regions

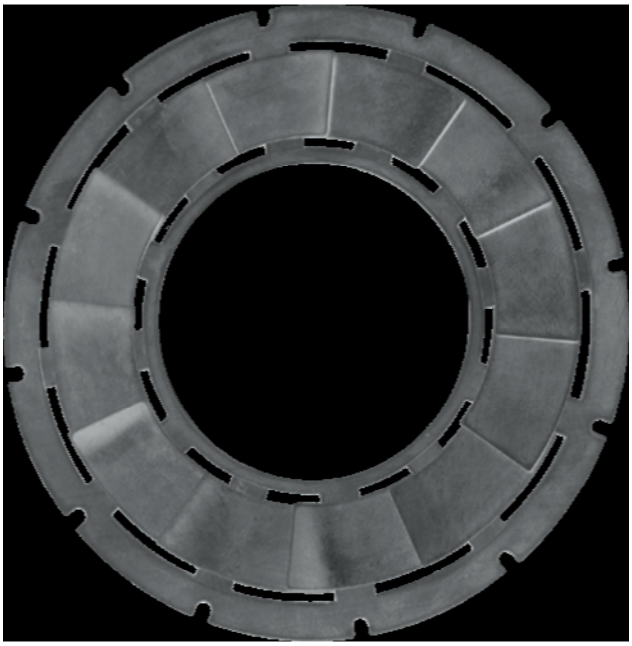


Fig. 9. Thrust spade gas dynamic bearing

As a result of the research, the МДГ-20 microturboexpander generator, Fig. 10, was designed, developed, manufactured, tested and put into production.

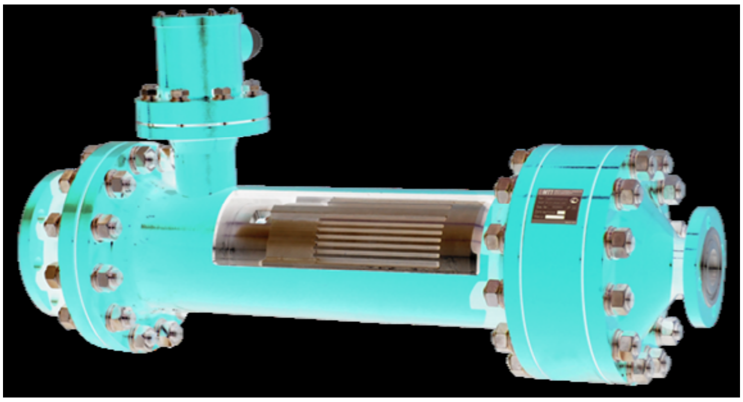


Fig. 10 МДГ-20 microturboexpander generator

The external characteristics of МДГ-20 are given in Table 3.

Table 3. External characteristics of МДГ-20

Electric power	kW	20
Output voltage (line voltage)	V	380
Output voltage (phase voltage)	V	220
Number of phases	-	3 + PE
Frequency	Hz	50
Output voltage waveform distortion factor	%	Not more than 12
Performance factor of the turbo-generator part with inverter during electrical energy generation	%	70
Assigned resource under a load factor of 0.6	year	20
Total number of starts, not more than	-	2500
Rotor speed	rpm	36000

Some of the special features of this turbo-generator are:

- high performance factor, not less than 70%;
- absence of a lubrication system and all its elements;
- extremely low size and weight parameters, and compactness of the unit - 20 kW of power at the generator terminals due to the operation of a single-stage turbine with a diameter of 126 mm;
- weight of turbo-generator rotor is only 8 kg;
- high explosive and fire safety;
- single case design made for the total gas pressure at the gas distribution station as required by regulations of Gazprom OJSC;
- low maintenance - maintenance is required not more than twice a year;
- highly ecological - no need to burn additional fuel to produce electricity
- МДГ-20 control system can:
    - a) automatically implement all types of protection;
    - b) remotely monitor and manage work;
    - c) automatically change over to a new mode of operation within a wide range of load change;
    - d) simultaneously operate several turbo-generators.

In addition to use in the gas industry, the above-mentioned independent power plants (IPP) of low power can be used in other fields that have low-grade thermal energy sources:

- industrial plants, thermoelectric power facilities and public facilities;
- cross-country gas pipelines, gas distribution stations;
- domestic waste plants in big cities;
- big livestock farms, agro-product processing enterprises, timber cutting product companies, and others in need of electrical and mechanical energy, etc.

The utilization efficiency of IPP of low power is determined by:

- reduction in unit cost of electric power and heat generation by using improved equipment;
- improvement in power supply reliability;
- substantial reduction in construction time;
- independence from the electric power system;
- reduction in size of territory needed for large power plants;
- possible increase in ecological compatibility of electric power and heat generation by a reduction in environmental control costs;
- usage of advanced state-of-the-art technologies and engineering solutions while developing new equipment.

3 Improvements in operation of gas compressor stations (CS) and linear section of gas pipelines

Electricity generated by applying the above proposals can be used to drive the air-cooling units' (ACU) fans.

When refrigerating gas in ACUs, heavy expenditures of electricity are required to drive ACU electric motors. At the same time, the increase in cooling depths can result in a decrease in hydraulic losses in the next gas pipeline section after the CS, which leads to reduced fuel gas consumption both in the current compressor station and those which follow. This highlights a rather complex and controversial balance between electrical energy expenses and fuel gas economy.

The purpose of this work is to identify the operation modes for air cooling units which, at the given gas pipeline productivity rate and thermal and physical characteristics of gas, will ensure minimal total expenditures for transporting gas via cross-country pipelines. These operation modes must take into account the influence of the ambient temperature in the gas pipeline system. The target of our research is the Russian section of the Yamal-Europe gas pipeline from its starting point in the town of Torzhok to the city of Smolensk located at the Republic of Belarus border.

The three pipeline sections are being considered are:

- Torzhok - Rzhev;
- Rzhev – Holm-Zhirkovski;
- Holm-Zhirkovski – Smolensk

The above sections are located between four compressor stations (CS), each containing a different quantity and types of air cooling units (ACU); Fig. 11 shows the configuration for an ACU at one of the CSs and Fig. 12 shows the exterior view of the ACU.

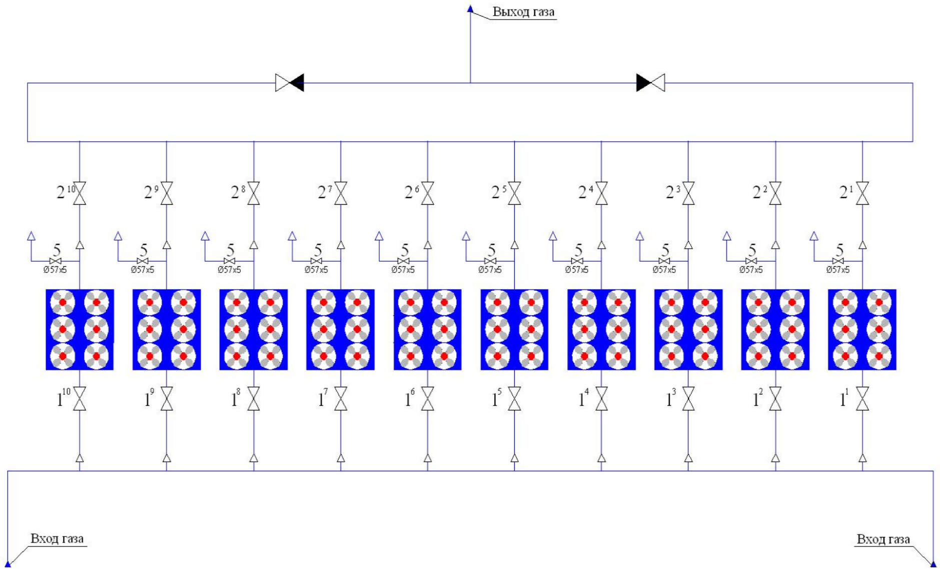


Fig. 11. ACU configuration at a CS.


Fig. 12. Exterior view of ACU

Power consumption for transmitting gas has two components:

- cost of electricity to drive the ACU's fans;
- gas-turbine unit's consumption of fuel gas to drive natural gas blowers.

The aim of the work is to determine the optimum mode, configuration, and quantity of ACUs at which the total power consumption for natural gas transmissions at the pipeline's given productivity rate is minimum.

To solve this problem a multifactor mathematical model was created. The model tests showed that the significant factors affecting calculation results are as follows:

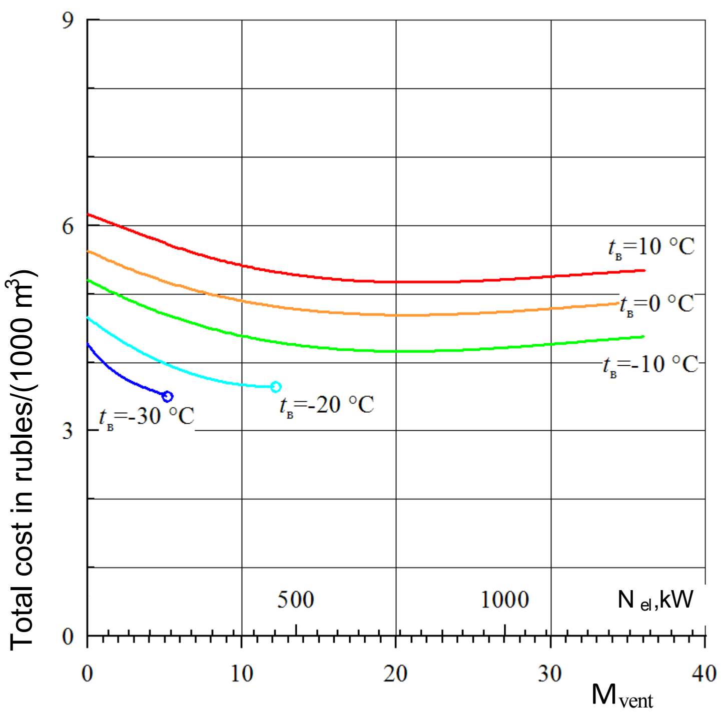
- gas pressure in the cross-country pipeline;
- gas flow rate via the cross-country pipeline section;
- ground temperature at the depth of the cross-country pipeline location;

- ambient air temperature;
- number and order of operating ACUs.

To confirm the validity of the model, tests were carried out at the Gryazovets-Leningrad pipeline section, which includes three compressor stations. One and a half months of successive start-stop tests of the ACUs were carried out, and changes in thermal and physical parameters of compressor stations, gas distributing stations and block valves were registered. Simultaneously, the same parameters were calculated for the model. The comparison of the estimated and test results showed the maximum deviation in temperature to be 2.5%, and in pressure 0.3%. This proved the model's validity and made it possible to perform the main portion of calculation work for the Yamal-Europe pipeline.

The calculation results were presented in monetary terms, i.e. change in cost in rubles for transmission of 1000 cubic meters of natural gas based on variations in the above parameters. Simultaneously, these calculations were compared to telemetric information received on the variations in the parameters registered on the compressor stations and block valves. The convergence of results between the model and this pipeline appeared to be even higher, i.e. the deviation in pressure did not exceed 0.64%, and in temperature not more than 0.58%.

The above results showed that there are combinations of parameters at which a clear-cut minimum of expenditures for gas transmission can be observed (Fig. 13); but there are also combinations of parameters that, when starting an ACU, actually increase expenditures (Fig. 14).



t_a=-30°C t_a=-20°C t_a=-10°C t_a=0°C t_a=-10°C

Fig. 13. Total cost for pumping 1000 m^3 of gas depending on the number of ACU ventilators turned on at Torzhok compressor station on the Torzhok – Rzhev pipeline, where Tgr = 2°C, q = 90 Mio m^3/twenty-four hours and p2н = 80 kg/cm^2

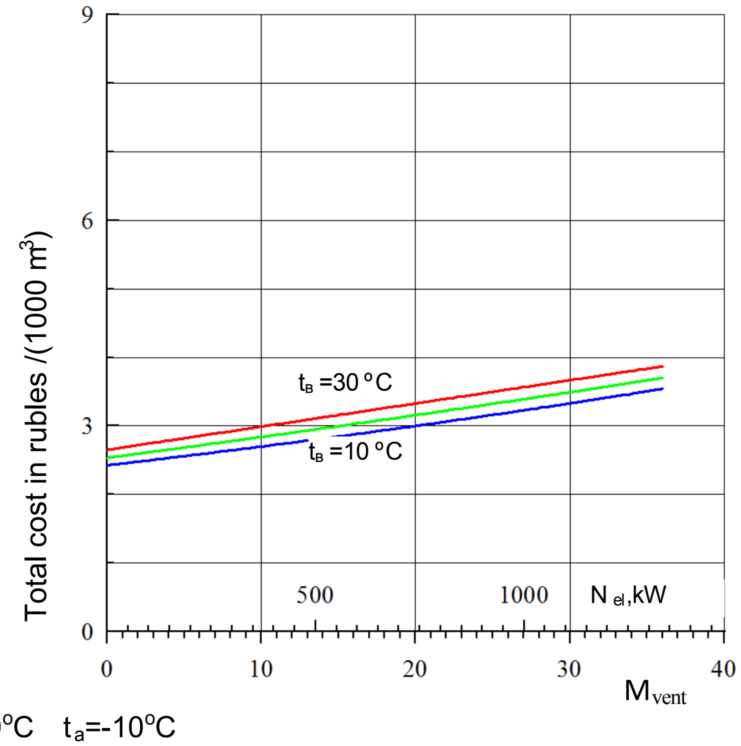


Fig. 14. Total cost for pumping 1000 m^3 of gas depending on the number of ACU ventilators turned on at Torzhok compressor station on the Torzhok – Rzhev pipeline, where Tgr = 13°C, q = 60 Mio m^3/twenty-four hours and $p2_H$ = 80 kg/cm^2

The results of the research performed in 2009-2010 showed that, depending on the pipeline gas flow rate, pipeline pressure and environmental conditions (mainly ground temperature and ambient air temperature), there are optimal modes to reduce the pumping gas costs to a minimum (at current prices for electricity and fuel gas), Fig. 15.

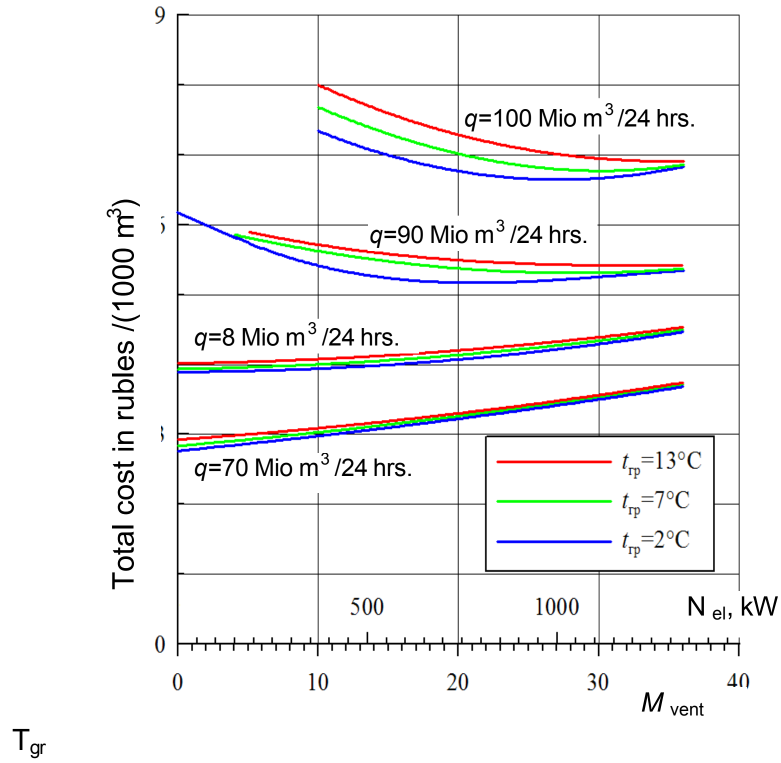


Fig. 15. Total cost for pumping 1000 m^3 of gas depending on the number of ACU ventilators turned on at Torzhok compressor station on the Torzhok – Rzhev pipeline, where Ta = 10°C and $p2_Н$ = 80 kg/cm^2

The results obtained can yield, for one compressor station (depending on natural gas flow rate) an annual saving of 1.6-2.8 Mio USD.

Therefore, the research-and-development activities of 2007– 2011 have made it possible to identify the ways of raising energy efficiency, power saving and improving the environmental friendliness of gas pipeline systems, as well as to outline development plans for the next few years.

CONCLUSIONS AND SUMMARY

The results of the research and pilot-plan work can be summed up as follows:

- **The principles** of design and application of utilisation steam turbines with unique specifications on weight and dimensions for generation of additional electric power, based on utilization of fuel gas used in gas compressor unit, have been justified. This technology allows to improve the heat efficiency up to 38-52%.

- **The methods** of costs definition and minimization related to natural gas transportation, considering the power energy costs for driving the fans of air cooling units, as well as the costs for fuel gas consumption at gas compressor units, allowing annual economy up to $2,8 Mio at one compressor station, have been developed.

- **The microturboexpanding generator** of 20 kW power capacity, using natural gas reduction energy at gas distributing station for electricity production (very ecologically friendly as it requires no additional fuel combustion for operation) has been designed, produced and put into operation.

The results of this work were presented at several international exhibitions, fairs and forums including:

- International forums ENERGY FRESH 2010 and ENERGY FRESH 2011 (Moscow, Central exhibition complex Expocenter, September, 23-24, 2010 and September, 28-29, 2011). Diplomas and special prizes for the best innovation were awarded.
- The 6th International Innovation Fair SIIF-2010 (Seoul, South Korea, December, 2–5, 2010). The gold medal was awarded.
- The 22nd International Innovation and New Technology Exhibition ITEX'11, (Malaysia, Kuala Lumpur, May, 20-22, 2011). The gold medal and one of the main prizes (special prize for the best ecological innovation of the highest quality) were awarded; it was emphasized that energy production does not require additional fuel burning, thus reducing environmental pressure, both in combustion products emission and thermal pollution.