Energy saving technologies during operation of the gas pipeline systems

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Abstract

Russia is the biggest country with powerful fuel and energy complex and with significant energy resources, which is important for economic development. The Russian energy policy is aimed on efficient utilization of natural energy resources. Nowadays Russian income from exports of energy resources is about 60% of total. That’s why energy saving policy is important for stability and secured economic in the country.

Nowadays Russia is producing annually about 600 billion m³ of natural gas and loses 50-60 billion m³ of natural gas and more than 17 billion kW/h of electricity during transportation. That is why energy saving for the Gas industry is needed, especially reducing energy consumption for own needs during gas transportation. Natural gas is non-renewable energy resource and at the present time old gas fields are operating in the mode of falling production while for developing of new gas fields huge investments are needed. That is why problem of energy saving takes significant role in gas industry. Primary direction of energy saving policy in gas industry is gas conservation during all steps of transportation chain from gas deposits to consumers. The main energy consumer during transportation is a compressor station, that is why new technologies and effective modes should be used. Gas consumptions vary seasonally, consumption during winter time is much higher than in summer. Seasonal fluctuations gas volumes passing through the pipeline leads to a deviation mode of the station and as a result losses are increased. That is why it is important to pay attention on gas compressor stations construction, number and power of installed units, and operation modes.
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Introduction

Russia has considerable reserves of energy resources and a heavy fuel and energy sector, which is the base for development of the national economy and the instrument for conduction of the domestic and foreign policy.

The energy sector ensures the functioning of the country and consolidation of the subjects of the Russian Federation, in many respects determining the formation of the basic financial and economical indexes of the country development. Natural fuel and energy, industrial, scientific-and-technical and human resources of the energy sector of the economy are the national patrimony of Russia. The purpose of the energy policy of the country is the maximally efficient utilization of the natural fuel and energy resources and the potential of the energy sector for the economy growth and improvement of the quality of life of its population.

In the late eighties of the past century, there was some reduction in the extraction (production) of all the basic types of fuel. At the same time, the energy intensity of the gross national product didn’t decrease; moreover, it increased and continued to grow over a period of years. Suffice to say that from 1990 to 1992 only, the energy intensity of the gross national products of Russia increased by 35%. Ignoring the problems of saving of the fuel and energy resources has played a defining role in it.

It should be noted that the lack of interest in saving of the fuel and energy resources is to some extent made possible by the low internal prices for the energy carriers as well.

Export of the energy carriers is a substantial part of the currency earnest of the state. In this connection, it is possible to conclude that the energy saving problem is also the problem of the financial security of the country.

Gas is one of the relevant components of the fuel and energy sector, and its realization considerably replenishes the Federal budget. The potential for the development of the Russian gas industry is great, which is promoted not only by the uniqueness of the energy resources, but also by its huge reserves in the territory of Russia, which make one third of the world’s reserves of natural gas.

The main gas company in the Russian Federation is OAO Gazprom. It is involved in exploration, extraction, transportation, storage, processing and realization of gas and other hydrocarbons, as well as generation and sales of the electric and thermal energy.

Among numerous problems, facing the gas industry and largely defining the outlook of its further development, the reduction of power consumption for in-house needs, and particularly for natural gas transmission pipelines, is one of the main issues. With mining of 487.02 billion m³ of gas and providing the transportation of 666.2 billion m³ of gas through its gas pipeline system in 2012, the Gazprom Group of Companies, consumed about 47 billion m³ of gas, over 15 billion kWh of electric energy, and over 25 million Gcal of thermal energy for in-house needs. Over 90% of natural gas and about 80% of electric power, consumed in the industry for in-house process needs, is accounted for the natural gas transmission pipelines at that.
Since natural gas refers to the non-renewable resource, main gas fields (Medvezhye, Urengoyskoye, and Yamburgskoye) are being operated in a declining production mode, and development of new gas fields requires huge investments, the problem of energy saving in the industry is of a particular concern.

Priority area of energy saving for natural gas transmission pipelines, as well as for the whole gas industry, is saving of gas at all stages of its transmission – from gas fields to consumers.

Considering that the major consumers of energy resources at gas transmission are compressor stations (CS), the problem of reducing the power consumption in the industry must be first of all aimed at the improvement in the efficiency of their operation, i.e. at the reduction in gas losses and leaks, improvement in the efficiency if gas compressor units (GCU) installed at CS, optimization of the operating conditions for the main CS systems, efficient utilization of secondary power resources, etc.

Operating conditions of a modern gas transmission line (GTL), as is known, is characterized by the non-uniformity of gas supply during the year. During winter, the gas lines are as a rule operated in the conditions of maximum gas supply, and in summer, when gas consumption is decreasing, in the conditions of partial loading. Seasonal fluctuations of gas supply in a gas line lead to deviation of the operating conditions of the station and units from the designed ones, which results in a non-uniform utilization of the power equipment installed, its shutdown when the CS loading is decreased, reduction in the average annual loading of GC, and as a consequence in the fuel gas overconsumption.

Essential consumptions of natural gas for the needs of its transmission in gas lines are linked to the low actual values of the efficiency for the gas-turbine units (GTU) – the main type of power drive for GCU at CS, which is connected with their operation in the off-design conditions (reduced loading) and deterioration of the technical state. In this connection, the actual efficiency for a part of gas-turbine units, operated on gas lines, frequently is at the level of 20 ÷ 28% at the rated values of 28 ÷ 35%.

Experience in the GTL operation shows that the essential overconsumption of energy resources is also linked with the non-optimality of the operating conditions for the gas transmission systems.

It all indicates the urgency of the studies, aimed at the reduction in the fuel and energy consumption for gas transmission, both in the theoretical and practical points of view.
1 Energy saving in gas industry

Analysis of the development of the national economy shows that the gas industry is now the major constituent of the fuel and energy sector of Russia, and natural gas remains in the foreseeable future one of the major types of a unique fuel and a valuable chemical raw material.

With respect to the energy industry, the XXI-st century is to become a century of gas, considering its huge reserves (which, by the last estimates, reach 190 trillion cubic meters, where over 33 trillion is the Gazprom’s share), modern technologies ensuring its extraction and transmission not only onshore, but also offshore, relatively low price, and high ecological friendliness.

1.1. Gas-transmission system of the country and its main facilities

Russia has considerable reserves of energy resources and a heavy fuel and energy sector, which is the base for development of the national economy and the instrument for conduction of the domestic and foreign policy. Role of the country on the global energy markets determines its geopolitical influence in many respects.

Priority problems of the energy policy of the country are as follows:

- Full and safe provision of the population and national economy with the energy resources at affordable and, at the same time, energy-saving stimulating prices;
- Mitigation of the risks and prevention of crisis situations in the country’s energy supply;
- Reduction of specific expenditures for the production and use of energy resources due to rationalization of their consumption, utilization of energy-saving technologies and equipment, reduction of losses at the extraction, transmission, and realization of the products of the fuel and energy sector (FES), etc.

Analysis of the development of the national economy shows that the gas industry is now the major constituent of the fuel and energy sector of Russia, and natural gas remains in the foreseeable future one of the major types of a unique fuel and a valuable chemical raw material.

At present, OAO Gazprom is the main company for production and realization of gas in the Russian Federation, having a great share in world’s gas reserves and its extraction (Table 1.1 [25]).

Table 1.1 – OAO Gazprom in the energy industry of Russia and worldwide

<table>
<thead>
<tr>
<th>Contribution to formation of the global gas industry indexes</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas reserves*</td>
<td>18.0%</td>
<td>18.0%</td>
<td>17.6%</td>
<td>18.3%</td>
<td>18.3%</td>
</tr>
<tr>
<td>Gas production*</td>
<td>16.7%</td>
<td>14.5%</td>
<td>14.8%</td>
<td>14.5%</td>
<td>13.6%</td>
</tr>
</tbody>
</table>

|-------------------------------------------------------------------------|------|------|------|------|------|
Controlled Russian gas reserves

<table>
<thead>
<tr>
<th></th>
<th>68.9%</th>
<th>69.8%</th>
<th>68.7%</th>
<th>71.8%</th>
<th>72.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas production**</td>
<td>82.7%</td>
<td>79.2%</td>
<td>78.1%</td>
<td>76.5%</td>
<td>74.4%</td>
</tr>
</tbody>
</table>

*Calculated on the basis of the data of the International center of natural gas CEDIGAZ and OAO Gazprom. Data of the international statistics on the extraction and global sales are normalized to the Russian standard conditions using the factor of 1.07.

** Calculated on the basis of the data of Rosstat (Federal State Statistics Service), State Enterprise Central Dispatching Department of Fuel Energy Complex, and OAO Gazprom.

Strategic target of OAO Gazprom is to save the leading positions of the leading producer of natural gas in Russia and establish the company as a leader among the global energy companies by increasing the in-house extraction of natural gas based on the stability and profitability, while effectively extending the base of hydrocarbon resources, optimizing the sales channels, and developing the new projects and new markets, diversifying the types of the activity, and ensuring the security of supplies. The main principle of gas production at OAO Gazprom is characterized by the demand for it. At present, the strategic regions of gas production for a long period are the Yamal Peninsula, Eastern Siberia and the Far East, and the continental shelf of Russia.

The Gazprom’s strategy for the development of perspective fields (Figure 1.1) is supported by the economic efficiency, which is determined by the synchronous building-up of the gas production capacities and facilities for its transmission, processing, and storage.
Due to the development of the gas industry in the Soviet Union and Russia, a high scientific-and-production potential of the industry was created; a number of strategic tasks was resolved on its basis:

- World’s largest gas and gas-condensate fields have been explored and developed and a safe feedstock base established;
- Production of the power-technology equipment for gas and gas condensate extraction, transmission and processing; as well as production of tubes, facilities, and automation and control systems has been mastered;
- Unique fields have been put on stream; gas transmission lines, gas-processing facilities, underground gas storages, and gas distribution stations and networks constructed; and
- Unified gas supply system of (UGSS) of the country have been generated.

It should be noted that formation of the industry took place at extremely low prices for energy resources and strong deficiency in tubes and equipment. In this respect, the gas-transmission system was being primarily formed from minimization of the metal and equipment consumption, and saving of energy resources was almost in the background, as a result of which the value of the average specific energy consumption of the Russian gas lines essentially exceeds this consumption on the foreign gas lines. It all indicates the possibility and the necessity to resolve the problem of reducing the energy consumption in the gas industry.

Unified gas supply system (UGSS) of the Russian Federation, established over many decades, is a unique technological complex, incorporating natural gas fields, a developed network of gas transmission lines, combined in a gas-transmission system (GTS), as well as gas storage and distribution facilities, which now enables transmission of more than 670 billion cubic meters of natural gas yearly.

As of the end of 2012, UGSS operated about 168.3 thousand km of gas lines and branches, 222 of CS, and 3,738 gas-compressor units of various types with the total capacity of the order of 44 million kW. Moreover, the gas-transmission system of the country includes 25 underground gas storages with the capacity of more than 68 billion m³ (Table 1.2 [25]).

Table 1.2 - Main technical characteristics of gas-transmission assets of the Gazprom Group in Russia

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of gas transmission and branch lines in terms of single strings, thousand km</td>
<td>159.5</td>
<td>160.4</td>
<td>161.7</td>
<td>164.7</td>
<td>168.3</td>
</tr>
<tr>
<td>Line compressor stations, units</td>
<td>214</td>
<td>215</td>
<td>215</td>
<td>211</td>
<td>222</td>
</tr>
<tr>
<td>Gas-compressor units (GCU), units</td>
<td>3,669</td>
<td>3,675</td>
<td>3,659</td>
<td>3,630</td>
<td>3,738</td>
</tr>
<tr>
<td>Installed capacity of GCU, thousand</td>
<td>41.6</td>
<td>42.0</td>
<td>42.1</td>
<td>41.7</td>
<td>43.9</td>
</tr>
</tbody>
</table>
Reliability and effectiveness of natural gas transmission is determined by reliability and effectiveness of operation of line sections and CS. It should be noted that as of the end of 2012, the average age of gas lines in GTS of Russia is about 28 years (Table 1.3, Figure 1.2).

Table 1.3 - Structure of gas transmission lines of the Gazprom Group in the territory of Russia by service life, as of December 31, 2012

<table>
<thead>
<tr>
<th>Service life of gas transmission line</th>
<th>Length, km</th>
<th>Share, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under 10 years</td>
<td>19,569</td>
<td>11.9%</td>
</tr>
<tr>
<td>11 to 20 years</td>
<td>21,745</td>
<td>13.2%</td>
</tr>
<tr>
<td>21 to 30 years</td>
<td>64,629</td>
<td>39.3%</td>
</tr>
<tr>
<td>31 to 40 years</td>
<td>31,832</td>
<td>19.3%</td>
</tr>
<tr>
<td>41 to 50 years</td>
<td>19,647</td>
<td>11.9%</td>
</tr>
<tr>
<td>Over 50 years</td>
<td>7,259</td>
<td>4.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>164,681</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Figure 1.2 - Age structure of OAO Gazprom gas lines

Treatment, compression and cooling of natural gas take place at compressor stations of gas transmission lines. The main energy consumption (over 85%) for natural gas transmission is due to the natural gas cooling and compression systems at CS of GTL.

The main consumers of energy resources at CS of GTL are gas-compressor units in the compression systems and air coolers (AC) in the natural gas cooling systems.

At present, gas-turbine, electric, and piston GCU of various capacities and types are used for compression of natural gas at CS of GTL.
The type of a GCU electric drive largely determines the value of energy consumption for gas transmission in a gas line. In this respect, increased requirements to the efficiency in all operating conditions, reliability, ecological friendliness, etc. are set to each type of the drives operated on gas lines.

According to the data of 2012, the fleet of gas-compressor units at CS of OAO Gazprom was as follows (in a quantitative sense): gas-turbine drives (GGCU) made approximately 80%, electric drives (EGCU) made ~16.4%, and piston ones (GEC) ~ 3.6% (Figure 1.3).

![Figure 1.3 – Share of CS power drive types](image)

Accounting that GGCU have, on the average, a capacity, which is higher than that of EGCU, and much higher than GEC, GGCU makes, in terms of the installed capacity, about 85%, and GEC makes less than 1%.

Heavy consumption of natural gas in the process sections of GTL at relatively low ratios of compression at the line CS predetermined the use of centrifugal blowers (CB) for gas compression and the use of gas-turbine units and electric motors as their power drives. Features of these types of power drives are as follows: a possibility of high power concentration in separate units, direct rotational motion, possibility of automation, etc.

The share of fixed GCU is 42.4%, aviation ones make 39.4%, and marine type accounts for 18.2% of the total number of gas-turbine gas-compressor units. The tendency to increase in the share of GCU of the aviation and marine types, which have great values of the efficiency, is observed at that.

At present, various GTU (main type of power drive for CB) with the rated efficiency value from 24% to 42.1% are operated at CS of OAO Gazprom.

The rated values of the efficiency for fixed GGCU are varied in the range from 24% (GT-6-750; GTN-6) to 35.5% (in GPA-32 Ladoga, being installed since 2011); in GGCU of the aviation type – from 24% (GPA-4 Ural; GPA-Ts-6.3) to 42.1% (in TRENT 60DLE units from Rolls-Royce, being installed since 2012), and in the units of the marine type – from 27.6% (GPU-10) to 35% (GPA-10PM, GPA-25 Dnepr).
At that, it should be noted that, as is shown by the analysis of performances of the gas-turbine GCU, a part of them, due to the deterioration of the technical state in the process of operation, works with the essentially lower efficiencies at the relative capacity of 0.8 ÷ 0.9 of the rating, which leads to a considerable fuel gas overconsumption.

Thus, the average capacity of a unit of type GT-750-6 (95 units in operation) is at the level of 5 ÷ 5.5 MW already after the operating time of 80 ÷ 90 thousand hours; the efficiency is at the level of 21 ÷ 23%. Units of type GTK-10 (~540 units) have on the average a capacity at the level of 8 ÷ 9 MW after the operating time of 90 ÷ 100 thousand hours, and the efficiency at the level of 22 ÷ 23%, etc. At that, a part of these units has a service life, exceeding the rated one by 2-3 times.

Among the aviation-type GCU, unit GPA-Ts-6.3 in different versions (over 300 units in operation now), belonging to the first generation of the aviation-type units, became rather common in the last quarter of the last century. These units, as was already noted, have the rated efficiency of the gas-turbine power drive $\eta_e = 24\%$ and can’t be considered as the units, meeting the requirements, set to the modern gas-compressor units.

The given data indicates the necessity for prevention of the further deterioration of the technical state of GCU which must lead to improvement in the reliability of GTS and decrease in the energy consumption for gas transmission. In these conditions, of a special concern are the problems of revamping and restoration of the technical state of the gas-compressor units, as well as replacement of worn and obsolete GCU with the units of a new generation during reconstruction of the compressor stations.

Gas-compressor units of the new generation have to ensure a high level of performance indicators, high reliability and improved ecological indexes, etc. In general, utilization of gas-compressor units of the new generation will enable 25–30% reduction in gas consumption for process needs, reduction of nitrogen oxides emissions and, which is important, essential improvement in the reliability of the gas-transmission system.

### 1.2. Operating conditions of gas transmission lines

Creation of a unified gas-transmission system in our country enables a generally effective and secure gas supplies to the household and industrial consumers of gas and thermal power stations, as well as export gas supplies to the CIS and non-CIS countries.

Within the period of 1980 ÷ 1990, the average daily gas supply via gas lines increased from year to year approximately by 100 million m$^3$ on the average. Increase in the gas supply in this period was primarily determined by putting of new gas lines on stream. At the same time, the specific values of energy consumption for gas transmission were improved; in particular, the specific consumption of fuel gas for the transmission needs was reduced.

Transfer of the country’s largest gas fields (Medvezhye, Urengoyskoye, and Yamburgskoye) to the stage of declining production led to declining of pressure and deterioration of quality of the natural gas
produced, which notably reduced the throughput capacity of some process sections of GTL adjacent to
the fields and predetermined increased in the non-uniformity of gas supply via the gas lines within a year.

Decline in production and volumes of the transmitted natural gas resulted in that a considerable
part of the process sections of GTL is underloaded, with essential fluctuations in the natural gas supply
within a year. It caused the growth in the specific energy consumption for natural gas transmission and the
reduction in the energy efficiency of the country’s GTS, which requires taking of special measures for de-
creasing the energy intensity of gas transmission in the new conditions.

Non-uniformity of gas supply via gas lines within a year can be characterized by one of the fol-
lowing indexes [10, 12]:

\[
\beta = \frac{Q_{\text{max}} - Q_{\text{m}}}{Q_{\text{m}}} ; \quad \alpha = \frac{Q_{\text{max}}}{Q_{\text{m}}} ; \quad \gamma = \frac{Q_{\text{m}}}{Q_{\text{max}}} , \quad (1.1)
\]

where \( Q_{\text{max}} \) is the average daily commercial consumption of natural gas, which is equal to the
volume flow rate, normalized to the standard conditions

\((\text{tst} = 20^\circ \text{C}, \text{pst} = 0.1013 \text{ MPa})\), for a month, in which the natural gas consumption was maximal,
million m\(^3\)/day; \( Q_{\text{m}} \) is the average daily commercial consumption of natural gas per year in general; \( Q_{\text{min}} \)
is the average daily commercial consumption of natural of a natural gas for a month, in which the natural
gas consumption was minimal.

Factor \( \beta \) describes the relative amplitude of fluctuations in gas supply via a gas line within a year,
factor \( \alpha \) is the ratio of the maximal gas supply to the minimal gas supply within a year, and factor \( \gamma \) is the
ratio of the average and maximal gas supply for a year.

The interrelation between indexes \( b, a, g \) is established by the following ratios:

\[
\alpha = \frac{l + \beta}{l - \beta} ; \quad \gamma = \frac{\alpha + 1}{2\alpha} = \frac{l}{l + \beta} ; \quad \beta = \frac{\alpha - 1}{\alpha + 1} = \frac{l - \gamma}{\gamma} \quad (1.2)
\]

Based on the ratios (1.1), (1.2), the change in the gas supply via a gas line within a year can be as a
first approximation described with one of the following equations:

\[
Q = Q_{\text{m}} [1 + \beta \cdot \cos (\varphi - \varphi_0)] , \quad (1.3)
\]

\[
Q = Q_{\text{m}} [1 + \frac{\alpha - 1}{\alpha + 1} \cdot \cos (\varphi - \varphi_0)] ; \quad (1.4)
\]

\[
Q = Q_{\text{m}} [1 + \frac{1 - \gamma}{\gamma} \cdot \cos (\varphi - \varphi_0)] \quad ; \quad (1.5)
\]
where \( \varphi = 2 \pi \cdot \frac{t}{T} \); \( \varphi_0 = 2 \pi \cdot \frac{t_0}{T} \); \( t \) is the time in days from the beginning of the calendar year \(( = 365)\); \( t_0 \) is the time in days from the beginning of the calendar year, corresponding to the maximal gas supply via a gas line for the year under consideration \(( t = t_0; Q = Q_{\text{max}})\).

Comparing the given factors of the gas supply non-uniformity within a year \((b, a, g)\) shows that factor \( b \) represents the non-uniformity of the gas line operation in the most obvious way. In this respect, it is expedient to adopt the equation (1.3) as the fundamental equation to estimate the influence of the non-uniformity in gas supply via a gas line on energy consumption.

With the assumption that the cumulative power spent for gas transmission is proportional to the cube of the natural gas flow rate in a gas line, the actual power \( N \), spent for compression of natural gas at CS at the considered time at the commercial gas flow rate in the gas line \( Q \), can be determined from the ratio

\[
\frac{N}{N_m} = \left( \frac{Q}{Q_m} \right)^3 = \left[ 1 + \beta \cdot \cos (\varphi - \varphi_0) \right]^3, \quad (1.6)
\]

where \( N_m \) is the power, spent for gas transmission via a gas line at its average daily flow rate \( Q_m \).

The ratio of the average annual power consumption via the compressor stations of a gas line to the cumulative power, spent at CS at its average daily flow rate \( Q_m \) is determined by the ratio

\[
\frac{N_n}{N_m} = \frac{1}{N_m} \cdot \int_0^t N \cdot \frac{dt}{T}, \quad (1.7)
\]

After substitution of the variable

\[
d\varphi = \frac{2\pi}{T} \cdot dt \quad (1.8)
\]

and use of a trigonometric ratio

\[
\cos^2 (\varphi - \varphi_0) = \frac{1}{2} \left[ 1 + \cos 2(\varphi - \varphi_0) \right], \quad (1.9)
\]

perform integration of the ratio (1.7) taking into account the expression (1.6).

As a result of the integration, we obtain

\[
\frac{1}{N_m} \int_0^t N \cdot \frac{dt}{T} = \frac{1}{2\pi} \int_{\varphi = -\varphi_0}^{\varphi = 2\pi - \varphi_0} \left[ 1 + \beta \cos (\varphi - \varphi_0) \right]^3 d\varphi =
\]

\[
= \frac{1}{2\pi} \int_{\varphi = -\varphi_0}^{\varphi = 2\pi - \varphi_0} \left[ 1 + 3\beta \cos (\varphi - \varphi_0) + 3\beta^2 \cos^2 (\varphi - \varphi_0) + \beta^3 \cos^3 (\varphi - \varphi_0) \right] d\varphi
\]
\[
\begin{align*}
= & \frac{1}{2\pi} \cdot \{2\pi + 3\beta \sin(\varphi - \varphi_0) + 3\beta^2 \int_{\varphi = -\varphi_0}^{2\pi - \varphi_0} \cos^2(\varphi - \varphi_o) d\varphi + \\
& + \beta^3 \left[ \frac{\cos^2(\varphi - \varphi_0) \sin(\varphi - \varphi_0)}{3} \right] + \frac{2}{3} \sin(\varphi - \varphi_0) \} = \\
= & \frac{1}{2\pi} \left[ 2\pi + 3 \pi \beta^2 \right] = l + \frac{3}{2} \beta^2 
\end{align*}
\]

(1.10)

Analysis of the operating characteristics for the process sections of gas lines shows that the relative amplitude of fluctuations in the gas supply from the end of 80’s to the mid of 90’s of the past century grew from \( \beta = 0.05 \) to the value \( \beta = 0.15 \), which led to increase of the mean fluctuations in the loading of GTL CS in terms of the power from 1.004 to 1.03.

The ratio of the greatest cumulative power, spent for compression of natural gas at the compressor stations of gas lines, to the power, spent at CS of gas lines at the average daily gas flow rate \( Q_{m} \), at the numerical values of the factor characterizing the relative amplitude of fluctuations in the gas supply at the level of \( b = 0.007 \div 0.15 \), is about 1.04 \( \div \) 1.44.

The ratio of the maximal and minimal power, spent for gas transmission via gas lines, can be determined from the expression

\[
\frac{N_{\text{max}}}{N_{\text{min}}} = \left( \frac{Q_{\text{max}}}{Q_{\text{min}}} \right)^3 = \left( \frac{l + \beta}{l - \beta} \right)^3
\]

(1.11)

At the numerical values of the factor, characterizing the relative amplitude of fluctuations in the gas supply via a gas line, at the level of \( b = 0.007 \div 0.15 \), the ratio of the maximal and minimal power, spent for gas transmission, is 1.35 \( \div \) 2.48.

The stated data indicates the influence of the non-uniformity of the operating conditions for gas lines within a year on the magnitude of energy consumption for natural gas transmission that indicates the necessity to account for the fluctuations in the operating conditions of gas lines when resolving a complex of energy-saving problems for gas transmission.

1.3. Basic concepts of energy saving

Continuous growth in the price for extraction, production and transmission of fuel and energy resources inevitably leads to the necessity for reviewing the problems of energy saving as one of the main tasks of the country’s energy policy. It also resulted in the adoption of the special Federal law “On energy saving” [20].

This law defines not only the areas of the energy saving policy of the country, but also states the basic concepts of energy saving.
Energy saving is taking of legal, organizational, scientific, industrial, technical and economic measures aimed at the efficient utilization of the energy resources and at the drawing of the renewable energy sources into the economic circulation.

Energy resource is understood as a carrier of energy, which is used at present or can be used in future.

Secondary energy resource is an energy resource, which is obtained as a by-product of the main production or is such a product.

Efficient utilization of energy resources is reaching of the economically justified efficiency of their use at the existing level of development of the engineering and technologies and under observance of the requirements to the environmental protection.

Energy efficiency index is an absolute or specific value of consumption or loss of energy resources at the output of products for any purpose, established by the national standards.

Nonproductive consumption of energy resources is caused by the nonobservance of the requirements, specified in the national standards and other statutory acts, production procedures, and ratings for the respective equipment.

The law On Energy Saving states that the policy of the state in the field of energy saving is first of all conducted by means of:

• Production incentives for efficient utilization of fuel and energy-saving equipment;
• Control over the consumption of energy resources;
• State supervision of the use of energy resources;
• Energy inspections of organizations;
• Energy appraisal of the design documentation for construction;
• Economic, informational, educational, and other areas of activity in the field of energy saving.

It should be noted that energy-consuming products for any purpose, as well as energy resources, must be subjected to obligatory certification to the appropriate energy efficiency indexes. Obligatory state metrological control and supervision in the field of energy saving must be carried out during extraction, production, processing, transmission, storage and consumption of energy resources, as well as during their certification.

Adoption of a number of national standard documents, the most important of which one are Federal law of the Russian Federation No. 261-FZ On Energy Saving and Improvement of Energy Efficiency and On Introduction of Changes in Separate Legal Acts of the Russian Federation dd. November 23, 2009 and Energy Policy of Russia for the Period till 2030, Decree of the President of the Russian Federation No. 889 “On some measures for improvement in energy and ecological efficiency of the Russian economy” dd. 04.06.2008 also indicates the relevance of the energy saving problem in the next years.
According to Energy Policy of Russia for the Period till 2030 [21], one of the major strategic goals of the long-term national energy policy of the country is the improvement of energy efficiency of the economy and energy industry. Among the main tasks of the energy policy are:

- Reduction of the specific energy intensity of the gross domestic product (GDP) at the first stage of the policy implementation (2013-2015) by not less than 22% in comparison with the level of 2005, and at the second stage (2020-2022) by not less than 43%;
- Annual reduction of the specific loss and consumption for in-house needs at the enterprises of FES;
- Bringing of the annual volume of the energy resources saving to 300 million TFOE / year (with the use of not less than 75% of the existing potential of organizational and technological energy saving).

Fundamental principles of legal regulation in the field of energy saving and improvement of the energy efficiency, stated in the Law On Energy Saving and Improvement of Energy Efficiency and on Instruction of Changes in Separate Legal Acts of the Russian Federation, are as follows:

- Efficient and rational use of energy resources;
- Support and promotion of energy saving and energy efficiency improvement;
- Consistency of and integrated approach to implementation of actions for energy saving and energy efficiency improvement;
- Planning of energy saving and energy efficiency improvement;
- Use of energy resources with allowance for the resource, industrial-and-technological, ecological, and social conditions.

1.4. Main areas of energy saving in gas industry

About 10% of the produced natural gas, as well as the great volumes of electric and thermal energy, is spent in our country for the technological processes of gas extraction, transmission, and processing.

According to the appraisals of OAO Gazprom, the total potential of energy saving in the industry is comparable to the volumes of possible growth of the extraction from traditional sources (Figure 1.4).
Thus, the magnitude of the average specific energy consumption on the Russian gas lines essentially exceeds this consumption on the foreign gas lines. Besides, transfer of some gas lines of the country’s GTS to the underloaded operation with the under the present-day conditions also resulted in the reduction of its energy efficiency, which requires taking of special actions for reduction of energy consumption for gas transmission under the new conditions.

In this respect, the reduction of natural gas losses and decrease of energy consumption at all stages of technological processes for gas extraction, transmission and, processing can be referred to one of the main problems of the gas industry. It should be also noted that implementation of the energy saving policy enables contributing to resolution of the problem for conservation of gas reserves for the future generations and some ecological problems.

Organizational structure of energy saving at OAO Gazprom is shown in Figure 1.5.
The goals of energy saving at OAO Gazprom:

- Improvement of energy efficiency of the primary and secondary production facilities;
- Reduction of negative environmental impact.

To meet the goals set, the company:

- Generates the programs of energy-saving actions;
- Develops the new vehicles for energy saving financing;
- Enhances the efficiency of energy saving management;
- Improves the monitoring system;
- Reacts to revisions of laws in the field of energy saving and improves its standard documents;
- Promotes the introduction of energy saving technologies and equipment at the subsidiaries;
- Conducts the obligatory certification of the equipment for compliance with the energy consumption rates;
- Carries out energy inspections of production facilities;
- Enhances the scientific-and-technical potential and develops the next-generation technologies;
- Improves the personnel qualification.

Considering the relevance of the problem, the following was prepared and adopted for the purpose of energy saving development in the gas industry:

- The energy saving concept of OAO Gazprom for 2001-2010;
- The energy saving program of OAO Gazprom for 2002-2003;
- The energy saving program of OAO Gazprom for 2004-2006;
- The energy saving program of OAO Gazprom for 2007-2010;
- The concept of energy saving and energy efficiency improvement for 2011-2020;
- The energy saving program for 2011-2013.

The main technologies and actions, implemented within the programs of energy saving, are as follows:

- Technology of gas transmission at the operating pressure up to 11.8 MPa, with the interior anti-friction coating of pipes;
- New generation of gas-turbine gas-compressor units;
- New generation of efficient gas compressors and their replacement flow channels;
- Modern powerful controlled electric drives;
- Process automation;
- System-level software optimization packages;
• Technologies for repair of pressurized pipelines;
• Remote monitoring of gas leaks;
• Mobile compressor stations for gas pumping-out when repairing gas lines.

Saving of FER in the amount of 11.7 million TFOE was achieved during implementation of the program in 2007-2010 [25].

Due to the implementation of energy saving programs, the total saving of FER total in the period of 2002-2010 made 29.8 million TFOE of the fuel and energy resources, including 25.1 billion cubic meters of natural gas and about 3 billion kWh of electric energy. It should be noted that Gazprom annually supplies the comparable volume of gas to Moscow – the largest gas consumer among the subjects of the Russian Federation. The main part of the energy saving potential was obtained in gas transmission (85.5%) and production (12.2%).

According to the concept of energy saving and energy efficiency improvement for 2011-2020, the main task is the maximal realization of the energy saving potential in all types of the activity and, consequently, the reduction of the technogenic load on the environment. This task will be resolved by utilization of the innovative technologies and equipment, as well as improvement of the energy saving management. The energy saving potential in 2011-2020 is determined at 28.2 million TFOE.

The target energy efficiency indexes for 2011-2020 determine the reduction of specific consumption of natural gas for in-house needs – not less than 11.4% (the minimum level of annual saving of natural gas for in-house needs must be 1.2%, at that), and the reduction of greenhouse gas emissions – not less than 486 million tons of CO₂ equivalent.

To achieve these indexes, the company will continue using the proved energy saving technologies and equipment.

Besides, to meet the requirements of the law On Energy Saving and Energy Efficiency Improvement, the company developed and approved the program for conduction of obligatory energy inspections of the subsidiaries. Such inspections will be conducted at 49 subsidiaries of Gazprom, the list of which is determined according to the law requirements. Inspections will facilitate a more precise identification of the energy saving potential at each subsidiary and correction of their operation in this area.

Within 2011-2013, it is planned to save 6.4 million TFOE of the fuel and energy resources. Including more than 5.4 billion cubic meters of natural gas, 459 million kWh of electrical energy, and 24.7 thousand TFOE of diesel and boiler-and-furnace fuels. Implementation of the program will require about RUR 5 bln, and the cost of the saved resources will make nearly RUR 12bln. Thus, as well as in the previous years, not only the technogenic impact on the nature will be minimized, but also billions of rubles will be saved. As for the financial aspect, gas transmission will account for the main planned effect of energy saving – about 83% [25].

Energy saving actions in gas transmission, as is known, are taken at the stages of designing and construction, reconstruction, operation, overhaul and dismantling of gas lines.
From the point of view of energy saving at the designing and construction stage, the use of pipes with the increased strength class, designed for the pressure up to 100-120 atm., with the inner anti-friction coating, is today considered as promising.

Such pipes are manufactured by the Izhora pipe mill and the Vyksa steel works. Besides, domestic manufacturers have mastered the production of connecting pieces for gas lines with the operating pressure up to 120 atm.

The technology of gas transmission at the increased operating pressure with the use of an inner anti-friction coating for pipes is developed for the purposes of the North-European Gas Pipeline (9.8 MPa) and the Bovanenkovo-Ukhta Gas Pipeline (11.8 MPa). GCU with the capacity of 16, 25, and 32 MW with the efficiency of the gas-turbine drive increased to 36-38% (onshore section) and branchless and modular configuration of GCU with the packaged gas AC were used for configuring. As a result, the specific energy intensity (per unit of goods transmission work), by the appraisals conducted, will be decreased by 30% in comparison with the level of the base gas pipelines of UGSS.

The production potential of the Russian machine works is now able to meet the demands of Gazprom for modern GCU both for construction of new gas lines and reconstruction of the existing CS. This is a very great scope – it is planned to revamp 433 GCU within five years.

New generation of gas-turbine GCU - Ural, Neva, Volga, and Ladoga - is developed on the basis of the Russian enterprises for the last decade. Efficiency of the engines of these units reaches 32-39%, which corresponds to the best world standards. It is not unimportant that the price of these gas-compressor units is by 25-30% on the average lower than that of the foreign equivalents, and the domestic systems of automatic control for GCU are approximately half as expensive as the imported ones.

However, the outlook of development of the Gazprom’s gas-transmission system demands the implementation of a new gas transmission equipment, which is capable to work under special conditions – mobile compressor stations and equipment, which is used in the offshore gas lines. The domestic industry doesn’t yet manufacture it.

One of the methods for improvement of the gas transmission efficiency is the recovery of heat from the GCU off-gas.

The most common method to recover the heat of GCU off-gas is today the use of waste heat exchangers. They are installed on 80% of the units operated at the line and booster CS of the Gazprom’s gas-transmission system. Total number of the waste heat recovery units is 2,750; their cumulative installed capacity is 11.6 thousand MW. Recover of the waste heat enables improvement of the fuel utilization factor to 45% and above. Thus generated thermal energy is used for the needs of CS sites and sometimes for the needs of neighboring small settlements.

In the long term, we are planning a wide application of full-scale heat recovery complexes on GCU, the base of which is a combined cycle gas turbine unit (CCGTU). Heat and electric energy, generated by such units, suffice both for the needs of CS and for commercial supply to the neighboring settlements. One of such complexes was successfully tested and is now operated at the Chaplygin CS of OOO Gazprom transgaz Moscow.
Feasibility study for the use of waste heat recovery complexes for generation of the electric energy using cyclopentane instead of water is being now prepared. The matter is that additional consumption for water heating are required in the periods of emergency or scheduled shutdown of CCGTU, while the use of cyclopentane gas doesn’t require heating and makes the operation of CCGTU more cost-effective and flexible without additional environmental risks. It is planned to start their use in 2014.

Full-scale implementation of the energy saving programs at any enterprise is today inconceivable without the use innovative solutions. At Gazprom, they are used at all stages of the life cycle of process facilities: designing, construction, commissioning, operation (including repairs), revamping, and dismantling.

Thus, for example, the software optimization packages, enabling the improvement of the efficiency of planning of gas streams in EGSS and the optimization of the operating conditions of the gas-transmission system, are created and already used. They provide up to 25% of the total amount of saving of the fuel and energy resources, planned for 2011-2013.

With a view of optimization of the operating conditions of the electric GCU (EGCU) at CS of OOO Gazprom transgaz Moscow and OOO Gazprom transgaz Nizhny Novgorod, the specialists of ZAO Nevsky Zavod, with the participation of the specialists of OOO Gazprom VNIIGAZ, developed the low-head modifications of replacement flow channels (RFC) 235-26-1 and 235 SPCh 1.32/76-5000 in the cases of centrifugal wheels (CW) of type 235. Introduction of seven sets of RFC of type 235 SPCh 1.32/76-5000 at the Sechenovskaya CS of OOO Gazprom transgaz Nizhny Novgorod enabled saving about 60 million kWh of the electric energy per year.

Substantial contribution to the energy efficiency improvement is made by the systematic implementation of integrated actions for automation of the control for the processes of natural gas production and transmission. Now, the gas-transmission subsidiaries of OAO Gazprom utilize various software optimization packages. Package for simulation and optimization of functioning of gas-transmission systems Astra provides the analysis of the actual operating conditions and generation of the guiding solutions for optimization of the GTS functioning conditions according to the optimization factors: minimum consumption of gas for in-house needs, maximum GTS productivity, minimum consumption of electric energy for in-house needs, minimum inlet pressure of GTS, etc. Sixteen gas-transmission enterprises of Gazprom are equipped with this package. Package for simulation and optimization of functioning of gas-transmission systems SAMPAG is used at OOO Gazprom transgaz Moscow.

Programming and computing package (PCP) Volna ensures optimization of the GTS operating conditions within the management information system of the gas-transmission enterprise. This package is used as a pilot specimen at OOO Gazprom transgaz Ukhta. Use of these packages in gas transmission ensures decrease of the fuel gas consumption by 3% max. due to optimization of the functioning conditions of the gas-transmission system of the enterprise; decrease in the cost of the scheduled maintenance; improvement of the efficiency of gas supply planning; and reduction of harmful emissions into the atmosphere.
PCP Magistral, ensuring monitoring of the energy efficiency indexes of the operation of the gas-transmission system facilities of Gazprom transgaz Yugorsk, is now in pilot operation. It incorporates the online monitoring of specific consumption of energy resources of the primary and secondary equipment (GCU, compressor shops and gas air cooler, boiler houses, etc.); calculation of consumption rates and rated demand for FER; online monitoring of the process parameters of the equipment; monitoring of meeting the target energy efficiency indexes for GTS facilities; development of timely actions for improvement of the performance efficiency of the GTS elements (optimization of the operating conditions of the GTS elements); increase of the level of utilization of the production facility to decrease the energy consumption; and generation of energy certificates of the equipment and balance of FER consumption. In case of positive results, this package will be proposed for introduction at other gas-transmission subsidiaries.

Developments for introduction of the unique units for production of methane-hydrogen mixtures, which will be used as a fuel gas for GCU, are being completed.

Equipment, which doesn’t require a considerable amount of energy, is now used in the line part of the gas lines; these are the means of industrial communication and cathodic protection, drive assemblies of valves, etc. For such equipment, it is planned to use solar and wind power sources and self-contained power supplies based on Stirling engines (they convert the thermal energy into the electric energy).

Promising is also the introduction of the innovative technologies for the use of so-called “secondary” resources. These are first of all high-temperature off-gases and process fluids.
2.1. Determination of power, consumed for compression of natural gas at compressor stations

One of the key issues when resolving the energy saving problem is the accuracy of determination of the power, consumed for natural gas compression at CS. At the existing ratios of compression ($\varepsilon = 1.2 \div 1.44$), it can be with the accuracy, which is sufficient for engineering designs, determined from the ratio [12]

$$N_{CS} = -\frac{1}{\eta} \cdot \int G \cdot v \cdot dp = -\frac{1}{\eta} \cdot G \cdot \frac{1}{p} \cdot \frac{2}{z \cdot R \cdot T} \cdot dp =$$

$$= -\frac{1}{\eta} \cdot G \cdot z_m \cdot R \cdot T_m \cdot \frac{1}{p} \cdot \frac{1}{\ln p} = \frac{1}{\eta} \cdot G \cdot z_m \cdot R \cdot T_m \cdot \frac{1}{p} \cdot \frac{1}{p_2},$$

(2.1)

where $h$ is the normalized efficiency allowing for the polytropic efficiencies of the centrifugal blowers and the power losses in the CS piping; $G$ is the mass flow of natural gas, kg/s; $v$ is the specific volume of gas $m^3/kg$; $z_m$ is the average value of gas-compressibility factor for CS; $R$ is the characteristic gas constant for natural gas, $J/(kg\cdot K)$; $T_m$ is the mean temperature of gas in the process of compression, $K$.

The effective potential (technical) work of an actual process for movement of a gas flow from the area of one pressure into the area of another pressure $\delta W^*$ is determined as a difference between the work of reversible pressure change $\delta W = -Vdp$ and the energy consumption for changing of the kinetic $G \cdot d \left( \frac{c^2}{2} \right)$ and potential $G \cdot g \cdot dz$ energy of a working medium flow, as well as for the work of irreversible losses $\delta W^{**}$

$$\delta W^* = \delta W - (G \cdot d \left( \frac{c^2}{2} \right) + G \cdot g \cdot dz + \delta W^{**}),$$

(2.2)
where \( c \) is the linear speed of gas in the pipeline cross-section under consideration, km/s; \( z \) is the height of the center of gravity of the flow, measured above any conditionally accepted reference level (usually above sea level); \( g \) is the acceleration of gravity, m/s².

The equation for distribution of the specific potential operation looks as follows:

\[
\delta w^* = \delta w - \left( \frac{c^2}{2} + g \cdot dz + \delta w^{**} \right),
\tag{2.3}
\]

Part of the potential work of the reversible pressure change (irreversible losses of work \( \delta W^{**} \)), related to the irreversibility of the process, turns into the heat of internal heat exchange (\( \delta Q^{**} \)).

In the conditions of nonisothermal flow of gas in the line sections of a gas pipeline, the effective work of the flow is equal to zero \( \delta w^* = 0 \), and the main summand in the equation for distribution of the potential work (2.3) is the irreversible work losses for friction and local resistance

\[
\delta w^{**} = -v \cdot dp^{**},
\tag{2.4}
\]

where \( dp^{**} \) is the pressure drop of the gas flow, related to friction and local resistance.

Pressure drop of gas flow per unit length the pipeline (\( dx \)) between CS can be determined from the Darcy equation

\[
\frac{dp^{**}}{dx} = -\lambda_{nom} \cdot \rho \cdot \frac{c^2}{2D} = -\lambda_{nom} \cdot u^2 \cdot \frac{2}{2\rho \cdot D},
\tag{2.5}
\]

where \( \lambda_{nom} \) is the normalized factor of friction resistance and local resistance, determined as a function of Reynolds number

\[
(Re = \frac{c \cdot D}{\nu} = \frac{4Q}{\pi \cdot D \cdot \nu}, \text{ or } Re = \frac{u \cdot D}{\mu} = \frac{4G}{\pi \cdot D \cdot \mu}) \text{ and relative roughness of the pipe}
\]

\[
\frac{D}{2k}; \text{ } k \text{ is the equivalent roughness of the inner pipe surface; } D \text{ is the inner diameter of gas line, m; } r \text{ is the gas density, kg/m}^3; \text{ } u \text{ is the mass velocities of the gas flow, kg } / (\text{m}^2 \text{ s}), \text{ } u = r \times c; \text{ } n \text{ and } m \text{ are kinematic and dynamic viscosity coefficients, } m = n \times r; \text{ } Q \text{ is the volume flow rate of gas.}
\]

The factor of flow friction resistance \( \lambda_{fr} \), when making engineering designs, can be determined from the general formula [12]

\[
\lambda_{fr} = 0.067 \cdot \left( \frac{158}{Re} + \frac{2k}{D} \right)^{0.2}
\tag{2.6}
\]

For the square resistance law, when \( Re << \frac{2k}{D} \), the formula (2.6) takes the following form:
\[
\lambda_{fr} = 0.067 \left( \frac{2k}{D} \right)^{0.2} \tag{2.7}
\]

For new pipes, when \( k \approx 0.03 \text{ mm} \), the equation (2.7) can be presented as follows:

\[
\lambda_{fr} = \frac{0.03817}{D^{0.2}} \tag{2.8}
\]

For GTL without backing rings, the value of additional local resistance (valves, transitions) usually doesn’t exceed 2 ÷ 5% of the friction losses. Therefore, when making engineering designs, the value of the normalized factor of the flow resistance is adopted as equal to

\[
\lambda_{norm} = (1.02 \div 1.05) \lambda_{fr} \tag{2.9}
\]

Using the assumption of the approximate numerical equality of the values for gas pressure rise at CS and natural gas flow pressure drop in a line section, following the station under consideration, and the average values of gas pressure \( P_m \) and temperature \( T_m \) in the compression system of CS and in the next line section of GTL, we will - taking into account ratio (2.1) and (2.5) - obtain an expression for calculation of the power, consumed for compression of natural gas \( N_{CS} \) (MW)

\[
N_{CS} = \frac{\lambda_{norm}}{\eta} \cdot G \cdot \frac{\tau^2}{R} \cdot \frac{T^2}{\frac{u^2}{2p_m^2}} \cdot D \cdot E \cdot L, \tag{2.10}
\]

where \( p_m \) is the average gas pressure in the line section of the gas pipeline, MPa; \( D \) is the inner diameter of the gas line, m; \( L \) is the distance between the compressor stations, m; \( E \) is the factor of hydraulic efficiency of the inner surface of pipes in the line section.

Analysis of the ratio (2.10) enables determining the main areas for reduction of the power consumption for natural gas compression at CS and, hence, reduction of energy consumption for gas transmission via GTL.

In particular, to reduce the power consumed for gas transmission, it is expedient to enhance the numerical value of the normalized efficiency \( \eta \) by means of optimization of the compression system and decrease of the pressure loss in the CS piping. For reduction of the energy consumption for transmission, it is also necessary to increase the average gas pressure in the line section of GTL \( p_m \) by maintaining the maximum permissible pressure of gas at the CS outlet, reduce the average temperature of natural gas in the line section of the gas line \( T_m \) by means of reduction in the gas temperature at the CS outlet, ensure high values of the hydraulic efficiency factor for the inner surface of pipes in the line section of gas line \( E \) by means of improvement of the quality and optimization of the gas line cleaning frequency, etc.

Studies shows that reduction of the numerical values of the hydraulic efficiency factor for the inner surface of pipes of the line sections of GTL in the process of operation leads to substantial growth of the power consumed for gas compression. Reduction of factor \( E \) from 1 to 0.9 leads to increase of the power by 18 ÷ 20%, and for reduction to the level of 0.80 – to increase of the power by 2 times almost (Table 2.1, Figure 2.1).
Table 2.1 - Influence of the value of the hydraulic efficiency factor for the inner surface of pipes in the line section of gas line E on the power consumed for compression of natural gas at CS

<table>
<thead>
<tr>
<th>E</th>
<th>ΔN_{CS} / N_{CS}, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>0.90</td>
<td>18+20</td>
</tr>
<tr>
<td>0.80</td>
<td>45+50</td>
</tr>
<tr>
<td>0.70</td>
<td>90+100</td>
</tr>
</tbody>
</table>

Figure 2.1 - Influence of the value of the efficiency factor for the inner surface of pipes in the line section on the relative power consumed for compression of natural gas at CS

Results of the calculation for the actual factor of the hydraulic efficiency for the inner surface of pipes in the sections of the multi-string gas transmission line between CS Davydovskaya and Kurskaya have shown that the value of this factor for the line sections under consideration changes depending on the quality of the transmitted gas, operating conditions of the gas line, and frequency and quality of gas line cleanings during the given period of time. Impairment of the state of the pipes interior in the section occurs as a rule in the summer months, when gas supply via the gas line is known to be decreasing. It is possible to explain this regularity only with the reduction in the flow head since the thermobaric gas parameters in this period don’t contribute to formation of condensate or hydrates. The same regularity has been also noted by other authors conducting similar studies in the sections of GTL Nadym – Punga, Urengoy – Petrovsk, Urengoy – Novopskov [5, 12].

To derive the ratio, with which it is possible to forecast the values of the hydraulic efficiency factor of the inner surface of pipes in the line sections of GTL under consideration, the test data were summarized and the relations of the hydraulic efficiency factor (E) to the commercial capacity \(Q_{actual}\), average velocity of the gas flow in the sections (c), and average specific kinetic energy of the gas flow \(s^2/2\)
were reviewed. There is a strong correlation between the value of the efficiency factor for the inner surface of pipes in the line sections (E) and the average velocity of the gas flow (c) (Figure 2.2).

![Figure 2.2](image)

Figure 2.2 – Changing of the operating characteristics of the line section of GTL between CS Donskaya and Dolgoye

- Efficiency factor
- Actual supply of natural gas
- Average linear velocity of the natural gas flow

In the range of the studied operating conditions of the considered sections of GTL, the link between the hydraulic efficiency factor of the inner surface of pipes and the average velocity of the gas flow can be described with the following relation [12]:

\[
E = 0.7133 + 0.0875 \ln c \quad (2.11)
\]

The obtained relation can be recommended for prediction of the values of the efficiency factor for the inner surface of pipes in the considered line sections of GTL. To derive the link of the hydraulic efficiency factor for the inner surface of pipes with the average velocity of the gas flow for other line sections of GTL, it is necessary to conduct a similar study on the basis of the operating characteristics of the considered line section.

Analysis of the obtained results shows that cleaning of the interior of a gas line can be conducted by means of creation of the increased movement velocities of the gas flow, transferring the operation of the section to the self-cleaning mode. In case of operation of a multi-string line, the transfer of the section to the self-cleaning mode can be implemented by means of a periodic putting of separate strings of the gas line put of operation. To reduce the pressure loss, which will inevitable occur, it is proposed to do this transfer periodically, according to the deterioration of the state of the inner surface of pipes, by permanent monitoring of the state of the inner surface of pipes of the line sections of GTL.
Specific consumption of energy for movement of a unit of quantity of gas per unit length of the pipeline (goods transmission work) $W_{fr}$ (MJ / (kg·km)) can be considered as a rather convenient characteristic for appraisal of the gas transmission efficiency

$$W_{fr} = \frac{N_{CS}}{G \cdot L} \quad (2.12)$$

Taking into account the relation (2.10), the expression for determination of the goods transmission work (2.12) looks as follows

$$W_{fr} = \frac{\lambda_{norm} \cdot z^2 \cdot R^2 \cdot T^2 \cdot u^2}{2 \cdot p^2_n \cdot D \cdot E^2} \quad (2.13)$$

Analysis of the relation (2.13) is illustrative of the influence on the value of the goods transmission work and, hence, on the energy consumption for natural gas transmission for the operating conditions of CS and line sections of GTL, technical state of GCU, and hydraulic efficiency factor for the inner surface of pipes in the line sections of gas pipelines.

### 2.2. Determination of gas pressure and temperature in a gas line

To resolve various energy technology problems of gas transmission, it is necessary to know the gas flow rate and distribution of natural gas pressure and temperature in the gas line.

Equations for their determination can be derived by reviewing the equation for distribution of the potential work.

Equation for distribution of the specific potential work in a reversible process of movement of the gas flow from the area of one pressure into the area of another pressure in an elementary section of GTL looks as follows:

$$\delta w = -v \cdot dp = \delta w^* + d \left( \frac{c^2}{2} \right) + g \cdot dz + \delta w^{**}$$

(2.14)

where $d W^*$ is the actual specific potential work, J/kg;

c is the linear speed of gas in the considered cross-section of the pipeline, m/s;

g is the acceleration of gravity, m/s²; $dz$ is the change in the position of center of gravity of the flow in the field of gravity, m; $\delta w^{**}$ is the specific irreversible losses of the work, which turn into the heat of the internal heat change.

Taking into account the Darcy equation, the irreversible losses of work in gas transmission in section $dx$ are determined from the ratio
\[ \delta W^{**} = -V \cdot dp^{**} = G \cdot v \cdot \lambda_{\text{norm}} \cdot \frac{\rho \cdot c^2}{D} \cdot dx = G \cdot \lambda_{\text{norm}} \cdot \frac{u^2 \cdot v^2}{2D} \cdot dx \]  
(2.15)

Specific irreversible losses of work in the elementary section of a gas line is found from the following expression

\[ \delta w^{**} = -v \cdot dp^{**} = \lambda_{\text{norm}} \cdot \frac{u^2}{2 \rho} \cdot v \cdot dx = \lambda_{\text{norm}} \cdot \frac{u^2 \cdot v^2}{2D} \cdot dx \]  
(2.16)

Change in the kinetic energy of 1 kg of natural gas while moving the gas flow from the area of one pressure into the area of another pressure in the elementary section of a gas line is determined from the following ratio

\[ d \left( \frac{c^2}{2} \right) = u^2 \cdot v \cdot dv \]  
(2.17)

After insertion of the ratios (2.14), (2.15) into the equation for distribution of the specific potential work (2.12), considering that the actual effective potential work in the line section is not performed \( \delta w^{*} = 0 \), and neglecting the change in the gas flow potential energy \( g \cdot dz = 0 \), we obtain

\[ -v \cdot dp = u^2 \cdot v \cdot dv + \lambda_{\text{norm}} \cdot \frac{u^2 \cdot v^2}{2D} \cdot dx \]  
(2.18)

By dividing the left and the right members of the equation (2.18) by \( v^2 \), we reduce it to the following form:

\[ -\frac{dp}{v} = u^2 \cdot \frac{dv}{v} + \lambda_{\text{norm}} \cdot \frac{u^2}{2D} \cdot dx \]  
(2.19)

By dividing and multiplying the left member of the equation (2.19) by pressure \( P \), and by designating the potential function as \( \Pi = pv \), we obtain:

\[ -\frac{p \cdot dp}{\Pi} = u^2 \cdot \frac{dv}{v} + \lambda_{\text{norm}} \cdot \frac{u^2}{2D} \cdot dx \]  
(2.20)

By integrating the ratio (2.20) into the length of the line section with the co-ordinates \( x_1, x_2 \), we will obtain the following equation:

\[ \frac{p_1^2 - p_2^2}{\Pi_m} = 2 \left[ u^2 \cdot \ln \frac{v_2}{v_1} + \lambda_{\text{norm}} \cdot \frac{u^2}{2D} \cdot (x_2 - x_1) \right] = \]

\[ = 2 \left[ u^2 \cdot \left( \ln \frac{\Pi_2}{\Pi_1} + \frac{p_1}{p_2} \right) + \lambda_{\text{norm}} \cdot \frac{u^2}{2D} \cdot (x_2 - x_1) \right], \]  
(2.21)
where $P_1, v_1, \Pi_1$ is the pressure, specific volume, and potential function of natural gas at the line section inlet; $P_2, v_2, \Pi_2$ is the pressure, specific volume, and potential function of natural gas at the line section outlet; $\Pi_m$ is the average potential function of gas in the considered line section

$$\Pi_m = \frac{P_2 - P_1}{\ln \frac{P_2}{P_1}} \cong \sqrt{\Pi_1 \cdot \Pi_2} \quad (2.22)$$

From the ratio (2.21), we obtain the expression for the mass rate of the natural gas flow

$$u^2 = \frac{P_1^2 - P_2^2}{\Pi_m} \cdot \frac{1}{\ln \frac{P_1}{P_2} + \ln \frac{P_1}{P_2} + \frac{\ln \Pi_{\text{norm}}}{D} \cdot (x_2 - x_1)} \cong \frac{P_1^2 - P_2^2}{\Pi_2 - \Pi_1 + \Pi_m \left( \ln \frac{P_1}{P_2} + \frac{\ln \Pi_{\text{norm}}}{D} \cdot (x_2 - x_1) \right)} \quad (2.23)$$

From the ratio (2.23), we obtain the equation for determination of the mass flow rate of gas in a single-string gas line ($G = u \times F$)

$$G = F \cdot \sqrt{\frac{P_1^2 - P_2^2}{\Pi_2 - \Pi_1 + \Pi_m \left( \ln \frac{P_1}{P_2} + \frac{\ln \Pi_{\text{norm}}}{D} \cdot (x_2 - x_1) \right)}} \quad (2.24)$$

Neglecting the change in the potential function of natural gas over the length of the considered line section of a gas line ($\Pi_2 \approx \Pi_1$), and the numerical value of the magnitude $\ln P_2$, since $P_1 \ll \frac{\ln \Pi_{\text{norm}}}{D} \cdot (x_2 - x_1)$, after a number of simple transformations, we obtain a simplified design equation for determination of the mass flow rate of gas in the pipeline

$$G = \frac{\pi}{4} \sqrt{\frac{D^3 \cdot (P_1^2 - P_2^2)}{\lambda_{\text{norm}} \cdot z_m \cdot R \cdot T_m \cdot L}} \quad (2.25)$$

where $L$ is the length of a line section between the adjacent CS.

Value of the average hydraulic efficiency factor for the inner surface of pipes of the line section of a gas pipeline between the adjacent CS $E^*$ can be determined by comparing the actual $G_{\text{actual}}$ and design $G_{\text{design}}$ flow rates.
G design flow rates of natural gas at the fixed value of the gas pressure at the inlet of the line section of GTL $P_l$ and equal natural gas pressure drop in the section ($\Delta p = p_1 - p_2 = \text{idem}$)

$$E = \frac{G_{\text{actual}}}{G_{\text{design}}} = \sqrt{\frac{\lambda_{\text{norm,design}}}{\lambda_{\text{norm,actual}}}} , \quad (2.26)$$

where $\lambda_{\text{norm,design}}$, $\lambda_{\text{norm,actual}}$ are the design and actual values of the normalized factor of the flow resistance.

Commercial flow rate of natural gas $Q_k$ - volume flow rate normalized to the standard conditions (pressure $p_{st} = 760$ mm hg and temperature $t_{st} = 20^\circ \text{C}$) - is used as the operating characteristics of gas transmission.

The commercial flow rate is determined by the ratio

$$Q_k = \frac{G}{p_{st}} = \frac{G \cdot R \cdot T_{st}}{p_{st}} = \frac{G \cdot R_{\text{air}} \cdot T_{st}}{\Delta \cdot p_{st}} , \quad (2.27)$$

where $p_{st}$ is the gas density at the standard conditions; $R$, $R_{\text{air}}$ are the gas constants for natural gas and air; and $D$ is the relative density of gas in terms of air.

From the ratios (2.25) and (2.27), we will obtain an expression for calculation of the commercial flow rate of natural gas

$$Q_k = K \cdot \sqrt{\frac{p_1^2 - p_2^2}{\lambda_{\text{norm}} \cdot z_m \cdot \Delta \cdot T_m \cdot L}} \cdot D^5 , \quad (2.28)$$

$$K = \frac{\pi \cdot T_{cm}}{4 \cdot p_{cm}} \sqrt{R_{\text{air}}} ,$$

where

The design ratio for the throughput capacity of the section of a gas line with allowance for the formulae (2.8), (2.9), (2.26), and (2.28) takes the following form:

$$Q_{k,\text{design}} = 16.7 \cdot 10^{-6} \cdot \alpha \cdot \varphi \cdot E \cdot D^{2.6} \cdot \sqrt{\frac{p_1^2 - p_2^2}{\Delta \cdot z_m \cdot T_m \cdot L}} , \quad (2.29)$$

where $Q_{k,\text{design}}$ is the throughput capacity of the section of a gas line, million m$^3$/day;

$D$ is the inner diameter of the gas line, mm; $p$ is the pressure, MPa; $T$ is the temperature, K; $L$ is the length of the section of the gas line, km.

Using the ratios (2.28), (2.29), we obtain an expression for calculation of the natural gas pressure $P$ in the gas line cross-section $x$

$$p = \sqrt{p_1^2 - c \cdot Q_k^2 \cdot x} , \quad (2.30)$$

where
\[ c = \frac{\dot{\lambda}_{\text{norm}} \cdot z_m \cdot \Delta T_m}{K^2 \cdot D^5} = \frac{z_m \cdot \Delta T_m}{(16.7 \cdot 10^{-6} \cdot \alpha \cdot \varphi \cdot E \cdot D^{0.6})^2} \quad (2.31) \]

Accounting that the natural gas pressure at the end of the line section of GTL \( P_2 \) is calculated from the ratio

\[ P_2 = \sqrt{p_1^2 - c \cdot Q_1^2 \cdot L}, \quad (2.32) \]

from the ratio (2.30), we obtain the design relation for determination of the natural gas pressure in any cross-section \( x \) of the gas line

\[ p = \sqrt{p_1^2 - (p_1^2 - p_2^2) \cdot \frac{x}{L}} \quad (2.33) \]

Analysis of the dynamics of the gas velocity change over the length of the line section of GTL shows that the intensity of its growth is increasing to the end of the line section. As the friction losses are proportional to the squared velocity, the increase in the intensity of the natural gas velocity growth leads to a sharper gas pressure drop at the end of the line section of GTL.

As the gas pressure drop in the gas line is of non-linear nature, the average gas pressure is determined as the average integral value

\[ p_m = \frac{1}{L} \cdot \int_0^L \! p \cdot dx = \frac{2}{3} \cdot \frac{p_1^3 - p_2^3}{p_1^3 - p_2^3} \quad (2.34) \]

In some cases, the arithmetic mean pressure of natural gas in the line section of GTL is used instead of the average integral value. Error in determination of the average pressure can thus reach the magnitudes of about 10 ÷ 12\%, depending on the values of the relation of the compression pressure at CS to the lengths of the gas line.

Movement of gas is associated not only with the drop of its pressure, but also with the drop of its temperature over the length of the gas line, due to the heat exchange between the gas and ground. It all should be considered when resolving such problems as optimization of the conditions for cooling of gas to be transmitted, appraisal of the gas line stability due to the arising thermal stresses, etc. To resolve this problem, the equation of the first law of thermodynamics for the balance of a working medium \([1]\) can be used as the initial equation

\[ \delta Q = \delta Q^* + \delta Q^{**} = dH + dW \quad (2.35) \]

where \( dQ \) is the total heat supplied to gas as a result of the external \( dQ^* \) and internal \( dQ^{**} \) heat exchange; \( dH \) is the change of the total enthalpy of gas; and \( dW \) is the potential work related to the movement of gas from the area of pressure \( p_1 \) into the area of pressure \( p_2 \).

Potential work in the reversible process \( dW \) is determined as the sum of the effective work \( dW^* \) and the work of irreversible losses \( dW^{**} \).
The work, lost in the irreversible processes \(dW^{**}\) (friction, diffusion, etc.), fully turns into the heat of the internal heat exchange \(dQ^{**}\), which is transferred to the gas to be transmitted.

Heat of the external heat exchange between the gas and ground is determined by the ratio

\[
\delta Q^{*} = -k \cdot \pi \cdot D_{\text{out}} \cdot (T - T_0) \cdot dx,
\]

where \(k\) is the heat-transfer factor from gas to ground, \(W / (m^2 \cdot K)\); \(D_{\text{out}}\) is the outer diameter of the pipeline, \(m\); \(T\) is the value of gas temperature, \(K\); \(T_0\) is the temperature of ground, \(K\); and \(dx\) is the elementary section of the gas line, \(m\).

The minus sign in the equation (2.36) shows that the heat is removed from gas to ground.

The heat-transfer factor \(k\) depends on many factors: pipeline depths, isolation type and thickness of, thermophysical characteristics of ground, etc. When doing the approximate calculations for a ground, consisting of dry sand, the heat-transfer factor is usually adopted as equal to \(k = 1.16 \ W / (m^2 \cdot K)\); for wet sand - at the level of \(k = 3.5 \ W / (m^2 \cdot K)\); and for wet clay - at the level of \(k = 1.6 \ W / (m^2 \cdot K)\).

Approximate average value of the heat-transfer factor in the approximate calculations can be adopted to be at the level of \(k = 1.75 \ W / (m^2 \cdot K)\) [15].

Change in the enthalpy of the actual gas is determined by the ratio

\[
dH = G \cdot c_p \cdot dT - G \cdot (c_p \cdot D_h) \cdot dp,
\]

where \(G\) is the mass flow of transmitted gas, \(\text{kg/s}\); \(c_p\) is the gas heat capacity, \(J / (\text{kg} \cdot K)\); and \(D_h\) is the Joule-Thomson factor for natural gas, \(K/\text{Pa}\).

Using the equation for distribution of the potential work in a reversible process of the movement of a gas flow from the area of one pressure into the area of another pressure in the elementary section of a gas line (2.14) and the ratios (2.36), (2.37), and accounting that the effective potential work in the line section of a gas line is not performed (\(dW^{*} = 0\)), the work of the irreversible losses of the work turns into the heat of the internal heat exchange (\(\delta W^{**} = \delta Q^{**}\)), and the nature of the change in pressure and height of the center of gravity of the natural gas flow over the length of a gas line is close to linear,

\[
dp = \frac{p_1 - p_2}{L} \cdot dx; \quad dz = \frac{\Delta z}{L} \cdot dx,
\]

we obtain

\[
-k \cdot \pi \cdot D \cdot (T - T_0) \cdot dx = G \cdot c_p \cdot dT + G \cdot (c_p \cdot D_h) \cdot \frac{p_1 - p_2}{L} \cdot dx + \frac{\Delta z}{L} \cdot dx + G \cdot c \cdot dc
\]

where \(p_1\) and \(p_2\) are the pressure of gas at the beginning and at the end of the considered line section of a gas line, MPa; \(L\) is the length of the line section of a gas line, \(m\); and \(Dz\) is the change of the center of gravity of the gas flow in the line section of a gas line, \(m\).
Expression (2.39) represents the energy conservation and transformation equation in the differential form for the process of the non-isothermal flow of natural gas in the line section of a gas line.

If we neglect the change in the kinetic energy for the natural gas flow in the line section of a gas line \( G \cdot c \cdot dc \cong 0 \), then, upon integration of the equation (2.39) from the beginning of the considered line section \((x = 0, T = T_0)\) to the cross-section \(x\) of the gas line \((x = x, T = T_x)\), we obtain an equation for determination of gas temperature in any cross-section of the gas line

\[
T_x = T_0 + (T_1 - T_0) \cdot e^{-ax} - D_h \frac{p_1 - p_2}{L} \cdot \frac{1 - e^{-ax}}{a} - g \cdot \frac{\Delta z}{L} \cdot \frac{1 - e^{-ax}}{c_p \cdot a} \quad (2.40)
\]

Complex \(ax\) in the ratio (2.40) is called the parameter of V.G. Shukhov, which is determined from the expression

\[
ax = \frac{k \cdot \pi \cdot D \cdot \chi}{G \cdot c_p} \quad (2.41)
\]

In the equation (2.40), the second augend after the sign of equality characterizes the influence of the external heat exchange on the change in the temperature of natural gas; the third augend – the influence of the Joule-Thomson effect on the change in the temperature of gas; and the fourth augend characterizes the influence of the change in the center of gravity of the gas flow in the gas line on the value of gas temperature.

Average temperature of natural gas in the line section of a gas line \(T_m\), the value of which can be determined from the ratio obtained from the equation (2.40), is required to make a hydraulic calculation for gas lines,

\[
T_m = \int_0^L T \cdot dx = T_0 \cdot \left[ 1 + \frac{T_1 - T_0}{T_0} \cdot \frac{1 - e^{-ax}}{ax} - D_h \cdot \frac{p_1 - p_2}{T_0 \cdot ax} \left( 1 - \frac{1 - e^{-ax}}{ax} \right) \right] = \Psi \cdot T_0,
\]

(2.42)

where \(\psi\) is the correction allowing for the non-isothermal nature of the natural gas flow in the line section of a gas line.

It is recommended to use the average temperature of natural gas in the line section of a gas line \(T_m\) (2.42) in ratios for determination of gas consumption and throughput capacity of a gas line (2.25), (2.28), (2.29) in order to account for the non-isothermal nature of the GTL gas flow. It should be noted that for the value of the V.G. Shukhov's parameter \(ax > 4\), the value \(\Psi \approx 1\), i.e.: the non-isothermal nature of the gas flow in the gas line is so small that it doesn’t make an essential influence on the throughput capacity of the gas line. When \(ax < 4\), the influence of the non-isothermal nature of the gas flow in the gas line on its throughput capacity is rather essential and it should be accounted for in the calculations.
Decrease in the temperature of the transmitted gas is one of the methods to increase the throughput capacity of a gas line and leads to reduction of energy consumption for compression of natural gas at GTL CS.

The most important method to change the temperature conditions of a gas line is to control the operating conditions of the cooling systems of GTL CS.

2.3. Interrelation of the process and energy characteristics of the pipeline transmission of natural gas

Designing, construction, reconstruction, and operation of gas-transmission systems require the identification and analysis of the interrelation between the basic process and energy characteristics of the pipeline transmission of natural gas for the purpose of reduction in the expenditures.

Drop in the natural gas pressure over the route of a gas line between CS is subject, as it is known, to the parabolic law [12]

\[ p_x = \sqrt{p_1^2 - (p_1^2 - p_2^2) \cdot x / L}, \quad (2.43) \]

where \( p_x \) is the pressure of gas in the cross-section of the gas line at the distance \( x \) from the beginning of the line section of GTL; \( p_1 \) and \( p_2 \) are the values of natural gas pressure at the inlet and outlet of the considered line section of GTL; and \( L \) is the length of the line section of a gas line between the adjacent CS.

Analysis of the nature of the change in the gas pressure of a gas line and the ratio for determination of the power, consumed for gas compression at CS, shows that, as the interval between CS is increasing, there is a growth in the compression ratio at CS, resulting in the increase of the energy consumption for compression and, therefore, the energy consumption for natural gas transmission. Thus, at the operating pressure for gas transmission \( p_1 = 7.5 \) MPa and the interval between CS \( x = L \), it is necessary to prove the ratio of natural gas compression at CS \( \varepsilon = 1.5 \) to compensate the drop of natural gas pressure in the line section of GTL. Gas flow power loss due to friction, equaling to the energy consumption at CS, is equivalent to area AFC (Figure 2.3).

With the same flow rate and operating pressure of natural gas and with reducing the interval between CS from \( x = L \) to \( x = 0.5L \), the required ratio of natural gas compression at CS is reduced from \( \varepsilon = 1.5 \) to \( \varepsilon = 1.22 \) that results in the reduction of energy losses due to friction, which are here equivalent to the sum of the areas of two triangles - ABD and DEF. Reduction of the interval between CS from \( x = L \) to \( x = 0.5L \) and the compression ratio of CS at the same flow rate and operating pressure of natural gas leads to the reduction in the energy consumption, equivalent to the area of rectangle BDEC.

Results of this analysis indicate that it is expedient to review the possibility for reduction in the interval between CS for gas lines to be designed.
For an integrated appraisal of the energy consumption for gas transmission in a gas line, it is expedient to review the interrelation of the basic process and energy characteristics.

The design equation for determination of the commercial gas flow rate over GTL, as was mentioned above (2.28), can be expressed as follows:

$$Q_k = K \cdot E \cdot D^{2.6} \cdot \sqrt{\frac{P_1^2 - P_2^2}{\Delta \cdot T \cdot z \cdot L}}$$  \hspace{1cm} (2.44)$$

where $P_1$ is the pressure of natural gas at the inlet of the line section;

$P_2$ is the pressure of natural gas at the outlet of the line section;

$E$ is the hydraulic efficiency factor for the inner surface of pipes in the line section.

Considering the relative stability of the characteristics $(C, \lambda, \Delta, T_m, z_m)$, the equation (2.44) can be transformed into this form

$$Q_k = C \cdot E \cdot \left[ \frac{(P_1^2 - P_2^2)}{L} \right]^{0.5} \cdot D^{2.6} = C \cdot E \cdot P_1 \cdot \left[ 1 - \left( \frac{1}{\varepsilon} \right)^2 \right]^{0.5} \cdot D^{2.6} \cdot L^{-0.5}$$  \hspace{1cm} (2.45)$$

Analysis of the ratio (2.45) shows that the throughput capacity of a gas line is proportional to the value of the maximum permissible pressure of natural gas at the inlet of the line section $P_1$: that is why the reduction in the maximum permissible pressure in a gas line due to its wear reduces the throughput capacity of the gas line. Besides, the throughput capacity of a gas line is substantially influenced by the value of the hydraulic efficiency factor for the inner surface of pipes in the line section: decrease in the
value of this factor in the process of operation leads to reduction of the throughput capacity of the gas line.

The energy, received by natural gas at CS, goes – according to the equations of Bernulli, Darcy-Weisbach, and distributions of the potential work – into the change of the kinetic and potential energy of the flow, useful work, and into overcoming of the flow resistance [12]

\[-vdp = \delta w^* + d\left(\frac{c^2}{2}\right) + gdz + \frac{\lambda \cdot c^2}{2D} dx\]  

(2.46)

Subject to the stable isothermal conditions of the gas flow in a horizontal gas line, as well as the absence of the external useful work \((\delta w^* = 0)\), the energy, received by natural gas at CS, primarily goes into overcoming of the flow resistance [10]

\[\delta w^{**} = -vdp = \frac{\lambda \cdot c^2}{2D} dx\]  

(2.47)

It should be noted that the stated single-valuedness conditions, at which the equation (2.46) is solved, don’t contribute to a considerable distortion of the physical image of gas flowing via GTL and, hence, don’t impair the reliability of the results obtained by means of the ratio (2.47) [12].

After integration of the equation (2.47) over the length of the considered line section and some transformations with the use of the equation for the actual gas state

\[p v = zRT\]  

(2.48)

we obtain a ratio for determination of the power consumption, required to overcome the flow resistance of the gas line

\[N_{ls} = G_{actual} \cdot W_{ls}^{**} = \frac{8}{\pi^2} \left(\frac{z_m \cdot R \cdot T_m}{E \cdot p_m}\right)^2 \cdot \frac{\lambda_{norm} \cdot L \cdot G^3}{D^3} = \]

\[= \frac{8}{\pi^2} \left(\frac{z_m \cdot R \cdot T_m}{E \cdot p_m}\right)^2 \cdot \frac{\lambda_{norm} \cdot L \cdot Q^3}{D^3 \cdot \rho_n^3},\]  

(2.49)

where \(rst\) is the natural gas density at the standard conditions; and \(R\) is the characteristic gas constant of natural gas.

The amount of energy, received by natural gas at CS, must be enough for gas pumping through the line section of a gas line downstream of CS. At this condition, it is possible to consider the ratio, enabling the calculation of the actual power consumed for compression of natural gas at CS, as true

\[N_{cs} = G \cdot \left| W_{1,2}^* \right| = G \cdot \Delta h_{1,2} = \frac{8}{\pi^2} \left(\frac{z_m \cdot R \cdot T_m}{E \cdot p_m}\right)^2 \cdot \frac{\lambda_{norm} \cdot L \cdot G^3}{D^3} = \]
Analysis of the ratio (2.50) shows that the power, consumed for compression of natural gas at CS\textsubscript{N\textsubscript{CS}}, is proportional to the cube of the commercial gas flow rate at the station \(Q^3\). Essential influence on the value of the power consumed for compression of natural gas at CS is made by the thermobaric conditions of the natural gas flow in the line section \((P_m, T_m)\) and the value of the hydraulic efficiency factor for the inner surface of pipes in the line section \(E\): the more the average pressure of natural gas \(P_m\) and the hydraulic efficiency factor for the inner surface of pipes \(E\) are, and the lower the average temperature of natural gas \(T_m\) is, the lower the energy consumption for compression of natural gas at CS\textsubscript{N\textsubscript{CS}} is.

Analysis of the ratio (2.50) shows the basic areas of energy saving in the operation of gas transmission lines.

### 2.4. Forecasting of natural gas temperature and pressure at the boundaries of line sections of gas transmission lines

Energy consumption for natural gas transmission in many respects depends on the temperature, pressure, and composition of gas at the inlet and outlet of GTL CS. In this respect, when solving the problem of calculation, analysis, forecasting, planning, optimization, and control of the gas transmission conditions, the accuracy of calculation and forecasting of the thermobaric parameters of the gas flow at the inlet and outlet of the considered line section of a gas transmission line is of a great importance.

Many well-known scientists were involved in the solution of the problem for calculation of the temperature conditions for the line part of a gas line in case of the non-isothermal flow. First of all, these are V.G. Shukhov, N.I. Belokon, V.I. Chernikin, Z.T. Galiullin, I.A. Charny, S.A. Bobrovsky, B.V. Shalimov, I.E. Khodanovich, B.L. Krivoshein, R.N. Bikhentay, V.I. Maron, V.I. Kochergin and others. [7, 11, 20, 40, 47, 65, 66, 67]. They derived a number of ratios for determination of the gas temperature distribution over the length of a section of a gas line.

The choice of the most precise design ratio for determination of the temperature and pressure of natural gas at the boundaries of the line sections of GTL was made in this paper by comparing the actual and design values of thermobaric parameters for the gas flow.

The comparison made showed that the best convergence with the experimental data is provide be the results of calculation of the natural gas temperature at the outlet of the line section of GTL \(T_2\), made using the ratios, obtained by V.I. Chernikin and S.A. Bobrovsky [6]
\[
t_2 = t_{gr} + (t_1 - t_{gr}) \exp(-a) - \frac{D_h(p_1 - p_2)[1 - \exp(-a)]}{a}
\]
(2.51)

and N.I. Belokon [1]

\[
t_2 = t_{gr} + (t_1 - t_{gr}) \exp(-a) - \frac{D_h(p_1 - p_2)[1 - \exp(-a)]}{a} - g \Delta \zeta \frac{[1 - \exp(-a)]}{a \cdot c_{pm}}
\]
(2.52)

where the complex

\[
a = k_m \cdot \pi \cdot D_{out} \cdot L / (G \cdot c_{pm})
\]
(2.53)

is the Shukhov's parameter; \(t_{gr}\) is the average ground temperature in the considered line section of a gas line, °C; \(t_1, p_1\) are the temperature and pressure of natural gas at the outlet of the considered line section, MPa; \(c_{pm}\) is the average isobaric mass heat capacity, J / (kg×K); \(D_h\) is the Joule-Thomson factor, K/MPa; \(G\) is the natural gas mass flow in the gas line, kg/s; \(L\) is the length of the considered line section of GTL, m; \(D_{out}\) is the outer diameter of the gas line, m; \(k_m\) is the average factor of heat transfer from natural gas to the environment in the GTL section, W / (m²×K); and \(\Delta \zeta\) is the difference of the final and initial marks of the gas line section.

For these ratios, the average deviation of the design and experimental values of the natural gas temperature at the outlet escaping of the considered line sections at 92 operating conditions makes about 5%.

If there is no actual data about the route profile, the relation of V.I. Chernikin and S.A. Bobrovsky (2.51) can be recommended as a ratio for determination of the natural gas temperature at the boundaries of the line section of a gas line (\(t_1\) or \(t_2\)). If there is data about the route profile, the N.I. Belokon's formula (2.52) can be recommended as a ratio for determination of the natural gas temperature at the boundaries of the line section of a gas line (\(t_1\) or \(t_2\)).

It should be noted that an essential, and occasionally defining, influence on the accuracy of the presented equations is made by the accuracy of determination of the heat transfer factor, included in the Shukhov's parameter. When designing GTL, it is necessary to resort to the use of semi-empirical ratios, which incorporate experimental data on thermophysical properties of soils at a location of laying of the gas line, laying depth, diameter of the pipeline, monthly average velocity of wind, thickness of snow cover, etc., in order to determine the heat-transfer factor. These relations are obtained as a result of some essential assumptions and calculation from them can have only an estimative nature. Determination of the heat-transfer factor from these ratios can lead to considerable errors in determination of gas temperature in the selected cross-section of the gas line, even when using the most precise design equations.
In this respect, it is offered to use the actual values of the heat-transfer factor, obtained from processing of the operating characteristics of the considered line section, for calculation of the natural gas temperature at the inlet and outlet of the line section of GTL.

For calculation of the average actual factor of heat transfer from the gas line in the operated line section under consideration, it is possible to offer the following ratio [6]:

\[
k_{m,\text{on}} = \frac{G}{\pi \cdot D_n \cdot L} \cdot \frac{h_1 - h_2}{t_m - t_{gr}},
\]

(2.54)

where \( h_1 \) and \( h_2 \) are the specific enthalpy of natural gas at the inlet and outlet of the considered line section of GTL; and \( t_m \) is the average temperature of natural gas in the section, \( t_m = (t_1 + t_2)/2 \).

Values of the specific enthalpy of natural gas at the inlet \( h_1 \) and outlet \( h_2 \) of the operated line section under consideration can be determined from the design ratio, obtained on the basis of summarization of the experimental data depending on thermobaric parameters \( (p, T) \) and composition of natural gas \( (\text{rmeth}) \) (Table 2.2).

Comparison of the experimental and design values of gas pressure at the boundaries of the considered line sections of GTL showed that the best convergence with the experimental data is provided by the results of the natural gas pressure calculation from the expression for the actual commercial gas flow rate \( Q_{k,\text{actual}} \), obtained as a result of a joint solution of the Bernulli and Darcy equations,

\[
Q_{k,\text{actual}} = 16.7 \cdot 10^{-6} \cdot \alpha \cdot \varphi \cdot E \cdot D_{\text{eq}}^{2.6} \cdot \sqrt{\frac{p_1^2 - p_2^2}{\Lambda_{\text{air}} \cdot z_m \cdot T_m \cdot L}},
\]

(2.55)

where \( Q_{k,\text{actual}} \) is the actual commercial flow rate of natural gas equal to the volume flow rate of natural gas in the GTL section, normalized to the standard conditions \( (t_{st} = 20^\circ\text{C}, \ p_{st} = 0.1013 \text{ MPa}) \), (million m³/day); \( \Lambda_{\text{air}} \) is the relative gas density in terms of air at the standard conditions; \( z_m \) is the compression ratio at the average design temperature \( T_m \) and pressure \( p_m \) of natural gas in the line section; \( L \) is the length of the line section, km; \( D_{\text{eq}} \) is the equivalent diameter of the multi-string pipeline with similar pipe diameters \( D_i \) in each of the strings \( D_{\text{eq}} = D_i \cdot n^{1/2.6} \), mm; \( n \) is the number of strings of the gas line; \( a \) is the factor allowing for deviation of the actual natural gas flow conditions from the squared conditions (at the squared conditions \( a = 1 \)); and \( j \) is the factor allowing for the influence of the backing rings (in the absence of them \( j = 1 \)).

Factor \( E \) in the ratio (2.55) accounts for the influence of the actual state of the inner surface of the pipeline on its throughput capacity and is determined from the ratio

\[
E = \frac{Q_{k,\text{actual}}}{Q_{k,\text{design}}} = \sqrt{\frac{\lambda_{\text{design}}}{\lambda_{\text{actual}}}},
\]

(2.56)

where \( Q_{k,\text{actual}}, Q_{k,\text{design}}, \lambda_{\text{actual}}, \lambda_{\text{design}} \) are the actual and design values of commercial flow rates and flow resistance factors.
It is recommended to be determine the design value of the flow resistance factor of a section of GTL from the formula [2]

\[ \lambda_{\text{design}} = \frac{0.03817}{\sqrt[0.2]{D_{\text{eq}}}} \] (2.57)

At a known value of natural gas pressure at the inlet of the line section of GTL \( p_1 \), the pressure at the outlet of the line section \( p_2 \) can be determined from the expression, obtained from the ratio (2.55)

\[ p_2 = \sqrt{p_1^2 - \frac{Q_{\text{actual}}^2 \cdot \Delta_{\text{air}} \cdot \alpha_m \cdot T_m \cdot L}{(16.7 \cdot 10^{-6} \cdot \alpha \cdot \varphi \cdot E \cdot D_{\text{eq}}^2)^2}} \] (2.58)

To determine the natural gas temperature and pressure at the boundaries of the line section of a gas line of GTL at a preset value of commercial gas flow rate in the line section \( Q_{\text{actual}} \), it is necessary to know the value of the efficiency factor for the inner surface of the gas line \( E \). Solution of the problem for determination of the actual values of the efficiency factor for the inner surface of the gas line will enable considerable improvement of the flexibility and practical value of the presented design ratios for forecasting of the thermobaric parameters of natural gas at the boundaries of GTL line sections.
3 Energy-Saving technologies in operation of gas transmission pipeline systems

As was already mentioned above, there are essential reserves for energy saving at all stages of the life cycle of GTL. This section will primarily discuss and offer some energy-saving approaches in operation of compressor stations for gas transmission lines, where there is an essential potential for saving of fuel and energy expenditures for gas transmission.

3.1. Improvement of the operating efficiency of a gas-turbine unit due to cleaning of the flow channel of an axial compressor

Presence of any suspended particles in the composition of cycle air, fed to the inlet of an axial compressor, despite the existing cycle air cleaning system before it is fed to the compressor inlet, leads to one or another level of contamination of the air duct of an axial compressor, decrease in the numerical value of its efficiency, and, as a consequence, to decrease in the power and efficiency of the whole unit.

Quality of atmospheric air as a working medium of GTU can be from this point of view characterized by its content of any aerosols, representing certain particles suspended in air with the size from 0.001 to 8,000 μm.

Inclusions differently affect the operation of gas-turbine units. Some of them lead to abrasion and corrosion of the flow channel of the units, and the other – to formation of different deposits, particularly in the flow channel of the axial compressor.

Different deposits in the gas-air duct of a gas-turbine unit can be formed by: fine particles of natural and industrial dust with the size of approximately up to 15 μm, salts of the evaporating water introduced from the atmosphere as individual drops or aerosols, atmospheric precipitations as drops of rain, particles of snow or fog, which can lead to freezing of the AC air inlet duct, etc.

Sticky deposits, especially dangerous to the flow channel of AC, are often formed on the basis of oil drops with the dust particles absorbed by, while foreign particles are primarily deposited on the first three stages of an axial compressor (Figure 3.1).
Figure 3.1 - Diagram of the airflow around the AC blades:

a – design conditions (clan blades);
b – reduced air flow rate (G) through AC
(there are deposits on the blades).

It should be noted that formation of any deposits in the gas-air duct of a gas-turbine unit, except for the reduction in the numerical value of the unit efficiency, also leads to a “shift” of the operating line of GTU towards the surge line (Figure 3.2). It all leads to the necessity to prevent the formation of deposits in the flow channel of the compressor and particularly to perform the works for periodic cleaning of its flow channel.

Crushed fruit kernel, ground walnut shell with the size from 0.5 to 2 mm, rice, wheat, etc. are used as hard cleaners. Special solutions such as Sinval, M-1, M-2, Progress, T-950, etc. are used as liquid oxidants.

Cleaning of the flow channel of AC with hard cleaners is usually carried out on operating GCU of the fixed type, when about 30 ÷ 35 kg of the crushed fruit kernel is fed through a special bin to the inlet of AC for 40 ÷ 50 seconds.

Figure 3.2 – Characteristic of axial compressor.
1 - Operating point; 2 - Boundary of stable operating conditions; 3 - Line of operating conditions; 4 - Line of permanent corrected rotational velocities; 5 - Boundary of stable operating conditions when AC is contaminated.

Flow channel of AC on the aviation-type units is usually cleaned with washing fluids during dry rotation of the compressor with a starter or on the operating machine. Special nozzles, which feed the washing fluid at the temperature of about 60 °C and pressure of approximately 0.5 ÷ 0.7 MPa, in the amount from 50 l/min to 100 l/min depending on the type of GCU and the level of contamination of the axial compressor, are installed at the air inlet of the unit for washing of the operating or dry-rotating compressor.

Frequency for washing of the flow channel of an axial compressor, both in operation and dry rotation, is usually determined by the GTU maintenance procedure at the actual operating conditions of the unit.

It is possible and expedient to evaluate the efficiency of the cleaning of the compressor’s flow channel, as well as the cleaning (washing) frequency, by the change in its relative efficiency and, therefore, the change in the efficiency and capacity of GTU in general. Numerical value of the AC efficiency (hk) at the operating conditions can be rather easily determined by means of the following ratio:

\[
\eta_k = \frac{h_0}{h} = \frac{c_{pm}(T_2 - T_1)}{c_{pm}(T_2^l - T_1^l)} \approx \frac{\Delta T}{\Delta T^l},
\]

(3.1)

where \(h_0\) is the reversible work of air compression in AC; \(h\) is the specific work of the actual compression process; \(T_1\) and \(T_2\) are accordingly the air temperatures at the inlet and output of AC in the reversible compression process; \(T_2^l\) is the air temperature after the compressor in the actual compression process (Figure 3.3).

Figure 3.3 – Air compression processes in the axial compressor

Air temperature at the end of the adiabatic compression process (\(T_2\)) can be determined from the adiabatic equation for the perfect gas:
\[
\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}; \quad T_2 = T_1 \cdot \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}, \quad (3.2)
\]

where \(k\) is the adiabatic exponent; in calculations, it can be adopted to be about \(k = 1.4\).

As a result of irreversible losses in the compressor and particularly due to contamination of its flow channel, the line of the actual compression process is shifted towards the entropy increment \((I - 2')\) (Figure 3.2). Shifting of the process is more for lower numerical values of the efficiency of the actual compression process is.

During cleaning of AC, its efficiency increases a little and the line of the actual compression process is shifted to the left \((I - 2'')\). The shift value is more for higher numerical values of the AC efficiency.

As a result of growth in the numerical value of the efficiency of the axial compressor, the capacity and efficiency of the gas-turbine unit in general naturally increases.

Change in the GTU capacity as a result of AC cleaning can be traced on the basis of the following arguments. Specific input work of the unit before AC cleaning is determined from the following known ratio:

\[
h_i = h_{im} - h_{ik} = \eta_{im} \cdot h_m - \frac{1}{\eta_{ik}} \cdot h_k
\]

(3.3)

As a result of the AC cleaning and accordingly the growth of its efficiency by the value \(\Delta e = \Delta \eta k / \eta_k\), the specific input work of the unit will make

\[
h_i^1 = h_{im} - h_{ik} = \eta_{im} \cdot h_m - \frac{h_k}{\eta_{ik} + \Delta e \cdot \eta_{ik}}
\]

(3.4)

By comparing the ratios (3.3) and (3.4), we will obtain

\[
\frac{h_i^1}{h_i} = \frac{\eta_{im} \cdot h_m - \frac{h_k}{\eta_{ik} + \Delta e \cdot \eta_{ik}}}{\frac{\eta_{im} \cdot h_m - \frac{1}{\eta_{ik}} \cdot h_k}{\eta_{ik}}} = \frac{1 - \lambda \cdot \Delta e}{1 + \Delta e}, \quad (3.5)
\]

where \(h_{im}, h_{ik}\) are accordingly the numerical values of the efficiency of the gas turbine and AC; \(l\) is the ratio of capacities of the axial compressor and gas turbine.

At the optimal energetic conditions of the effectively thermodynamic cycles of GTU \(\eta_e = \text{max}\), the value \(l\) is stable enough and, for modern types of GTU, changes in the range \(l = 0.60 \div 0.65\). In this respect, the value of this characteristic in calculations can be adopted to be about \(\lambda = 0.62 \div 0.63\).

The equation (3.5) allows – on the basis of variants calculations – to determine, how the relative capacity of the unit will change at the changed AC efficiency after cleaning of its flow channel. With a
great accuracy, it is possible to consider that the change of the AC efficiency after its cleaning practically will not affect the numerical change of the relative efficiency of the gas turbine itself.

Results of the done calculations shows, how much the unit’s capacity can rise with AC cleaning, and indicate that for the "worst" state of the compressor, influence of cleaning of its flow channel on improvement of the unit’s capacity is greater (Table 3.1).

Table 3.1 - Change of the GTU relative capacity at the changed efficiency of the axial compressor as a result of cleaning of its flow channel

<table>
<thead>
<tr>
<th>Δe</th>
<th>0.01</th>
<th>0.02</th>
<th>0.03</th>
<th>0.04</th>
<th>0.05</th>
<th>0.06</th>
<th>0.08</th>
<th>0.10</th>
<th>0.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ = 0.60</td>
<td>1.015</td>
<td>1.030</td>
<td>1.044</td>
<td>1.058</td>
<td>1.071</td>
<td>1.085</td>
<td>1.111</td>
<td>1.136</td>
<td>1.161</td>
</tr>
<tr>
<td>λ = 0.62</td>
<td>1.016</td>
<td>1.032</td>
<td>1.048</td>
<td>1.063</td>
<td>1.078</td>
<td>1.092</td>
<td>1.121</td>
<td>1.148</td>
<td>1.175</td>
</tr>
<tr>
<td>λ = 0.65</td>
<td>1.018</td>
<td>1.036</td>
<td>1.054</td>
<td>1.071</td>
<td>1.088</td>
<td>1.105</td>
<td>1.138</td>
<td>1.169</td>
<td>1.199</td>
</tr>
</tbody>
</table>

This equally relates to the nominal and underloaded operating conditions of GTU as well, during transfer to which the value l increases a little. Having determined the numerical value of the relative efficiency of AC after washing by means of the ratio (3.4), it is easy to determine the rise in the GTU capacity as well (ratio 3.5, Table 3.1, Figure 3.3).

Figure 3.3 - Influence of the change in the relative efficiencies of an axial compressor (--) and a gas turbine (___) Δe on the relative change in the capacity δh_i and efficiency δη_i of GTU at the different values of l

-46-
For example, if after cleaning of the compressor, its efficiency \( \eta_{ik} \) at \( \lambda = 0.60 \) grew from the value of 0.82 to the value of 0.85, which makes its relative growth approximately \( \Delta \epsilon = 0.04 \), it is possible to state that the growth of the unit’s capacity makes about 6% (Figure 3.3).

The efficiency of the gas-turbine unit can be estimated as a ratio of the specific work of the unit to the specific amount of the heat, fed in the combustion chamber to 1 kg of the supplied air

\[
\eta_i = \frac{\eta_{im} \cdot h_m - \frac{1}{\eta_{ik}} \cdot h_k}{q} = \frac{\eta_{im} \cdot h_m \cdot (1 - \lambda)}{q}, \quad (3.6)
\]

where \( q \) is the specific amount of the heat, fed in the combustion chamber to 1 kg of the supplied air, at the initial value of the efficiency of an axial compressor,

\[
q = \frac{c_{pm} \cdot (t_3 - t_2)}{\eta_{cc}}; \quad (3.7)
\]

\( t_3 \) is the gas temperature at the outlet of the combustion chamber (at the inlet of HP turbine);
\( t_2 \) is the air temperature at the inlet of the combustion chamber (in non-regenerative GTU – at the outlet of AC); and \( h_{CC} \) is the efficiency of the combustion chamber.

Efficiency of GTU after cleaning of the flow channel of the axial compressor is determined from the ratio

\[
\eta_{i}^{' \prime} = \frac{\eta_{im} \cdot h_m}{q^{' \prime}} - \frac{h_k}{\eta_{ik} + \Delta \epsilon \cdot \eta_{ic}} = \frac{\eta_{im} \cdot h_m \cdot (1 - \frac{\lambda}{1 + \Delta \epsilon})}{q^{' \prime}} \quad (3.8)
\]

By comparing the ratios (3.6) and (3.8), we will obtain an expression for appraisal of the relative change in the efficiency of the unit at the changed relative efficiency of the axial compressor

\[
\frac{\eta_{i}^{' \prime}}{\eta_i} = \frac{1 - \frac{\lambda}{1 + \Delta \epsilon} \cdot \frac{q}{q^{' \prime}}} {1 - \frac{\lambda}{1 - \Delta q} \cdot \frac{h_i^{' \prime} \cdot (1 - \Delta q)}{h_i \cdot (1 - \Delta q)}} \quad (3.9)
\]

where \( q_1 \) is the specific amount of heat, fed in the combustion chamber at the AC new efficiency, obtained after cleaning of its flow channel.

Value \( \Delta q \) characterizes a kind of increase in the fuel supply to the combustion chamber due to the drop of air temperature after AC as a result of cleaning of its flow channel. However, this conclusion can be only made at the condition that the rotational speed of the AC shaft remains unchanged at reduction of the load on the CC shaft. If the compressor speed is decreasing along with the drop of the efficiency of the compressor, the air temperature after AC can also remain unchanged, which will indicate the equal relative influence of the change in the compressor efficiency on the capacity and efficiency of the unit in general.
Results of the conducted studies indicate the expediency of periodic cleaning of AC. For example, if as a result of cleaning of the compressor, its relative efficiency grew from the value of 0.82 to 0.86, which corresponds to the relative increase by $D \approx 0.05$, the unit's capacity growth at $\lambda = 0.60$ will make about 7.2% (Figure 3.3).

We will show the economical appraisal of the expediency of periodic cleaning of the AC flow channel for maintaining of the capacity in operation and saving of the fuel gas with determination of its frequency by the example of unit GPA-Ts-6.3.

Consider the cleaning of an axial compressor using detergents according to the following procedure: one cleaning in operation every 15 days of operation and one cleaning in dry rotation of the unit every 1,500 hours. If we assume that the unit is operated 6,000 hours per year, then about 20 washings is conducted for a year in total. It should be noted that the cleaning frequency will be naturally depend on the region of GCU operation must be determined on the basis of the AC diagnostics results.

Assume the cost of detergent of type T-950 is $10 per liter. Total consumption of detergent for the unit of type GPA-Ts-6.3 can be adopted for the approximate calculations to be about 200 l/year.

Cost of the kernel from walnut shell or sunflower seeds is $\approx 1,000 per ton. Approximately $30 \div 35$ kg of the kernel is consumed for one cleaning.

Average annual consumption of fuel gas for unit GPA-Ts-6,3 will make

$$\frac{N_e \cdot T}{Q_n \cdot \eta_e} = \frac{6,000 \cdot 3,600 \cdot 6,000}{33,500 \cdot 0.22} = 17.58 \text{ million m}^3/\text{year},$$

where $N_e$ is the GCU capacity adopted for calculations to be 6,000 kW; $Q_n$ is the lower heat value of the fuel gas, kJ/m$^3$; $T$ is the GCU operating time in the year, $T = 6,000$ hrs $\eta_e$ is the operating efficiency of GTU is adopted for calculations to be about 22%.

For cleaning of the compressor and growth of its relative efficiency from the value of 0.82 to 0.85 at $\lambda = 0.62$, on retention of the GCU capacity, the relative growth of the effective efficiency of GTU $\delta \eta_e$ and, hence, the fuel gas saving will make approximately 6% (Table 3.1). Under these conditions, the total fuel gas saving for one GCU per year as a result of periodic washings of the axial compressor of GTU will make

$$\Delta B = B \cdot \delta \eta_e = 0.06 \cdot 17.58 = 1.05 \text{ million m}^3/\text{year}$$

At the fuel gas price of about $p_{fg} = 30/1,000$ m$^3$, the reduction of operating costs due to the fuel gas saving will make

$$\Delta C = p_{fg} \cdot \Delta B = 30 \times 1,050 = 31,500 / \text{year.}$$

For the detergent consumption of about 200 l/year and its price of approximately $10 / \text{liter}$, the cost of the detergent used for washing AC of one unit in a year will make approximately $2,000 / \text{year}$. Hence, the cumulative reduction of the operating costs will make: $31,500 - 2,000 = 29,500 / \text{year}$. 
If we take into consideration that the cost of an AC washer with all devices for preparation and feeding of the detergent is at the level of $15 \div 20$ thousand, the payback time of the washer and washing technology for each GCU can be no more than one year.

For cleaning of the flow channel of an axial compressor using hard cleaners, the annual consumption of the kernel is estimated at the value of less than one ton for a unit and, hence, the cost of its annual consumption is less than one thousand dollars. Therefore, the economic efficiency of the use of hard detergents for stabilization of the fixed GCU capacity in field conditions with simultaneous reduction in the consumption of fuel gas becomes obvious. The payback time for construction of the filling bins for hard cleaners and provision of the cleaning technology will make less than year as well.

It all indicates the expediency of periodic cleanings of the flow channel of an axial compressor in the process of operation of gas-turbine units. Time between AC cleanings depends on the type of GTU, type and operating efficiency of the air filtering and conditioning system (AFCS), region of CS, and operating conditions of the unit, but on the average, it is expedient to clean an axial-flow compressor at least once in $2 \div 2.5$ weeks based on the results of AC diagnostics.

Influence of the change in the internal relative efficiency of a gas turbine on the efficiency of GTU at the different values of the previously introduced characteristic $l$ can be traced from the analysis of the following ratio. At the preset values $h_{im}$ and $h_{im}$ the equation for determination of the internal efficiency of GTU is recorded as follows:

$$\eta_i = \frac{\eta_{im} \cdot h_m - \frac{l}{\eta_{ik}} \cdot h_k}{q}$$

When the internal relative efficiency of a gas turbine changes by the value magnitude

$$\Delta \varepsilon = \frac{\Delta \eta_{im}}{\eta_{im}}$$

the efficiency of GTU can be determined from the ratio

$$\eta_i' = \frac{\left(\eta_{im} + \Delta \varepsilon \cdot \eta_{im}\right) \cdot h_m - \frac{l}{\eta_{ik}} \cdot h_k}{q}$$

By comparing the equations (3.10) and (3.11), on condition that the specific consumption of heat in GTU $q$ remains unchanged, when the relative efficiency of the gas turbine changes, we obtain

$$\eta_i' = \eta_i \cdot \frac{\eta_{im} \cdot h_m - \frac{l}{\eta_{ik}} \cdot h_k + \Delta \epsilon \cdot \eta_{im} h_m}{\eta_{im} \cdot h_m - \frac{l}{\eta_{ik}} \cdot h_k} = \eta_i \cdot \left(1 + \Delta \epsilon \cdot \frac{l}{l - \lambda}\right)$$

(3.12)

Using the ratio (3.12), we obtain that if as a result of repair works, the relative internal efficiency of the turbine is increased $\Delta \epsilon \equiv 0.01$, then at $l = 0.67$, it leads to the relative improvement of the GTU
efficiency \( \eta_i \) approximately by \( \% \), and at \( l = 0.60 \), the relative growth of the GTU efficiency will make approximately 2.5\%, etc. The stated data indicate that the less the numerical value \( l \) is, the less the influence of the change in the relative efficiency of the turbine on the GTU efficiency is, and vice versa.

3.2. Control of CS operating conditions at a joint operation of gas-turbine and electric gas-compressor units

The most important feature of the most EGCU in the fleet of OAO Gazprom is the impossibility to control the operation of the unit by changing the rotational velocity of the CB impeller. In this respect, control in the shops equipped with EGCU can be carried out by starting and stopping the units, gas throttling at the inlet of the blower, installation of the inlet guide vanes before the blower impeller, bypassing of the partial flow from the discharge line to the inlet of the blower, replacement of the flow channel of the blower, changing of the gear ratio of the gearbox, and by installation of the hydrocouple.

As the experience in operation of the units shows, none of these methods for control of the electric GCU is optimal, as they are associated with the growth of energy and, therefore, operating expenses, or lead to essential increase of capital expenses. Besides, when using these methods for control of electric units, it is impossible to implement a smooth control of the operating conditions for CS without essential increase in the energy consumption, and to implement some methods of control by GCU, it is necessary to shut down the units.

One of the possible methods for elimination of the stated disadvantages in the multi-string CS is to install the gas-turbine units, along with EGCU. For reduction of the energy consumption for gas transmission, control of the operating conditions of the compression systems for such stations in joint operation of GGCU and EGCU for a common header is carried out by the units with the gas-turbine actuator. Gas-turbine units enable a smooth control of the operating conditions for GCU and the whole compression system by changing the rotational velocities of power shafts of GTU in a rather wide range. To implement such methods of control under conditions of a variable gas supply via the gas line and a varying ratio of a natural gas compression at CS, it is necessary to use the intershop bypasses.

Such CS as Davydoeskaya, Pervomayskaya, and other stations of OOO Gazprom transgaz Moscow, as well as a number of CS of other gas-transmission companies can serve as an example of such stations.

For joint operation of electric and gas-turbine units, it is expedient to operate EGCU at the base conditions, and GGCU in the mode of control of natural gas supply and compression ratio. By changing the rotational velocity of the power shaft of GTU, it is possible to change the ratio of compression of EGCU and, hence, the gas flow rate through it.

Consider the joint operation of EGCU and GGCU by the example of a parallel operation of electric unit STD-12.5 with the capacity of 12.5 MW and gas-turbine unit of type GTK-25IR with the rated
capacity of 25 MW. The superposed characteristics of the blower for unit STD-12.5 having the form of a single curve ($n = 4,800$ rpm) and blower PCL-804-2 for unit GTK-25IR are shown in Figure 3.4 [12].

Figure 3.4 - Control of operating conditions of the compression system of CS, equipped with EGCU and GGCU in case of reduction of supply and permanent ratio of natural gas compression:

A - Characteristic of blower for EGCU;

B - Characteristic of blower for GGCU;

1, 1’ - points, characterizing the operating conditions of the GGCU blower before control and at the end of control;

2 – a point characterizing the operating conditions of the EGCU blower.

When the natural gas supply in GTL is reduced and the ratio of natural gas compression at CS is kept, the operating conditions of the compression system are controlled by reducing the rotational speed of the blower rotor (Figure 3.4). Flow rate of natural gas is thus reduced by $\Delta Q$.

Such control is only possible, when the natural gas flow rate through the blower of GGCU at the end of the control process $Q'_{ggcu}$ is above the minimum permissible flow rate $Q_{perm}$, upon reaching of which the possibility of CB surge is rising. If this condition is not met, the control must be implemented by shutting down EGCU.

It is necessary to consider the case, in which reduction of the natural gas supply leads to a gas pressure rise at the inlet of CS and, hence, provided that the gas pressure at the station outlet remains unchanged, to reduction in the ratio of compression at CS e (Figure 3.5).
Figure 3.5 - Control of operation of the compression system for CS, equipped with EGCU and GGCU in case of reduction in the gas supply and ratio of compression at CS:

A - Characteristic of blower for EGCU;
B - Characteristic of blower for GGCU;
1, 1’ - points, characterizing the operating conditions of the GGCU blower before control and at the end of control;
2, 2’ - points, characterizing the operating conditions of the EGCU blower before control and at the end of control.

It should be noted that when the ratio of compression at CS is reduced from e 1 to e 2 and the flow rate of natural gas by $\Delta Q$, the operating conditions of CS can be controlled by reducing the rotational speed of the impeller of the GGCU blower. Reduction of the flow rate of natural gas through CB $\Delta Q_{ggcu}$ must be more than the reduction of the natural gas flow rate through CS $\Delta Q_{egcu}$, as the control of the operating conditions of the CS compression system under these conditions is associated with the growth in gas consumption through the EGCU blower by $\Delta Q_{egcu}$

$$\Delta Q = \Delta Q_{ggcu} - \Delta Q_{egcu}$$  \hfill (3.13)

If the natural gas flow rate through the GGCU blower at the end of the control process $\Delta Q_{ggcu}'$ is less than the permissible value of gas consumption, the conditions must be controlled by shutting down EGCU.

When supply of a natural gas in GTL is increased, the operating conditions can be controlled by increase of the rotational velocity of the impeller of the GGCU blower. If the ratio of gas compression at CS remains unchanged, the increase of the natural gas flow rate causes increase of the gas flow rate.
through the GGCU blower $\Delta Q = \Delta Q_{ggcu}$, and the gas flow rate through the EGCU blower in the process of control doesn’t change $Q_{egcu} = idem$ (Figure 3.6).

Figure 3.6 – Control of operation of the compression system for CS, equipped with EGCU and GGCU, when the natural gas supply is increased and the ratio of compression at CS remains unchanged:
A - Characteristics of blower for EGCU;
B - Characteristics of blower for GGCU;
1, 1 $\varepsilon$ - points, characterizing the operating conditions of the GGCU blower before control and at the end of control;
2 – a point characterizing the operating conditions of the EGCU blower.

If the growth of the natural gas supply through CS can’t be provided by increase of the supply of CB for the operating GGCU, it is necessary to start one or more GCU. By doing so, there is a problem of selection of the type and capacity of GCU introduced into the compression system.

As the flow rate of natural gas through the line section before CS is increasing, there is as a rule a pressure drop growth in this section that leads to reduction in the pressure of natural gas at the inlet of CS.
This circumstance entails the necessity for increase of the ratio of compression at CS from $e 1$ to $e 2$ to ensure the pressure of natural gas at the station outlet is equal to the design or maximum permissible pressure in the subsequent line section (Figure 3.7), which ensures the reliability of operation of the line section and high throughput capacity of the gas line, as well as in many cases reduces the energy consumption for gas transmission.
Figure 3.7 - Control of CS operation at joint operation of EGCU and GGCU as the natural gas supply and CS compression ratio are increasing:

A - Characteristic of blower for EGCU;
B - Characteristic of blower for GGCU;
1, 1’ - points, characterizing the operating conditions of the GGCU blower before control and at the end of control;
2, 2’ - points, characterizing the operating conditions of the EGCU blower before control and at the end of control.

Operating conditions of the compression system for CS with the combined drives are in this case controlled using GGCU by increasing the rotational speed of the power shaft of the gas-turbine unit. In this case, the increase of the natural gas supply through the GGCU blower must compensate both the growth of the flow rate of natural gas through CS and the reduction of supply of the EGCU blower. If the increase of the flow rate of natural gas through CS can’t be compensated by the increase of the natural gas supply by the blower of the operating GGCU, it is necessary to start other GCU installed at CS. Selection of the type and unit capacity of the started GCU is determined by the number and types of the units installed at CS, their technical state, and the forecasted fluctuations of the natural gas supply in the considered section of GTL. This choice is made on the basis of results of the technical and economic calculation performed for the possible operating configurations of the operating GCU. In this comparison, it is necessary to consider the dynamics of the change in the prices for electric energy, fuel gas, and maintenance GCU of different types.

It is necessary to point out that for controlling, it is necessary to use the normalized characteristics of the blowers with allowance for their technical state, corrected upon the results of their diagnostic tests.
3.3. Control of the operating conditions for a gas line by shutting down the compressor shops and compressor stations

Analysis of results of the theoretical and experimental studies of the operating conditions for the process sections shows that minimization of the energy and operating expenses for gas transmission only due to the change in the ratio of gas compression at CS without allowance for the operating conditions of the line sections and the next stations is not possible. It is determined by the fact that at any possible operating conditions of GTL, it is expedient, from the energetic and economic point of view, to maintain the optimum value of natural gas pressure at the outlet of CS, determined from determination of the energetically and technologically justified load distribution between CS $p_2 = p_{1\text{\textdagger}}^{\text{opt}}$, and the gas pressure at the inlet of CS $p_1$ is determined by the operating conditions of the upstream CS and pressure loss in the upstream section [5, 6].

Thus, the change in the ratio of natural gas compression at CS is just a consequence of the change in the operating conditions of the process section (PS) of GTL. It can be associated with the changes of the natural gas flow rate through the process section $Q_s$, hydraulic efficiency factor for the inner surface of pipes of the line section $E$, and operating conditions of the compression and cooling systems at the upstream CS. It is possible to consider the shutdown of CS as the extreme case of the change in its operating conditions.

The method of control of the operating conditions for PS of GTL by shutting down of the compressor shops is rather widely used on the multi-string gas lines equipped with bypasses. The method of control of the operating conditions by shutting down of CS is used much less.

The question on the use of the method for control of the operating conditions for the process sections of a gas transmission line by shutting down of the compressor shops and CS arose because a certain number of process sections of GTL of the country is now operated with the natural gas supply below the design values. Reduction in the supply natural gas in a gas line leads to underloading of the line sections of GTL and CS and to reduction in the ratio of compression at CS, which leads to decrease of the efficiency of the compression process at CS and to growth of the specific energy and operating expenses for gas transmission when using full-head blowers.

Theoretical studies show that shutting down of CS for the purpose of minimization of the energy consumption for natural gas transmission is not expedient in principle [12]. However, it should be noted that drawing of the theoretical conclusions on the inexpediency of CS shutting down for minimization of the energy consumption for gas transmission doesn’t consider that implementation of this method of control enables prevention of pressure loss in the piping and energy consumption in the cooling system of the shutdown compressor shops and CS. Use of this method leads to drop of the average gas temperature in the line section, which also contributes to decrease in pressure drop of natural gas in the section. Shutting down of shops and CS causes reduction of the natural gas temperature at the inlet of the next CS and
leads to increase of the compression ratio at the subsequent CS, bringing the operating conditions of the compression system closer to an optimum, which enables reduction of energy consumption.

The stated reasons offer a possibility to suggest that it is expedient to shut down the compressor shops and CS at a certain loading of the process sections of GTL to reduce the energy consumption for gas transmission. By doing so, there is a problem of development of criteria, determining the possibility and expediency of the use of this method of control, and identification of the conditions, at which shutting down the compressor shops and CS is technologically possible and justified from the energetic and economic point of view.

The value of the compression ratio of CS downstream of the shutdown station \( \varepsilon_2' \) can be considered as a criterion, determining the technological possibility of operation of a process section of GTL at the condition of a shutdown CS. If CS downstream of the shutdown CS utilizes one-stage gas compression, and GCU are operated in parallel using full-head blowers, the value of the compression ratio of CS downstream of the shutdown station must be \( \varepsilon_2' \leq 1.4 - 1.45 \) after shutting down of the previous CS.

When this condition is met, transfer of the process section to the operation with the shutdown CS is technologically justified, as it will not require additional operations related to the changing of the subsequent CS piping during shutting down and starting of the previous station.

To determine the energetic and economic feasibility of shutting down of CS at the actual values of natural gas supply in the process section, it is necessary to compare the energy and operating expenses for implementation of the alternative operating conditions of the section: for the operated and shutdown CS.

Shutting down of the compressor station (CS-1) can be considered energetically expedient if the sum of energy consumption for natural gas transmission at the considered (CS-1) and subsequent (CS-2) stations is more than the value of energy consumption at CS-2 after shutting down of CS-1 at the unchanged operating characteristics of other facilities of the considered process section of GTL and PS itself

\[
N_{e1} + N_{e2} + N_{\text{cool}1} + N_{\text{cool}2} > N_{e2}' + N_{\text{cool}2}', \quad (3.14)
\]

where \( N_{e1}, N_{e2} \) are the actual capacities of the power drive consumed for compression of natural gas at the considered (CS-1) and subsequent (CS-2) CS before shutting down of the station; \( N_{\text{cool}1}, N_{\text{cool}2} \) are the capacities of the drive for the air cooler fans in the cooling systems the considered and subsequent CS before shutting down of the station; \( N_{e2}', N_{\text{cool}2}' \) are the capacities consumed for compression of natural gas, and the capacity of the drive for the air cooler fans in the cooling system at the next CS (CS-2) after shutting down of the station (Figure 3.8, 3.9).
Calculation of the characteristics, incorporated in the basic condition of the energetic expediency for shutting down of CS-1 (3.14) for the considered alternative operating conditions of GTL PS must be performed with the similar values of the actual commercial gas flow rate through PS $Q_k$, natural gas temperatures and pressures at the inlet of the first line section (LS-1) $t_{1ls1}$, $p_{1ls1}$, and gas temperatures and pressures at the outlet of CS-2 $t_{2ls3}$, $p_{2ls3}$.

Besides, it is necessary to consider the cases, in which the natural gas pressure at the outlet of the previous (CS-0) and next (CS-2) after the shutdown station is maintained at the level of the maximum permissible value for the line sections: $p_{1ls1} = p_{\text{max, permiss}1}$, $p_{2ls3} = p_{\text{max, permiss}3}$.

Determination of the natural gas pressure and temperature values at the inlet of the compression system for the considered CS-1 $t_{2ls1}$, $p_{2ls1}$ must be based on the following ratios [7, 12]:

$$p_{2ls1} = \sqrt{\frac{Q_{k, \text{actual}}^2 \cdot \Delta z \cdot z_{mi} \cdot T_{mi} \cdot L_2}{(16.7 \cdot 10^{-6} \cdot \alpha_1 \cdot q_1 \cdot E_1 \cdot D_{sq}^{2.6})^2}};$$

$$t_{2ls1} = t_{gr1} + (t_{ls1} - t_{gr1}) \cdot \exp(-\alpha_1) -$$

Figure 3.8 - Diagram and operating characteristics of GTL PS before shutting down of CS-1

Figure 3.9 - Diagram and operating characteristics of GTL PS after shutting down of CS-1
\[- \frac{D_{m\text{l}} \cdot (p_{1\text{sl}} - p_{2\text{sl}}) \cdot [1 - \exp(-a_{i})]}{a_{i}} - \frac{g \cdot \Delta z_{i} \cdot [1 - \exp(-a_{i})]}{a_{i} \cdot c_{\text{pmi}}} \tag{3.16}\]

In calculation of the natural gas temperature and pressure at the outlet of the line section, it is necessary to use the actual values of the hydraulic efficiency factor for the inner surface of pipes $E$ and average factor of heat transfer from natural gas in the operating conditions $k_{m}$ in the considered line section, preliminary obtained by processing of the operating characteristics of the considered PS.

The capacity value for compression of natural gas at the considered CS-1, provided that the natural gas temperature and pressure at the inlet of the CS compression system are equal to the gas temperature and pressure at the outlet of the first line section $t_{2\text{sl}} = t_{11}, p_{2\text{sl}} = p_{11}$, can be found from the following expression:

$$N_{e1} = G \cdot w_{\text{comp}}^{*} = \frac{k \cdot G}{k - 1} \cdot p_{11} \cdot v_{11} \cdot \left| 1 - \frac{k - 1}{\varepsilon_{1}^{\text{pol}} \cdot \eta_{\text{pol}}} \right|,$$  \tag{3.17}

where $k$ is the average adiabatic exponent in the process of compression; $\varepsilon_{1}$ is the average ratio of gas compression at CS-1 $\varepsilon_{1} = \frac{p_{21}}{p_{11}}$; $p_{11}, v_{11}$ is the pressure and specific volume of natural gas at the inlet of the compression system of CS-1; and $p_{21}$ is the pressure of natural gas at the end of the natural gas compression process at CS-1.

Average polytropic efficiency of the natural gas compression process in the compression system of CS-1 for the parallel operation of $x$ GGCU and $y$ EGCU with allowance for supply and consumption of the internal interior capacity for gas compression in each blower $N_{i}$ can be found from the following relation:

$$\eta_{\text{pol}} = \frac{1}{N_{\Sigma}} \cdot \left( \sum_{i=1}^{x} \eta_{\text{pol},i} \cdot N_{i} + \sum_{j=1}^{y} \eta_{\text{pol},j} \cdot N_{i,j} \right) \tag{3.18}$$

The capacity, consumed in the cooling system of the first CS, can be adopted as equal to the cumulative capacity of the drives of the activated fans

$$N_{\text{cool1}} = \sum_{i=1}^{n} S_{i} \cdot N_{i,j}, \tag{3.19}$$

where $N_{i,j}$ is the capacity of the electric drive for one fan of the air cooler of the $i$ - th type, kW; and $S_{i}$ is the number of the activated fans in the air cooler of the $i$ - th type.
Values of the polytropic efficiency of the compression process $\eta_{\text{pol}}$ and internal capacity $N_i$ of the blowers must be determined from the actual corrected characteristics of the blowers with allowance for their technical state.

Calculation of the thermobaric characteristics for natural gas at the outlet of the second considered line section LS-2 is performed by the analogy to calculation of the first LS, just as calculation of the actual characteristics of the compression and cooling systems of CS-2 is performed according to the algorithm similar to calculation of CS-1, with determination of $N_{e2} N_{\text{cool}2}$.

Thermobaric characteristics of natural gas before CS-2, energy consumption for compression of natural gas $N_{e2}$, and driving of the fans in the cooling system $N_{\text{cool}2}$ of CS-2 after shutting down of CS-1 are determined at the same values of temperature and pressure of natural gas on the outlet of CS-0 ($L_{\text{ls-1}}, P_{\text{ls-1}}$) according to the above provided that the length of the line section between these CS is $L_{\text{ls}} = L_{\text{ls-1}} + L_{\text{ls-2}}$ (Figure 3.9).

Final conclusion on the possibility and efficiency of shutting down of the shops and CS of GTL should be drawn only after comparison of the cumulative energy consumption, in money terms, for the alternative operating conditions for the process section: with the operated and shutdown CS-1.

Condition of the economic feasibility of the CS shutdown can be expressed as follows

$$C_{e1} + C_{e2} + C_{\text{cool}1} + C_{\text{cool}2} > C_{e2} + C_{\text{cool}2},$$

(3.20)

where $C_{e1}, C_{e2}$ is the energy consumption, in money terms, for compression of natural gas at the considered CS-1 and the next CS (CS-2) before shutting down of the station; $C_{\text{cool}1}, C_{\text{cool}2}$ is the energy consumption, in money terms, for driving of fans in the cooling systems of the considered CS-1 and the next CS before shutting down of the station; $C_{e2}, C_{\text{cool}2}$ is the energy consumption, in money terms, for compression of gas and driving of fans in the cooling system at the following shutdown station KS-2.

Energy consumption, in money terms, for natural gas compression per hour at CS with the parallel operation of $x$ GGCU and $y$ EGCU in the compression system, can be determined from the ratio

$$C_e = c_e \cdot N_e = \frac{3.6 \cdot P_{\text{fg}}}{Q_{\text{hp}}} \cdot \sum_{i=1}^{x} \frac{N_{i}}{\eta_{e,\text{gus}},i \cdot \eta_{\text{mech},i}} + P_{\text{ee}} \cdot \sum_{j=1}^{y} \frac{N_{j}}{\eta_{e,\text{el},j} \cdot \eta_{\text{pet},j}},$$

(3.21)

where $c_e$ is the average cost of the energy unit for compression of gas in the blowers at CS, RUR / (kW×h); $N_e$ is the actual power consumed for compression of natural gas, kW; $P_{\text{fg}}$ is the fuel gas price, RUR/1,000 m³; and $P_{\text{ee}}$ is the price of electric energy at the considered CS, RUR / (kW×h).

The energy component of the hourly operating expenses for the cooling system of CS if it is equipped with several types of air coolers, will make
The presented method for appraisal of the technological capability and energy and economic efficiency of shutting down of the compressor shops and CS was tested in a process section of a multi-string GTL with the use of its operating characteristics.

Summarization of the heat engineering calculation enable determination of the ranges of the commercial flow rate \( Q_k \), at which shutting down of CS-1 is technologically expedient at the actual characteristics of natural gas \( t_{1st} \), \( P_{1st} \) and maximum permissible pressure of gas in \( P_{max, presl} = 7.36 \) MPa at the outlet of the previous station KS-0 (Figure 3.10).

![Figure 3.10 - Relation of the compression ratio at CS-2 \( \varepsilon_2' \) to the commercial flow rate of natural gas in GTL \( Q_{comm} \) when shutting down CS-1:](image)

1 – At the actual values of gas pressure at the outlet of CS-0 \( P_{1st} \);  
2 – At the gas pressure at the outlet of CS-0 \( P_{1st} = P_{max, presl} = 7.36 \) MPa.

At the actual values of natural gas pressure at the outlet of CS-0 \( P_{1st} \), shutdown of CS-1 is technologically justified at the commercial flow rate of natural gas \( Q_k \) not more than 170 million m\(^3\)/day, and at the pressure of natural gas at the outlet of CS-0 \( P_{1st} = P_{max, presl} = 7.36 \) MPa – when the value of the commercial flow rate of natural gas in the considered process section of GTL \( Q_k \) doesn’t exceed 190 million m\(^3\)/day (Figure 3.10).
Analysis of the actual operating characteristics and results of the calculation shows that the value of the cumulative energy consumption at CS-1, CS-2 for the alternative operating conditions of the process section of GTL largely depends on the commercial flow rate of natural gas in the process section of GTL (Figure 3.11).

Figure 3.11. Relation of the cumulative energy consumption for natural gas compression at CS-1 and CS-2 $\Sigma N_e$ to the natural gas feeding in GTL $Q_k$:

1 – For the operated CS-1;
2 – For the shutdown CS-1 and gas pressure at the outlet of CS-0

$P_{\text{tit1}} = P_{\text{max, prest}} = 7.36$ MPa.

Results of the calculation show that, for the natural gas pressure at the outlet of CS-0 $P_{\text{tit1}} = P_{\text{max, prest}} = 7.36$ MPa and gas consumption in the process section between CS-1 and CS-2 $Q_k$ over 200 million m$^3$/day, the cumulative energy consumption for this section $\Sigma N_e$ is less when the station CS-1 is operated. In case of drop in the commercial flow rate to the level below 200 million m$^3$/day, it is possible to consider shutdown of this station justified from the energetic point of view when the condition of technological expediency is met.

Similar heat engineering and technical-and-economic calculations for determination of the technological expediency and energetic and economic justification of shutdown of the compressor shops and CS should be made for the process sections of GTL, in which a drop in the gas supply below the design level is observed or expected.
3.4. Control and optimization of the operating conditions for cooling systems of the compressor stations

Natural gas cooling systems at CS of the process sections of GTL, located outside the permafrost zone, ensure cooling of natural gas to a temperature, which must be above the hydrating temperature and under the maximum permissible values of the temperature for operational stability of the line sections of GTL and insulation material of the gas line. In this temperature range, it is possible to control the operating conditions of the cooling system at CS from the point of view of reduction of the energy consumption for gas transmission and operating expenses.

Most common at the line CS of GTL are now the cooling systems utilizing air cooling units (ACU) for natural gas cooling, which have simple designs, are environment-friendly, reliable in operation, and are rather simply enough connected to the piping of compressor stations.

Control of the operating conditions of the cooling systems equipped with ACU can be implemented in different ways, particularly by changing the angle of the fan blades, bypassing a parts of the natural gas flow of the cooling system, and switching on or off the fans installed on ACU.

Control of the ACU operating conditions by changing the angle of fan blades is possible only on the shutdown units. Besides, unbalance of the fans rotors is possible when using this method, which drastically limits its application.

Control of the cooling system operation by means of bypassing the natural gas flow, while reducing the value of pressure drop of the gas flow, leads to reduction of the thermal capacity of the cooling system of CS. At that, only a part of the cooling systems is equipped with bypass gas ducts, which also limits the application of this method of control.

Now, control of the operating conditions of cooling systems at CS is overwhelming performed by switching on or off the fans installed on ACU, which enables changing the thermal capacity of the units and the cooling system in general.

As is shown by the analysis of results of processing of the operating characteristics, the key parameter, determining the value of the thermal capacity of ACU, is the maximum difference of the temperature between the natural gas and atmospheric air $\Delta t_{\text{max}} = t_1' - t_{\text{amb}}$. In this respect, by processing the operating characteristics, it is necessary to determine the relations of the thermal capacity of one ACU $Q_1$ to the value of the maximum temperature difference between the natural gas and atmospheric air $\Delta t_{\text{max}}$

$$Q_1 = f(\Delta t_{\text{max}})$$ (3.23)

It should be noted that the flow rate of natural gas through ACU has a rather insignificant effect on the thermal capacity of the units. It is related with the fact that the value of the factor of heat transfer from the natural gas flow to the atmospheric air $k$ is primarily determined by the value of the factor of
heat emission from the external surface of ACU pipes into the air $\alpha_2$ and the value of thermal resistance of the contaminations formed on the heat-exchange surface $\sum(\delta_i/\lambda_i)$. The factor of heat transfer from gas to atmospheric air and, hence, the thermal capacity of the unit fluctuates within ± 5% at the gas consumption changing in the range of ± 30%.

Analysis of the operating characteristics of the cooling systems of CS in the considered process sections of GTL showed that the most ACU are operated with the shutdown fans in winter (with the free convection from the external surface of ACU pipes to air). It enables determination of the thermal capacity of the units with the shutdown fans $Q_{\text{lec}}$ and its relation to the maximum average daily temperature difference between the natural gas and atmospheric air $\Delta t_{\text{max}}$.

If all ACU are operated with the shutdown fans, the thermal capacity of one unit $Q_{\text{lec}}$ is determined from the ratio

$$Q_{\text{lec}} = \frac{Q_{\text{cool}}}{i} = \frac{G \cdot c_{\text{pm}} \cdot (t'_1 - t''_1)}{n}, \quad (3.24)$$

where $i$ is the number of ACU in the cooling system; $n$ is the number of ACU, operated under free convection; $Q_{\text{cool}}$ is the necessary thermal capacity of the cooling system, kW; $G$ is the natural gas mass flow, kg/s; $c_{\text{pm}}$ is the average isobaric heat capacity of gas, kJ / (kg×K); $t'_1$ is the temperature of natural gas after compression in CB; and $t''_1$ is the gas temperature at the outlet of cooling system.

In autumn and spring, one part ACU $n$ in the cooling systems is operated with the shutdown fans, and another part – with one activated fan $m$, which enables determination of the thermal capacity of the units with one activated fan $Q_{11\alpha}$

$$Q_{11\alpha} = \frac{Q_{\text{cool}} - n \cdot Q_{\text{lec}}}{i - n} = \frac{G \cdot c_{\text{pm}} \cdot (t'_1 - t''_1) - n \cdot Q_{\text{lec}}}{m}, \quad (3.25)$$

In summer, when the maximum temperature difference between the natural gas and atmospheric air has the lowest values in the year, one part of ACU in the cooling systems is operated with one activated fan $m$, and another part – with two activated fans $r$, which enables determination of the thermal capacity of the units with two activated fans $Q_{12\alpha}$ and its relation to the maximum average daily temperature difference between the natural gas and atmospheric air

$$Q_{12\alpha} = \frac{Q_{\text{cool}} - m \cdot Q_{11\alpha}}{i - m} = \frac{G \cdot c_{\text{pm}} \cdot (t'_1 - t''_1) - m \cdot Q_{11\alpha}}{r}, \quad (3.26)$$

The basic types of ACU in the cooling systems of the considered CS are the home-manufactured units of type 2AVG-75 and air cooling units manufactured by the Italian company Nuovo Pignone. The
actual heat engineering characteristics in the operating conditions were determined for these types of ACU.

Comparison of the efficiencies of ACU of the considered types in case of their operation with the shutdown fans shows that the units from Nuovo Pignone have, despite a smaller heat-exchange surface area, a higher thermal capacity than ACU of type 2AVG-75 (Figure 3.12). It indicates their greater design excellence.

Figure 3.12 – Relation of the ACU thermal capacity to the maximum temperature difference between the natural gas flow and atmospheric air with 2 fans in operation:

1 – In the units manufactured by Nuovo Pignone;
2 – In the units of type 2AVG-75 manufactured domestically.

Transfer of ACU, manufactured by Nuovo Pignone, to the operation with one activated fan improves their thermal capacity by almost 3 times: during this transfer, the thermal capacity of ACU is increased from 800 kW to 2,200 kW at $\Delta t_{max} = 40^\circ$.

Transfer of ACU of type 2AVG-75 to operation with one activated fan improves their thermal capacity by almost 3 times as well. However, these types of ACU also remain less efficient than ACU, manufactured by Nuovo Pignone, by almost 40% in the considered operating conditions.

Transfer of ACU, manufactured by Nuovo Pignone, from operation with one activated fan to operation with two fans enhances their thermal capacity by not more than 30%. In this case, the amount of the consumed electric energy is increased by 2 times at practically the same gas pressure drop in ACU. It indicates the relative reduction of the energy efficiency of ACU for the considered transfer.
Transfer of ACU of type 2AVG-75 from operation with one activated fan to operation with two activated fans also enhances the thermal capacity of the unit, all other things being equal, by not more than 30%. At this operating conditions, the efficiency of ACU of type 2АВГ-75 remains also lower than that of the units manufactured by Nuovo Pignone.

At the known value of the natural gas temperature after compression in CB $t'_1 = t'_2$ and the preset value of natural gas temperature at the inlet the next line section of GTL $t''_1$, the required thermal capacity of the cooling system $Q_{cool}$ (kW) is determined from the ratio

$$Q_{cool} = G \cdot c_{pm} \cdot (t'_1 - t''_1),$$

(3.27)

At known value of the maximum temperature difference between the natural gas and atmospheric air $\Delta t_{max}$, it is possible to determine the thermal capacity of ACU of the gas cooling system with the shutdown fans $\Delta t_{max}$, as well as with one $Q_{116}$ and two $Q_{126}$ operated fans.

When $Q_{cool} \leq i \cdot Q_{116}$, there is no necessity to activate the ACU fans, i.e.: all ACU are operated with the fans shutdown.

When $Q_{cool} > i \cdot Q_{116}$, the number of units $m$, where it is necessary to activate one fan for each, is determined

$$m = \frac{Q_{cool} - i \cdot Q_{116}}{Q_{116} - Q_{116}}$$

(3.28)

If all ACU in the cooling system, operated with one activated fan, don’t provide the required thermal capacity $Q_{cool} > i \cdot Q_{116}$, it is necessary to transfer some or all ACU to the operation mode with two fans. The number of ACU, in which 2 fans must be operated, can be thus found from the ratio

$$r = \frac{Q_{cool} - i \cdot Q_{116}}{Q_{126} - Q_{116}}$$

(3.29)

Thus, the analysis of the obtained heat engineering characteristics of ACU at the different conditions of their operation shows that as the ambient temperature and the required thermal capacity of the cooling system, associated with changing of the operating conditions of the gas line section, are rising, the control of the operating conditions for the cooling system must be performed in the following sequence:

1. At first, all ACU in the cooling system are operated under free convection;
2. As the required thermal capacity or the ambient temperature is increasing, one fan in each unit must be sequentially activated;
3. After one fan is activated in each ACU, the units must be sequentially transferred to the operation mode with two activated fans as appropriate.
When the required thermal capacity of the cooling system $Q_{\text{cool}}$ or the ambient temperature $t_{\text{amb}}$ is decreased, it is expedient, from the energetic and economic point of view, to control the operating conditions of the cooling system in the inverse sequence.

Operating conditions of the cooling system, at which one part of ACU is operated under free convection, and another part with two operating vanes in each unit, should be considered as not favorable from the energetic point of view.

Analysis of the operating conditions of the cooling systems of the considered CS shows that, in some cases, the operating personnel of the stations doesn’t observe the stated principles of energetically optimal control.

For example, in one of the considered operating modes of the shop cooling system, consisting of 16 ACU, manufactured by Nuovo Pignone, 5 units were operated with the shutdown fans (free convection), 6 – with one activated fan, and 5 – with two activated fans. In this way, 16 fans were operated in the system. The maximum temperature difference between the natural gas and air was $\Delta t_{\text{max}} = 22^\circ\text{C}$. In such operating conditions, the considered cooling system enables recovery of 16,500 kJ of heat per second from natural gas. The same thermal capacity as showed by the results of the calculation, made with the use of the actual characteristics of ACU, can be provided by the alternative operating mode of the cooling system, in which 13 units are operated with one activated fan, and 3 – with the shutdown fans. Transfer of the considered cooling system to the alternative mode of operation enables reduction of the number of the activated fans from 16 to 13, which would lead to essential saving of electric energy.

Determination of the optimal values of the natural gas temperature at the inlet of the line section of GTL should be conducted in the range of permissible values of the natural gas temperature from the point of view of minimization of the energy consumption and operating expenses for gas transmission.

Activation of n additional fans to reduce the value of the natural gas temperature at the inlet of the line section downstream of CS can be considered as energetically expedient, when the cumulative electric capacity of the newly activated fans is less than the reduction of the capacity required for compression of natural gas at the next CS

$$n \cdot N_{e 1} < N_{e 1} - N_{e 2}, \quad (3.30)$$

where $N_{e 1}, N_{e 2}$ are the actual power consumed in the compression system at CS downstream of the line section before and after actuation of additional fans.

When n additional fans are activated, the thermal capacity of the cooling system will increase by

$$\Delta Q_{\text{cool}} = G \cdot c_{\text{pm}} \cdot (t_{11}^n - t_{12}^n) = m \cdot (Q_{11e} - Q_{1c}) + (n - m) \cdot (Q_{12e} - Q_{11e}), \quad (3.31)$$
where \( t^{''}_{11}, t^{''}_{12} \) is the natural gas temperature at the outlet of the cooling system before and after activation of additional fans; \( m \) is the number of ACU, in which one fan is activated; \((n-m)\) is the number of ACU, in which two fans are activated.

Based on the ratio (3.31), the temperature at the outlet of the cooling system can be found from the ratio

\[
t^{''}_{12} = t^{''}_{11} - \frac{m(Q_{11e} - Q_{12a}) + (n-m)(Q_{12a} - Q_{11e})}{G \cdot c_{pm}}
\]

Provided that the temperature of the natural gas flow at the outlet the cooling system after activation of additional fans is approximately equal to the natural gas temperature at the inlet of the line section downstream of CS \( t^{''}_{12} = t^{''}_{11} \), the temperature and pressure of natural gas at the outlet of the line section after activation of additional fans, as well as the value of the energy consumption for natural gas compression at CS downstream of the line section, can be calculated from the known ratios [12].

Determination of an optimum, energetically justified temperature at the inlet of the line section should be conducted sequentially by calculating the gas transmission characteristics for each step, characterized by activation of one or several fans. Such value of the temperature at the outlet of the cooling system \( t^{''}_{1opt} \) can be considered optimal, at which the subsequent activation of additional fans in the cooling system won’t result in the drop of compression capacity equaling to the value of the drive capacity of the activated fans.

The final conclusion on the value of the optimum temperature of natural gas at the outlet of the cooling system \( t^{''}_{1opt} \) can be drawn only on the basis of a technical and economic calculation.

Transfer of the cooling system to the operating conditions with deeper cooling is economically expedient when additional expenses for gas cooling are less than the drop in the energy component of the operating expenses for gas compression at the next CS

\[
|\Delta C_{cool}| < |\Delta C_{compr}|, \quad (3.33)
\]

where \( \Delta C_{compr} \) is the drop of the energy component of the operating expenses for gas compression at the next CS, RUR/hr; \( \Delta C_{cool} \) is the growth in the energy component of the operating expenses for gas compression at the considered CS, RUR/hr,

\[
\Delta C_{cool} = p_{ele} \cdot n \cdot N_{11}, \quad (3.34)
\]

\( n \) is the number of the activated fans; \( p_{ele} \) is the price of electric energy at the considered CS, RUR / (kW\times hr); and \( N_{11} \) is the capacity of the electric drive of one fan, kW.
Drop in the energy consumption, in money terms, for natural gas compression per hour at the next CS for the parallel operation of $X$ GGCU and $Y$ EGCU in the compression system can be determined from the ratio

$$\Delta C_{\text{compr}} = c_{e1} \cdot N_{e1} - c_{e2} \cdot N_{e2} =$$

$$= \frac{3.6 \cdot p_{fg}}{Q_{up}} \sum \left( \frac{N_{i1i}}{\eta_{e,\text{gtu},i} \cdot \eta_{\text{mech},i}} - \frac{N_{i2j}}{\eta_{e,\text{gtu},2i} \cdot \eta_{\text{mech},2i}} \right) +$$

$$+ p_{ee2} \cdot \sum \left( \frac{N_{i1j}}{\eta_{el,1i} \cdot \eta_{\text{red},1j}} - \frac{N_{i2j}}{\eta_{el,2j} \cdot \eta_{\text{red},2j}} \right) \quad (3.35)$$

where $c_{e1}, c_{e2}$ are the average costs of the energy unit required for compression of natural gas in blowers at CS downstream of the line section at the comparable operating conditions, RUR / (kW×hr); $N_{e1}, N_{e2}$ are the actual capacities consumed for compression of natural gas at the comparable operating conditions, kW; $N_{i1i}, N_{i2j}$ are the internal capacities consumed for compression of gas in the blower of the $i$ - th operating GGCU, included in the compression system, at the comparable operating conditions, kW; $N_{i1j}, N_{i2j}$ are the internal capacities consumed for compression of gas in the blower of the $j$ - th operating EGCU at the comparable operating conditions, kW; $Q_{h}^{p}$ is the lower heat value of fuel gas, kJ/m$^3$; $p_{fg}$ is the fuel gas price, RUR/1,000 m$^3$; and $p_{ee2}$ is the price of electric energy at the station following the considered section, RUR / (kW×h); $\eta_{e,\text{gtu},i} \eta_{e,\text{gtu},2i}$ are the effective efficiencies of the $i$ - th operating GTU at the comparable operating conditions, $\eta_{\text{mech}}$ is the mechanical efficiency of GGCU allowing for the mechanical losses of power transmission from GTU to the blower; $\eta_{el,1i} \eta_{el,1j}$ are the efficiencies of the electric motor of the $j$ - the operating EGCU at the comparable operating conditions; and $\eta_{\text{red}}$ is the efficiency of the reduction gear.

When determining the optimum depth of natural gas cooling in the cooling system, the optimum operating conditions of the cooling system with energetic and economic justification of the number of the operating fans are determined as well.

### 3.5. Evaluation of the efficiency of the operating conditions for compressor stations and process sections of gas transmission lines

In the process of determination of the energy and economic efficiency of GTL CS, it is necessary to evaluate the efficiency of the operating conditions of all systems of the station with allowance for their
interaction, taking into account the influence of the operating conditions of the examined CS on other facilities of GTL. It is proposed to use the sum of operating over-expenses for operation of all systems of the station associated with the non-optimal operating conditions as a criterion for the operating efficiency of GTL CS.

Analysis of the values and reasons for over-consumption of the energy component of the operating expenses for operation of all systems of the station enable to identify the priority of energy-saving actions at the examined CS. To resolve solution this problem, a criterion, which is determined as the sum of operating over-expenses for operation of all systems of the compared stations associated with the non-optimal operating conditions, referred to the commercial flow rate of natural gas through CS, is proposed

\[
K_{eff,CS} = \sum_{j=1}^{m} \frac{\Delta C_{en.j}}{Q_{,actual}}
\]  

(C.36)

Criterion of the operating efficiency of GTL CS can be also used for comparison of the efficiency of the operating conditions for GTL CS.

In the course of an integrated evaluation of the operating efficiency of GTL CS, it is necessary to compare the values of the actual gas pressure at the outlet of the considered CS with the optimal, energetically and economically justified value of gas pressure at the inlet of the next line section. In the event that the gas pressure at the outlet of CS doesn’t correspond to the optimal value of the pressure at the inlet of the next line section, it is necessary to determine the over-consumption of the energy component of the operating expenses, associated with this mismatch, analyze the reasons for this mismatch, and determine the methods for its elimination.

In the analysis of the operating conditions of CS, it is necessary to compare the operating compression system with the optimum one in the range of the actual operating characteristics and determine the over-consumption of the energy component of the operating expenses, associates with the selection of the non-optimal compression system. Selection of the optimum compression system is made upon results of the technical and economic calculation performed for the possible systems taking into account the technical state of GCU and expected supply of natural gas.

In the course of the energy audit of CS, it is necessary to analyze the process of control of the operating conditions for the compression system. Disturbances in the control process or delay in it when the gas parameters at the inlet of CS are changing, can be a cause for occurring of transient conditions, associated with pulsations of gas flows in the high-side piping of CS, and thus additional vibrational processes,
which might lead and sometimes does lead to emergency situations. At that, it is necessary to determine the additional expenditures for reduction of vibrations in the CS piping $\Delta C_{\text{piping,cs}}$.

Necessity for optimization of the operation of natural gas cooling systems at GTL CS is associated with the change of the thermal capacity of the air cooling units in the process of operation depending on their operating and weather conditions, as well as with the essential consumption of electric energy for driving the fans in ACU. When conducting an energy and economic audit of GTL CS, it is necessary to determine the optimum temperature of natural gas at the outlet of cooling system of the considered CS, compare it with the actual temperature, and calculate the over-consumption of the energy component of the operating expenses, related to this mismatch $\Delta C_{\text{en,cool}}$, to analyze the reasons for this mismatch and determine the methods for its elimination. In the evaluation of the operating efficiency of GTL CS, it is necessary to pay attention to the process of control of the operating conditions for the cooling system and compare them with the energetically justified control algorithm developed on the basis of the analysis of the actual heat engineering characteristics of ACU. Thus, it is also necessary to evaluate the energy power, in money terms, associated with the mismatch of the implemented and optimum process of control at CS $\Delta C_{\text{en,cool,control}}$. In the event that a multi-shop CS, operating underloaded, is audited, it is necessary to consider the possibility and expediency of the use of bypasses between the groups of shop ACU.

In the course of the energy audit, it is expedient to determine the throughput capacity of CS taking into account the actual state of the inner surface of pipes in the line sections and the technical state of GCU, evaluate its effect on the throughput capacity of the process section of GTL and, if the considered station is the closing section, it is necessary to select a method for increase in its throughput capacity.

In case of underloading, the process section, incorporating the audited CS, it is expedient to determine the threshold value of the natural gas supply in the section, at which it is technologically, energetically and economically expedient to operate the process section of GTL with the shutdown station. Implementation of this methods for control of the operating conditions of the process sections of GTL enables prevention of pressure loss in the piping and energy consumption in the cooling system of the shutdown CS, leads to reduction of the average temperature of natural gas in the line section, reduces the natural gas temperature at the inlet of the next CS, and enhances the ratio of compression in it, which also contributes to reduction of power losses and expenses. In the event that shutdown of the considered CS is technologically justified and economically favorable, and the station is not shutdown, it is necessary to determine the over-consumption of the energy component of the operating expenses, associated with the non-implementation of this action $\Delta C_{\text{en,shut}}$.

In the course of the energy audit, it is necessary to analyze the operation of the power supply system of CS and determine the expediency of transfer to power supply from the in-house power station. If the power supply system used at CS is not optimal, it is necessary to evaluate the loss from it $\Delta C_{\text{el}}$, and develop a plan for reconstruction of the power supply system of the station. Transfer of CS in the process
line of GTL to the independent power supply should be planned with allowance for the dynamics of change in the prices for the electric energy and fuel gas.

In the course of the energy audit of GTL CS, it is recommended to evaluate the results of the implemented methods for revamping of the power equipment, determine their economic feasibility and develop a program of revamping with identification of the most effective ways to conduct it.

Auditing of CS in the areas presented above enables evaluation of the technological, energy and economic efficiency of their operating conditions, identify mistakes in operation and determine the program of actions aimed at improvement of the operating efficiency of GTL CS. In comparison with the currently used methods, relying on the concept of cost of the goods transmission work, the proposed method enables a rather fair appraisal of the operating efficiency of CS irrespective of the operating conditions of the process section of the gas transmission line and level of equipment of GTL CS.

It is proposed to evaluate the efficiency of the operating conditions of the process sections of GTL based on the value of the criterion accounting for over-consumptions of the energy component of the operating expenses at all CS $\Delta C_{en,CS,i}$, commercial flow rate of natural gas $Q_{e,actual}$, and length of the process section $L_{PS}$

$$K_{eff,CS} = \sum_{i=1}^{n} \Delta C_{en,CS,i} / (Q_{e,actual} \cdot L_{PS})$$ \hspace{1cm} (3.37)

Results of the energy and economic audit of the process sections and CS of GTL can be used for evaluation and improvement of their operating efficiency and all gas-transmission system in general.

As was already mentioned above, the basic consumers of the energy resources in natural gas transmission are the compression systems of GTL CS.

Resolution of the problem for reduction in the energy consumption for compression of natural gas at CS can be conditionally divided in three stages:

- At the first stage, the problem of an optimum load distribution between compressor stations is resolved;
- At the second stage, the problem of selection of the compression systems at CS, ensuring the minimum energy consumption for natural gas compression, is resolved;
- At the third, final stage, the optimum load distribution between GCU is determined with the parallel piping of CS or between groups of serially operated GCU with the combined piping of CS.

Correct solution of each of these problems to reduce the energy consumption for natural gas transmission is only possible with allowance for the actual technical state of GCU, identified with the use of the methods for thermal gas-dynamic (parametric) diagnostics.

Results of the solution of the problem for optimization of the operating conditions of compression systems at CS (not considered in this paper and are a subject of a separate study) can be also used for appraisal of the efficiency of the operating conditions of CS during energy audits of compressor stations and process sections of the gas transmission lines.
3.6. Technological losses of gas in gas transmission lines and methods of their reduction

Natural gas losses for its transmission in the gas transmission lines are generally determined by a number of reasons: presence of any leaks in gas lines and shutoff devices, conduction of maintenance and repair operations, start-up and shutdown of gas-compressor units at CS, as a result of which the natural gas, in the absence of waste heat recovery devices, is discharged into the atmosphere, etc.

Indirect reasons of gas losses in the gas lines are also the deficiencies of the methods for its metering in the fields and gas lines.

The emphasis should be placed on reduction in gas consumption for transmission needs, reduction of the losses associated with leaks of valves, core and auxiliary equipment of compressor stations, line part of gas lines, etc. It is also necessary to pay attention to the technological losses, associated with purging of the process equipment of the gas treatment systems at GTL CS, start-up, and shutdown GCU. Gas losses during emergencies in CS and gas lines, as well as during scheduled repairs of the line part, are also a significant share of gas losses in its transmission. Lack of safe and precise instruments for gas metering at the stations, leads to so-called “gas imbalance” between the gas suppliers and consumers. These "losses" can make up to 2% of the gas volume transmitted via GTL.

Calculations show that, if within one CS and the route section adjacent to it, the equivalent leakiness reaches a value of about 0.5 ÷ 0.7 cm2, the amount of total gas leaks at all CS of OAO Gazprom can reach, in theory, the value of about 5 ÷ 7 billion m3 / year, which naturally indicates the urgency of identification and elimination of gas leaks in CS and gas lines.

Natural gas loss during purging of dust collectors is one of the most essential for GTL CS. Purging of dust collectors is, as a rule, performed once a shift for 30 ÷ 40 seconds. The amount of lost gas depends on the diameter of the discharge header, duration of purging, pressure in dust collectors, number of dust collectors at CS, etc. A number of systems is proposed for recovery of the purge gas, one of which is shown in Figure 3.13.

Figure 3.13 - Diagram of purge gas recovery at CS
According to this diagram, the purge gas is fed via pipelines 1 through header 2 to separator 3, where moisture and solids are separated from gas. Treated gas is routed to accumulating tank 4, from where it is periodically pumped by booster compressor 5. Role of the separator in the conditions of CS can be played by one of the dust collectors of the cyclone or oil type, and a pipe-header 1,000 ÷ 1,400 mm in diameter can serve as a accumulating tank. As a booster compressor, it is possible to use, for example, a gas engine compressor of type 10 GKN. The recovered gas is used for the process needs of CS or is supplied to the outside consumers.

A considerable amount of gas is discharged at CS into the atmosphere during starts and shutdowns of GCU. The analysis of operation of the units of type GTK-10 shows that the number of starts of the units in a year reached 2,000 ÷ 2,500, and gas losses thus exceeded 4 ÷ 5 million m3/year. Besides, during shutdowns of GCU, the CB circuit, depending on the capacity consumed by it, can contain up to 2,200 m3 of gas (GT-750-6 and GT-6-750 – up to 900 m3, GTK-10 – up to 1,500 m3, GTK-25 – up to 2,200 m3 of gas), which also is discharged via the flare into the atmosphere.

In some cases, for example, during disconnection of the external power supply and failure of the backup power supplies, there is a necessity for emergency shutdown of all CS and discharge of natural gas from all process facilities of the station.

Losses of natural gas in the course of start-up of a gas-turbine unit and its shutdown include the amount of gas for operation of the turbine expander, and gas required for purging of the blower circuit, which, for different types of GCU, total from 40 to 200 m3, and consumptions of impulse gas for process valves.

To eliminate the losses of gas during starts and shutdowns of GCU, a number of systems for recovery of the start-up gas has been proposed. One of the simplest recovery systems is shown in Figure 3.14.

The dotted line in the diagram (Figure 3.14) shows the existing system of GCU start-up, in which gas, after passing through turbine expander 3 via pipeline 4 and through flare 5, is discharged into the atmosphere. According to the proposed system, accumulating tank 6, from where gas is supplied to the consumers, is connected with valve 7 to the existing piping of the blower. As gas pressure after the turbine expander is, as a rule, close to the atmospheric one, gas can be pumped out by ejector 9 during operation of the turbine expander. High pressure gas fed through gate valve 8 from discharge header 11 is used as the active gas. The blended gas after the ejector can be fed through gate valve 10 in fuel 1 or start-up 2 headers.
Besides, for elimination of natural gas losses during starts of GGCUs, starters with a diesel or electric drive are used instead of turbine expanders.

In the process of operation of the line part of GTL, there is periodically a necessity for preventive, scheduled and other types of maintenance of its separate sections. Performance of the listed types of operations is always preceded by an atmospheric discharge of large volumes of the transmitted gas when emptying the gas line sections. In a number of cases, gas is for safety discharged into the atmosphere from the adjacent upstream section, which leads to its even higher, irrational losses in the gas lines.

Various systems for recovery of natural gas during repair of the gas lines, have been proposed both for single-string and multi-string gas lines. The basic problem of the systems for natural gas recovery consists in the development a special mobile (transportable) GCU.

A distinctive feature of all the proposed systems is the division of the gas, taken-off from the emptied section of GTL, in two flows (Figure 3.15).
When using a gas recovery system during repair of a section of a single-string gas line, one gas flow is compressed in blower 2 operated by engine 1 and, after cooling in cooler 12, is fed to the inlet of the high-head chamber of ejector 11 (Figure 3.15). The second gas flow is fed through back-pressure valve 4 to the inlet of the low chamber camera of the ejector after the blower. The total flow of the mixed gas is fed to gas line 10. The system provides for turbine expander 5 with the electric generator 6 for generation of the electric energy for in-house needs. Valve 3 serves for control and stabilization of gas parameters at the inlet of the blower.

Application of this mobile unit is not limited only to gas pumping during gas line maintenance. They can be also used as a backup in case of emergency or scheduled repairs of the fixed GCU at CS. A mobile unit, meeting the requirements of peak situations: fast start-up, relative simple delivery to the installation site, almost full independence, enables their efficient use as the peak units at CS with electric GCU, where installation of additional fixed units is frequently impossible because of deficiency of the electric power.

3.7. Energy saving by waste heat recovery

One of the areas for energy saving is the use of heat of the waste combustion products from GTU. Analysis of the energy balance of GTL CS showed that the total energy losses with the waste combustion products of gas-turbine units at the average actual value of the GTU efficiency are more than 75% of the energy released from fuel combustion in the combustion chambers of GTU.

The volume of secondary heat energy resources at CS makes about 800 million GJ per year. Less than 10% of them is now effectively used. In this respect, solution of the problem for waste heat recovery from combustion products of GTU as a result of a quantitative and qualitative analysis of the volume of
the available energy resources with identification of priority areas for their use and development of methods, systems, and equipment, resolving this problem is urgent.

Under operating conditions of GTU on GTL, it is necessary to consider them as the units, which generate two types of energy: mechanical - on the shaft of CB for its drive and calorific in the form of waste heat, the most complete and rational use of which is one of the area for the energy-saving technologies of natural gas transmission.

The amount of heat, which is possible and rational to recover during operation of gas-turbine units, depends on many factors: type and design of GTU units, its capacity and operating condition, ambient temperature, methods of heat recovery, etc.

In general, the amount of heat, which one can be obtained when using the waste gases of GTU, is determined by the following ratio:

$$ Q_p = q \cdot N_e \cdot k_{off} \cdot k_{amb} \cdot k_{load}, \quad (3.38) $$

where $q$ is the specific, theoretically available amount of the recovered heat; $N_e$ is the rated power of GTU; $k_{off}$ is the factor of utilization of the GTU waste heat depending on temperature of gases behind the waste heat recovery unit; $k_{amb}$ is the factor, allowing for the effect of the ambient air temperature; $k_{load}$ is the factor, allowing for the effect of GTU loading depending on the gas line operating conditions.

The specific, theoretically available amount of the recovered heat is determined from the ratio

$$ q = \frac{G \cdot c_{pm} \cdot (t_{waste} - t_{off})}{N_e}, \quad (3.39) $$

where $G$ is the mass flow of the waste combustion products of GTU, kg/s; $c_{pm}$ if the average isobaric heat of waste combustion products $kJ/(kg \cdot K)$; $t_{waste}$, $t_{off}$ are the temperatures of the waste combustion products before and after waste heat exchangers $^0C$; and $N_e$ is the effective capacity of GTU, kW.

When reviewing the problems of improvement in operating efficiency of GGCU at CS, the following basic area are expedient: heat recovery by the use of recovery units, use of waste heat exchangers for generation of hot water and steam for heating of different green houses, station rooms and neighboring settlements in the autumn and winter period of operation, generation of additional electric power for the needs of CS, generation of cold, etc.

A rather promising area of the waste heat use is the possibility for its use not only at CS directly, but also for heating of housing settlements adjoining to the station. In this case, there is naturally a problem of identification of an optimum radius of heat supply from the compressor station to the consumer.

As the maximum, economically expedient distance for transmission of hot water for heat supply to the adjoining settlements, it is necessary to consider a length of the transit network from CS to heat
consumers, at which total expenses for the GTU waste will be less than or are equal to the expenses for heat supply from the district or local boiler-houses.

When making calculations for determination of the economically expedient length of a heating main from CS to consumers, it is necessary to take into consideration the investments for construction of heat power units (boiler-houses and waste heat units), construction of heat supply networks and service points; consider various annual costs for maintenance and operation of the heat supply networks, expenses for fuel, etc.

Since the designed expenses for heat distribution networks, service points and water treatment remain almost identical both for heat supply from district boiler-houses and from waste heat units of CS, they can be ignored when making comparative calculations.

As the thermal output of the waste heat units depends on the number and operating conditions of GTU at CS, location of the station and variety of other factors, the designed amount of heat at the compressor stations will be naturally different, even for the same type of GTU; the optimum length of the heating main from CS to the adjoining settlements will be different as well. Apart from the maximum thermal load, the justified length of the heating main from CS to the heat consumers depends on the ambient air temperature, operating time of the heat supply system in the year, factor of heat transfer from the network water to the environment, type of heating main laying and temperature of the network water supplied to the consumer.

In general, the optimum length of a heating main can be expressed as function of the following parameters:

\[ L = f(Q, t_a, T, k, S, c_{fuel}, t_{carrier}) \]  

where \( Q \) is the thermal load; \( L \) is the length of the heating main; \( t_a \) is the ambient air temperature; \( T \) is the operating time of GTU in the year; \( k \) is the factor of heat transfer from the network water to the environment; \( S \) is the method of heating main laying from CS to consumers (tunnel, surface or craw-

ways); \( c_{fuel} \) is the fuel price; \( t_{carrier} \) is the heat carrier temperature in the feed main.

It is natural that the parameters, included in the ratio \( f(\cdot) \), have a different effect on the length of the heating main. So, the change of the ambient air temperature in the range from \( t_a = +10^\circ C \) to \( t_a = -25^\circ C \) and thermal load \( Q \) in the range of \( 4 \times 10^6 - 80 \times 10^6 \) kJ/hr leads to a change in the heating main length by no more than 1%, which gives grounds to make all calculations for the heating main length at any one temperature, for example, winter ambient air temperature at the level of \( t_a = -25^\circ C \).

Operating time of separate GTU in the year and factor of heat transfer from the network water to the environment have a little effect on the heating main length. Thus, at the thermal load \( Q = 80 \times 10^6 \) kJ/hr (~ 20 Gcal/hr), the increase in the operating hours of the heat supply system by 1,000 hrs in the range of 4,000 ÷ 6,000 hrs of GTU operation in the year leads to increase of the heating main length by no more than 1.0 ÷ 1.5%. In this respect, the operating time of the heat supply system in the year can be adopted, from this point of view, at the level of 5,000 ÷ 6,000 hr/year.
Increase in the heat-transfer factor by approximately 1.5 times from the values, recommended by SNiP (Sanitary regulations) for calculation of similar heating mains, leads to reduction of the route length by approximately 2 ÷ 5%.

The most important factors, affecting the length of the heat networks from CS to consumers, are as follows: thermal load, method of the heating main laying, heat-carrier temperature in the feed main, and fuel price.

Results of calculations for determination of the economically justified length of a heating main depending on the change in the stated values at the values of the heat-transfer factor \( k = 1 \);

\[
1.5 \frac{W}{(m^2 \cdot K)}
\]

for laying of the heating main in crawways (laying of pipes in a simple trench) are presented in Figure 3.16. The heat-carrier temperature in the feed main was adopted equal to \( t_{\text{carrier}} = 95; 150^\circ C \). The temperature of the network water in the return main of the heat network was in both cases adopted at the level of \( t_2 = 70^\circ C \).

![Figure 3.16 - Relation of the heat supply distance to the thermal load, heat-carrier temperature and heat-transfer factor (k) for laying of the heating main in crawways:](image)

1. \( k = 1 \) \( \frac{W}{(m^2 \cdot K)} \); 2. \( k = 1.5 \frac{W}{(m^2 \cdot K)} \).

Calculation results show that the economically justified length of the heating main for laying in crawways and at the water temperature in the feed main at the level of \( t_{\text{carrier}} = +95^\circ C \) changes from \( L = 1,000 \text{ m} \) at \( Q = 3 ÷ 5 \text{ Gcal/hr} \) to \( L = 6,000 \text{ m} \) at \( Q = 60 \text{ Gcal/hr} \). At the water temperature in the feed
main at the level of tcarrier = +150°C, the length of the heating main at the same thermal loads changes in the range of 2,000 ÷ 12,000 m. If, for example, two units, generating 12 ÷ 20 Gcal of heat for possible recovery, are operated at the station, it is quite possible to ensure heating of the adjoining settlements at a distance of up to 4,000 m.

As is shown by calculations, the surface routing appears less cost-effective, and, hence, the economically expedient length of the route is less than for crawlways (Figure 3.17).

Figure 3.17 - Relation of the heat supply distance to the thermal load, method of laying, and temperature of heat-carriers (at t₁ = -25°C; k = 1 W/(m² · K));
- Tcarrier = 95°C; t₂ = 70°C (solid line);
- Tcarrier = 150°C; t₂ = 70°C (dotted line);
1 – surface laying; 2 - crawlway.

Fuel cost has almost directly proportional impact on the change of the heating main length, i.e.: with the rise in the price for fuel, the distance, at which it is expedient to “transport” the heat of GTU waste gases, is increasing.

For heavy thermal loads of the consumers and their remoteness from CS, the most rational is supply of a heat-carrier with the temperature of approximately 150°C into the heating main, as the temperature factor here makes essential impact on the length of the heating main.

According to the reference data, the thermal load, consumed by one inhabitant of the midland of the European part of Russia, is 2.19 kW. This thermal load includes the heat used for heating, ventilation and hot water supply in the private premises. Therefore, it is possible to determine the cumulative thermal load for each specific housing settlement. For example, for a gas workers’ settlement, located nearby CS, with the population of approximately 700 ÷ 800 persons, the required thermal capacity of the boiler-house
must be \(\approx 1600 \div 1800\) kW. With allowance for thermal loss in the networks (up to 25%), the required thermal capacity will make approximately \(2 \div 2.25\) MW.

Given that the waste-heat boiler, installed on the exhaust of the unit, event of a small capacity, such as GPA-Ts-6.3, for example, ensures generation of heat power of about 5 MW, it is obvious that the cumulative thermal capacity required for this housing settlement will make approximately 50% of the heat generated in the waste-heat boiler.

Approximate results of calculations for central heating of a CS gas workers’ settlement with the population of 700 \(\div\) 800 persons are presented in Table 3.2.

According to calculation results, the average thermal capacity of the system in the heating period, required for heating and hot water supply of the settlement, is approximately \(Q_{\text{average}} = 7,000\) Gcal (Table 3.2).

### Table 3.2

<table>
<thead>
<tr>
<th>Quantity of people</th>
<th>Volume of buildings (V_{H}), m³</th>
<th>Heat demand</th>
<th>Gas consumption (V), million m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>700÷800</td>
<td>~65,000</td>
<td>~5,000</td>
<td>~21,000</td>
</tr>
</tbody>
</table>

For calculation of the peak (maximum) thermal capacity of the heating and hot water supply system of the settlement, it is necessary to consider the minimum temperature of air for this region. With allowance for the minimum air temperature, it turns out that the value of the maximum thermal capacity of the system, required for the settlement habitability in the coldest day, makes about \(Q_{\text{max}} = 12,000 \div 14,000\) Gcal.

Therefore, it is possible to consider that the thermal capacity generated even by one waste-heat boiler of the unit of type GPA-Ts-6.3, will be sufficient for heat supply to the settlement even in the coldest period.

About 1 million m³ of gas per year is thus released from burning in the boiler-house (table 3.5), while the possible construction of the heating main from CS to the settlement will pay off for approximately \(2 \div 3\) years at the existing prices for fuel.

Except heating and hot water supply, the waste heat of GTU at CS should be used, for example, for replacement of the fired heaters for fuel gas.

The existing technology of gas transmission in gas lines provides for pre-heating of start-up and fuel gas at CS, equipped with GGCU. Fired heater of type PTPG-30 is primarily used at CS for pre-heating of the start-up and fuel gas. Burning a quantity of the process gas releases the heat, which, through an intermediate heat-carrier (aqueous solution of diethylene glycol), is transferred to the fuel and start-up.
gas. The gas is thus heated up to 45 ÷ 50°C after its pressure is reduced to the pressure of the fuel and start-up gas.

Heater PTPG-30 automatically maintains the temperature of gas after the heater at the level from 15 to 70°C at the rated thermal output of about 1 MW. Rated gas consumption of the heater is not more than 110 m3/hr at the efficiency of not less than 80%.

Fuel gas preheating leads to the improvement of the combustion process in the combustion chamber of GTU and reduction of the fuel gas consumption, which can be demonstrated by reviewing of the heat balance equation as well.

The combustion chamber heat balance is calculated relative to the temperature of calorimetric measurements (tQ = 20°C) and has the following form:

\[ \eta_{cc} \cdot B \cdot Q^p + G_a \cdot c_{pm,a} \cdot (t_2 - t_Q) + B \cdot c_{pm,g} \cdot (t_r - t_Q) = \]

\[ = G \cdot c_{pm} \cdot (t_3 - t_Q) + b_f \cdot B \cdot c_{pm,f} \cdot (t_f - t_Q) \] (3.41)

where \( \eta_{cc} \) is the combustion chamber efficiency; \( B, G_a, b_m \) are the flow rates of fuel gas, air, and the relative mass of solid, not burnt residuals of fuel, respectively; \( Q^p \) is the lower heat value; \( t_2, t_r \) are the air and fuel temperatures at the inlet of the combustion chamber; \( c_{pm} \) is the average isobaric heat of air (a), fuel gas (g) and solid, not burnt residuals of fuel (f).

Analysis of the equation (4.4) shows that the rise in the fuel gas temperature at the inlet of the combustion chamber of GTU reduces its consumption by the unit in general.

Calculations show that the GTU waste heat use for heating of the fuel and start-up gas provides the annual saving of fuel gas for the heater only at the level of 0.9 ÷ 1.0 million m3 while simultaneously improving the ecological situation at CS.
Conclusions

1. Continuous growth in the price for extraction, production and transmission of fuel and energy resources inevitably leads to the necessity for reviewing the problems of energy saving as one of the main tasks of the country’s energy policy. The total potential of energy saving in the industry is comparable to the volumes of possible growth of the extraction from traditional sources.

2. Among numerous problems, facing the gas industry and largely defining the outlook of its further development, the reduction of power consumption for in-house needs, and particularly for natural gas transmission pipelines, is one of the main issues. Considering that the major consumers of energy resources at gas transmission are compressor stations (CS), the problem of reducing the power consumption in the industry must be first of all aimed at the improvement in the efficiency of their operation, i.e. at the reduction in gas losses and leaks, improvement in the efficiency if gas compressor units (GCU) installed at CS, optimization of the operating conditions for the main CS systems, efficient utilization of secondary power resources, etc.

3. The greatest effect of energy saving is reached when it is implemented at all stages of the life cycle of gas transmission lines.

4. The energy and process characteristics on the basic facilities of the gas-transmission system, used for resolving the power technology problems of gas transmission, have been reviewed.

5. A package of energy-saving technologies at the operation stage has been reviewed – cleaning of the flow channel of an axial compressor, control of the CS operating conditions for joint operation of gas-turbine and electric GCU, and use of waste heat.

6. Possibilities of energy saving by rational control and optimization of the operating conditions of the CS cooling system have been examined.

7. Criteria for evaluation of the expediency of the control of the operating conditions for the process sections of a gas line by shutdown of the compressor shops and compressor stations have been proposed.
Bibliography

18. Heat exchange in oil and gas pipeline transmission / E.O. Antonova, G.V. Bakhmat, I.A. Ivanov,


