The methodology of redundant design schemes and the method of contour minimization for tracing systems of field gas and oil pipelines

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Abstract. The goal of the work is to develop a methodology and a method for optimizing the tracing of oil and gas field pipelines. The analysis showed that the solution to this problem does not receive due attention from both designers and specialists in the automation of design solutions. The paper proposes to solve this problem on the basis of redundant design schemes that represent a graph of possible routes for the passage of field pipelines. As a method, the procedure of the contour (coordinatewise relative to the contour variables) minimization of the cost function of the life cycle of the pipeline system is proposed. A procedure for rejecting inefficient connections in the column of an excessive scheme of field pipelines is proposed. The proposed methodology and method are implemented in the TRACE-NG software package, which is successfully used in practice to substantiate the structure and parameters of pipelines for various technological purposes. Findings. The proposed methodology, method and software package are an effective computing tool useful for designers.

1. Introduction
The field pipelines of gas and gas condensate, oil and gas and oil fields (PTNG) include [1]: gas collectors from piping gas wells, untreated gas pipelines, stable and unstable gas condensate pipelines, regardless of their length; pipelines for supplying purified gas and an inhibitor to wells and other field development facilities; sewage pipelines with a pressure of more than 10 MPa for supplying it to wells and injection into absorbing formations; methanol pipelines; inhibitor lines; oil and gas gathering pipelines (oil and gas pipelines) for transporting oil well products from metering units to points of the first stage of oil separation; gas pipelines for transporting oil gas from oil separation plants to integrated gas treatment plants, oil pipelines for transporting gas-saturated or degassed irrigated or anhydrous oil from an oil collection point and a booster pump station to a central collection point; gas pipelines for transporting gas to production wells with a gas-lift production method; gas pipelines for supplying gas to reservoirs in order to increase oil recovery; pipelines of waterflooding systems for oil reservoirs and systems for burial of formation and wastewater into deep absorbing horizons; oil pipelines for transporting commercial oil from the central collection point to the construction of the main transport; gas pipelines for transporting gas from the central collection point to the construction of the main transport.
of gas mains; inhibitor pipelines for supplying inhibitors to wells or other oil field facilities; gas pipelines of underground gas storages: pipelines between the sites of individual objects of underground gas storages, etc. Tracing issues of the listed gas storage facilities are the most important and most difficult tasks of their design [1]. However, in the current practice of designing this task is reduced to the analysis of one, two options for routes. However, it is not difficult to verify that even these two options generate a redundant scheme, on which you can outline many other options and solve optimization problems.

Among the first works on automation of the choice of pipeline routes can be attributed to the works of Professor P. Wart. et al. [1-4], which formulated criteria for optimizing the choice of pipeline routes, and related atematic problems of finding the optimal pipeline route between two points. Based on the Steiner-Weber problem [4], methods for finding the optimal pipeline route with bends are proposed. However, in such a formulation, it was almost impossible to avoid the listed limitations and factors.

2. Methods

The task of choosing the optimal configuration and parameters of the oil-and-gas pipelines field systems according to the criteria of the life cycle costs can be formulated as follows. Let a redundant scheme be given, including all kinds of connections between existing and new fields, gas, oil storage facilities and other structures. It is necessary to highlight on this diagram a subnet in the form of a tree that meets the minimum of the total estimated costs for the construction and operation of the PTNG. To solve this problem, a new approach is proposed, consisting of a complex iterative process in which each of the external (large) iterations is implemented in two stages. At the first stage, one of the possible trees of the initial approximation is constructed and the life cycle costs for this variant of the scheme are calculated. At the second stage, this solution is improved by successively replacing the branches of the resulting tree with chords (a chord is a section that does not enter the tree). After that, the transition to the next iteration is carried out, for which the best version of the scheme obtained at the previous iteration, etc., is already taken as an initial approximation, until the convergence condition for the computational process is fulfilled.

As an initial approximation, it is planned to build either a tree of minimum length (DMD), or a configuration option for the pipeline system that the designer outlines, or it is an existing version that requires reconstruction and development.

3. Results and discussions

We illustrate the mathematical and algorithmic aspects of this approach.

The distribution of fluid and gas flows in piping systems is subject to certain systemic laws of conservation of mass and energy. Such laws are analogues of the first and second postulates of Kirchhoff. To formally describe them, we use the algebra of hydraulic chains [5]. To take into account the law of conservation of mass in PTNG, we use the matrix of the connection of nodes and branches of the circuit Figure 1, the dimensions of which will be as follows: (m, n is the number of nodes and sections of the circuit). Here aji = -1, if the branch i is directed to the node j; ji = 1 if branch i originates from j; ji = 0 when the node j does not belong to the branch i. For example, for the circuit shown in Figure 4, this matrix will look like this:

![Figure 1. Matrix of the connection of nodes and branches of the circuit.](image-url)
The use of the matrix will allow you to write the equation of material balances for all nodes Figure 2 of the calculation scheme as follows:

\[ A \cdot x = Q \quad (1) \]

\[ x = (x_1, \ldots, x_n)^T; \quad Q = (Q_1, \ldots, Q_m), \]

where is the cost vector for network sections and nodal loads (selections, inflows). Let us write this equation for the circuit shown in Figure 1.

![Figure 2. The equation of material balances.](image)

The connection between the pressures in nodes (P) and their differences (Y) Figure 3 over network sections in the theory of hydraulic networks is usually written in the following matrix form:

\[ A^T \cdot P = y \quad (2) \]

where T is the sign of transportation; P is the vector of nodal pressures. For the circuit shown in Figure 4:

![Figure 3. The connection between the pressures in nodes (P) and their differences (y).](image)

In order to calculate the pressure loss over sections of the network or pressure over the nodes of the circuit, it is necessary to know or fix the pressure in one of the nodes of the design circuit. For the network shown in Figure 4, as a given we take the pressure of the pumping station in the source (node 3) and transform the system of equations by successively eliminating \( P_3 \).
As a result, equation (2) will be presented in the form of two groups of equations:

\[ \text{Figure 4. The stages of the computing process.} \]
The first group is an analogue of the second Kirchhoff law Fig. 5 and in the theory of hydraulic circuits is written in the following matrix form:

\[ BY = 0 \]  \hspace{1cm} (5)

where \( B \) is the contour matrix( \( B = [b_{ir}] \), is the number of contours), which fixes the coincidences of the selected base system of contours and branches: \( b_{ir} = 1 \), if the branch \( i \) enters the contour and its orientation coincides with the direction of the contour; \( b_{ir} = -1 \), when the orientation of the branch entering the contour \( r \) is opposite to the direction of traversal of the contour and \( b_{ir} = 0 \) if the branch does not enter the contour.

For PTNG systems shown in Figure 1, a formula (5) has the following form:

![Figure 5. Analogue of the second Kirchhoff law.](image)

The second group characterizes the connection of the piezometric pressure \( P_{j*} \) through the "chain" of values of \( U_i \) along the branches of the tree connecting each of the nodes \( j \) with the node \( j^* \). In matrix form, this system of equations is written as follows:

\[
\begin{align*}
P_j &= eP_{j^*} - R_g \cdot \text{y},
\end{align*}
\]

where \( e \) is a single vector; \( R_g \) is the matrix of paths (connecting any node \( j^* \) with all other network nodes along the branches of the selected tree: \( r_{ii} = 1 \), if branch \( i \) belongs to the path leading from \( j^* \) to \( j \) and its orientation coincides with the direction of the path; \( r_{ii} = -1 \), if the branch \( i \) belongs to the path leading from \( j^* \) to \( j \), but its orientation is opposite to the direction of the path; \( r_{ii} = 0 \), if the branch \( i \) does not belong to the path leading from \( j^* \) to \( j \);

\( j = 1, \ldots, m - 1, i = c + 1, \ldots, p. \)

The selected (base) tree is shown in Figure 4 bold lines. This tree uniquely determines the structure and orientation of the branches Figure 6 in the matrix \( B \).

For an example (see Figure 4) this expression has the following form:
Obviously, for PTNG systems with a branched (tree-like) structure, the first group will be absent.

If you select some connected spanning tree on the original redundant scheme, then all parts of the given scheme will be divided into two subsets: (m-1) tree branches and (c) sections that are not included in the tree and are called chords. Adding some chord to the tree (r, r = 1, ..., c) forms a contour (or cycle). Consequently, each spanning tree of the network will be answered by a single fundamental (chord) system of contours. In accordance with this, dividing the adjacency matrices of sections and nodes, sections and circuits, and gas and oil flow vectors, pressures at network nodes into matrices and vectors of chords (Ax, Bx, Xx) and tree branches (Hx, Vd, Xd), we write the problem of optimizing the structure of PTNG as follows:

\[
\Phi(x) = \sum_{i=1}^{n} \Phi_i(x) + \sum_{i=m+1}^{n} \Phi_i(x),
\]

at \( A_x \cdot X_x + A_h \cdot X_h = Q \).

Here \( \Phi(x) \) is the criterial function of the life cycle costs in the system of PTNG.

The conditions of the material balance are transformed as follows:

\[
x_h = A^{-1}_h \cdot (Q - A_x \cdot x_x);
\]

\[
x_h = A^{-1}_h \cdot Q - A^{-1}_h \cdot A_x \cdot x_x.
\]

From graph theory [6–11] it is known that \(-A^{-1}_h \cdot A_x = B^T_x\), \(-A^{-1}_h = R^T_0\). There is a transposed matrix of paths.

As a result, we obtain the following expression:

\[
X_{jy} = \sum_{j=1}^{c} a_{jy} \cdot x_{x_j} - \sum_{j=1}^{c} a_{jy} \cdot Q_j; \quad i = 1, ..., m - 1.
\]

After substituting expression (7) into formula (6), we arrive at the following problem of unconditional minimization of functions:

\[
\min \left( \sum_{i=1}^{c} \Phi_i(x_h) + \sum_{i=m+1}^{n} \Phi_i(x_h - \sum_{j=1}^{m-1} a_{ij} \cdot Q_j) \right).
\]

According to expression (8), with a change in the chord variable Xx in the circuit r, the values of xgi change only on the tree branches belonging to this circuit, and the loads of the remaining sections remain unchanged. Consequently, it is possible to organize the process of contour (coordinate-wise relative to contour expenditures) minimization of the criterion function, fixing at each step the values of the remaining independent variables. Moreover, minimization for each next contour variable is carried out for the optimal values of the contour costs obtained in the previous steps (that is, a procedure such as the Seidel method [6] is formed). Figure 1 illustrates the operation of this approach and the stages of the computational according to (8).

The justification of the described method and its testing on various pipeline systems of water supply, heat supply and water disposal are described in [12–22].
4. Conclusions

Proposed to optimize the routes of pipeline oil and gas systems allows us to find the global minimum of the nonlinear life cycle cost function. It is implemented in the TRACE-NG software package, which allows you to calculate and optimize PTNG systems of any complexity and configuration and can be used by designers in the development and development of oil and gas fields.

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