The issue of energy safety of any country is primarily related to the rational and prudent use of natural resources. The specific feature of the use of natural resources in Ukraine is in the major natural resource being the gas from the gas- and gas condensate fields, and, the accompanying gas from oil fields [1, 2].

The stable and failure-proof operation of the main energy-consuming enterprises in Ukraine and the uninterrupted supply of gas to general consumers is ensured by the production of natural gas in the scope of no less than 25% of the total annual volume of gas consumption. This explains the urgency of the issue of ever increasing the gas production volumes in Ukraine.

The task of further stabilizing or increasing of gas production from the active fields becomes particularly urgent considering the fact that the process of year-to-year extraction of natural gas from a field causes a gradual deterioration in the volume of gas production throughout the whole life of the field [3, 4, 5].

A solution to the above task lies in the implementation of a certain set of measures specifically for each field. Prior to taking a closer look at such measures, we need to consider the results of analysis and systematization of all problematic issues relating to the exploitation of fields at the final stage of development [1, 5].

![Figure 1 – Problematic issues in the exploitation of fields at the final stage of development](image-url)
Now let us consider the issues from the above figure in detail.

The primary problematic issue is the gradual drop of formation pressure, which, following the decrease of pressure difference between the formation and the mouth of the well, results in the deterioration of the production rate of the well.

This problem may be solved by decreasing the operating pressure in the wells of the field. The desired result may be achieved in the following ways:

- by engaging an additional consumer for the low-pressure gas, e.g. by constructing auxiliary gas pipelines;
- by introducing compressor equipment providing for adjustment of pressure at inputs to aggregates.

The above two ways allow for gradual decrease of pressure in the mouth of wells, while also ensuring stabilization of gas production in the field.

The disposal of natural gas to consumers constitutes the second problematic issue. Firstly, the disposal of natural gas of equity production is supposed to provide for the scope of gas consumption in the area of extraction; secondly, the disposal in question concerns the low-pressure gas. In the majority of regions of Ukraine, the value of output pressure at the gas fields where no gas compression is done ranges within 0.3-1.0 MPa; and, in cases of gas compression at booster compression stations (BCS), the appropriate value is 1.2-2.0 MPa.

The third problematic issue is that the final stage of exploitation of a field is characterized by the withdrawal off the formation of considerable amounts of water and solid deposits, which causes pollution of the cavities of flowlines, industrial gas pipelines and gas-main pipelines. The major reason for the above is the increase of gas velocity; the solution to this problem requires an improvement of operational indices of the separation equipment, and, introduction of new methods for cleanup of internal cavities of gas pipelines.

Let us now consider the above problematic issues and ways of solution for these using a practical example from the exploitation of an active field. A fairly good piece of such example featuring all the signs peculiar of the final stage of exploitation is the Shebelynsky Gas Condensate Field (GCF) that has been under development for
over fifty years, yet still keeping the largest residual gas reserves and being the gas field number one in Ukraine. This field includes as many as 24 Complex Gas Treatment Stations (CGTS), which encompass a whole park of over 500 wells. The principal diagram of the Shebelynsky GCF is presented in Figure 2.

Figure 2 – Principal diagram for collection of equity-production gas at the Shebelynsky gas field

The CGTSs are connected to each other and to the BCS via a system of industrial gas pipelines that comprise a circular gas-collecting system. As of 2009, the operating pressure has decreased to 0.9 MPa in the gas-collecting system, and, to 1.1 MPa – at the mouth of wells. Following the stage of compression at the BCS, the value of pressure does not exceed 1.75 MPa.

The gas field is located in the Eastern industrial region of Ukraine featuring a branched system of gas-main pipelines and a large number of consumers (Figure 3).
Figure 3 – Scheme of natural gas disposal from the field

The general algorithm for solving the problem of further exploitation of the gas field is presented in Figure 4 below.

![Diagram](image)

**Figure 4 – Algorithm of evaluations**
Particularly for the Shebelynsky GCF, the above algorithm shall be presented as follows.

Task – Increase of natural gas production

Ways of achievement

1. Reduction of pressure at input of current BCS
2. Installation of small-size BCSs for all 24 CGTSs
3. Establishment of 8 group plants for gas collection and compression
4. Establishment of new gas compression station based on current IGDS

Disposal of natural gas – Via three current gas-main pipelines + Disposal of natural gas to large consumers via a system of industrial gas pipelines

Compressor equipment

1. 2 gas-turbine units, or 3 "Solar" type units
2. 72 screw-type units
3. 34 "Ajaks" piston-type units
4. same as item 1 + 6 "Ajaks" piston-type units

Minimization of pressure loss at the stage of gas collection and transportation:
- Insertion of drainage systems;
- Cleanup of gas-main pipelines cavities using rubber balls;
- Cleanup of well cavities using helium pistons;
- Purging of wells into low-pressure gas-collecting system using the purge gas of equity production.

Figure 5 – Algorithm of evaluations for the Shebelynsky GCF
The optimal variant for development of the gas field was selected through work-back calculation of the pressure loss at the various points of the field, e.g. the flowline, CGTS, industrial gas pipelines, gas-collecting main, BCS tie-in, also making allowance for the change in system loading. Thus, the overall pressure loss shall be calculated by the formula below [6]:

\[ \Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3 + \Delta P_4 + \Delta P_5 \]  

Where:

- \( \Delta P_1 \) – pressure loss in well flowline, MPa;
- \( \Delta P_2 \) – pressure loss in CGTS tie-in, MPa;
- \( \Delta P_3 \) – pressure loss in industrial gas pipeline, MPa;
- \( \Delta P_4 \) – pressure loss in gas-collecting main, MPa;
- \( \Delta P_5 \) – pressure loss in BCS tie-in, MPa.

The pressure at the mouth of the wells in the field is calculated on the basis of a certain value of pressure at the input of a check point:

\[ P = P_{\text{ct}} + \Delta P \]  

Where:

- \( P \) – pressure at the well mouth, MPa;
- \( P_{\text{ct}} \) – pressure at the check point.

It is clear that the closer is the check point to the well mouth, the fewer constituents are calculated in equation 1; so, the lower level of pressure can be attained at a particular group of wells in the field.

The major factors determining the hydraulic resistance in the gas pipelines are the roughness of internal walls, and, the level of contamination of the internal cavity, of the pipes. The level of contamination of internal cavity of a pipeline, and, the changes of hydraulic pressure relating to fluctuation of roughness throughout the service life, are included into the value of Efficiency Factor \( E \), which is a ratio between the actual gas-flow rate (volumetric or mass) and the estimated loss based on actual values of the transportation mode. Thus, the actual gas-flow rate in a pipeline is defined as a product of the estimated (theoretical) flow rate by the efficiency factor \( E \). The operational estimation of the actual hydraulic resistance of, and the level of contamination of, a gas pipeline section is based on prior periodic determining of the
efficiency factor $E$ using the actual parameters of the mode, and, the following dependence:

$$E = \frac{Q_a}{Q_{th}}.$$  (3)

Where: $Q_a$ - actual volumetric gas-flow rate in a pipeline defined on the basis of measurement data;

$Q_{th}$ - theoretical (estimated) volumetric gas-flow rate in a pipeline calculated according to normative procedures and on the basis of actual data.

The parameters of a formation are calculated based on the dependence of nonlinear filtration:

$$P_{fm}^2 - P_{bh}^2 = a \cdot q + b \cdot q^2,$$  (4)

Where: $a, b$ - filtration resistance factors of the wells, determined by gas-dynamic survey;

$P_{fm}, P_{bh}$ - absolute formation- and bottom-hole pressure, MPa;

$q$ - flow rate of well, thou. m$^3$/day.

The flow of gas in well is calculated as per the following formula:

$$P_M = \sqrt{P_{bh} \cdot e^{-2 \cdot S} - 1.377 \cdot \lambda \cdot \frac{z^2 - T^2 \cdot (1 - e^{-2 \cdot S}) \cdot q^2}{d^5}},$$  (5)

Where: $d$ - internal diameter of well, mm;

$P_M$ - Absolute pressure at mouth of well, MPa;

$P_{bh}$ - Absolute pressure at bottom-hole of well, MPa;

$P_{fm}$ - Absolute formation pressure, MPa;

$\lambda$ - Hydraulic resistance factor;

$z$ - Gas compression factor;

$T$ – Absolute temperature of gas, K;

$q$ - Flow rate of well, thou. m$^3$/day;

$S$ - Coefficient to be defined by the formula: $S = 0.03415 \cdot \frac{\Delta \cdot L}{z \cdot T}$;

$\Delta$ - Relative density of gas.

The parameters of operation of flowlines are calculated using the dependence of gas flow in gas-main pipelines indicated below:
\[
q = 3.26 \cdot 10^{-7} \cdot d^{2.5} \cdot \sqrt{\frac{P_1^2 - P_2^2}{\lambda \cdot z \cdot T \cdot L}} \cdot 10^3 \text{ thou.m}^3/\text{day},
\]

Where:  
- \( d \) - internal diameter of gas pipeline, mm;  
- \( P_1, P_2 \) - Absolute gas pressure at start and end of gas pipeline, MPa;  
- \( \lambda \) - Hydraulic resistance factor;  
- \( z \) - Gas compression factor;  
- \( T \) – Absolute temperature of gas, K;  
- \( L \) - Length of gas pipeline, km;  
- \( \Delta \) - Relative density of gas.

As is seen from the above described approach, the closer is the compressor to the well mouth, the lower is the gas loss caused by friction pressure and by local resistance, this ensuring the lower value of pressure at the well mouth and allowing for increase of gas extraction volumes.

With that duly said, the next question is whether it is expedient to install compressor equipment at each well, or at each CGTS, which is suggested in the above statement concerning the minimization of pressure loss at the stage of gas collection prior to compression.

Let us consider the histogram presented in Figure 6 below.

Figure 6 – Histogram of distribution of pressure loss at collection, treatment and transportation of equity gas at the Shebelynsky gas field
As is seen from Figure 6 above, the major part of pressure loss occurs in the gas-collecting main and the tie-in of the BCS currently in use. Therefore, should the question of further development of the gas field be solved using Ways 1 and 4 of Figure 5, this would necessarily entangle a more than one half greater loss of pressure at gas collection, and, the resultant lower value of gas extraction volumes.

The next question to solve concerns the expediency of investing finances into a project of further development of the gas field involving the idea of installing compressor equipment at each CGTS (Way 2), or, establishing group plants for gas collection and compression (Way 3). Let us consider the data of table 1 below relating to the economic efficiency and expediency of such projects.

Table 1 – Data relating to the calculation of cost effectiveness of the four Ways of development for the gas field

<table>
<thead>
<tr>
<th>Project</th>
<th>Additional gain of gas production compared to basic version, %</th>
<th>Object for capital investment</th>
<th>Pay-off period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Way 1 – Modernization of the current BCS</td>
<td>27</td>
<td>Additional compressor equipment, reconstruction of BCS tie-in and separation equipment</td>
<td>Three years</td>
</tr>
<tr>
<td>Way 2 – Installation of BCS at each CGTS</td>
<td>40</td>
<td>Installation of 72 screw-type compressors; re-equipment of current CGTSs</td>
<td>None</td>
</tr>
<tr>
<td>Way 3 – Establishment of group plants for gas collection and compression</td>
<td>38</td>
<td>Installation of plants on the basis of objects currently in use; installation of 34 aggregates</td>
<td>Four years</td>
</tr>
<tr>
<td>Way 4 – Establishment of additional high-capacity center for gas compression</td>
<td>31</td>
<td>Reconstruction of current BCS; installation of new plant for gas collection and compression; installation of 6 additional piston-type aggregates</td>
<td>Four years</td>
</tr>
</tbody>
</table>

It is obvious from the table above that the most necessary and economically expedient line for development of the gas field is according to Way 3.

The set of technological and economical calculations has been performed using the licensed software complexes developed under the database management systems VisualFoxPro and SQL. The accuracy of output data used in the calculations is based
on constant operational monitoring of BCS and CGTS in the gas field; monitoring of hydraulic state of the system of pipelines for gas extraction and collection; and, monitoring of the operation modes of flowlines and wells.

It is noteworthy that the question of solving the problem of development of depleted fields shall sooner or later become urgent for the majority of countries engaged in the extractive industry; therefore, the specialists of UkrNDIGaz (Scientific Research Institute of Natural Gases of Ukraine) already regard as a perspective line to substantiate the operation modes for fields of low operating pressure going through the final stage of development. Another important note is that the approach to solving such problematic issues at the final stage of development of a field is of comprehensive and systematic nature, thus combining the major constituents comprising the process of gas extraction and transportation, namely:

- Extraction and collection of natural gas from wells at the CGTS;
- Preparation of natural gas; operation modes of separation equipment;
- Transportation and disposal of natural gas via a system of industrial- and gas-main pipelines;
- Compression of gas at BCS; selection of optimal operation modes for equipment.

**Conclusions**

The final stage of development of gas fields characterized by the drop of pressure at the mouth of wells, and, by overall decline of gas production volumes, raises an important issue of selection of appropriate site to locate the BCS relative to the gas-collecting network; and, selection of the type of gas pumping units, and the number of such units in the course of further increase.

The drop of pressure is typically attended by withdrawal off the formation of liquid and solid deposits, which accumulate in the gas-collecting network, causing reduction of the hydraulic efficiency and throughput of gas pipelines; this, in its turn, requires further implementation of certain measures for pipeline cleanup and utilization of purgings resulting from the cleanup.
Another important issue relates to the optimization of transportation of low-pressure gas via gas-main pipelines to consumers, which use their own gas distribution network, and, impose certain requirements as to the transportation modes and quality of gas; and, defining the effect of variations in gas consumption rates during the summer and winter periods of the year.
Bibliography


