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Method of Discrete-Continuous Search for Flow Direction in Hydraulic Calculation of Annular Gas Networks

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Abstract

The paper deals with the method of discrete-continuous search of flow direction for hydraulic calculation of circular gas networks with one gas inlet node and several extraction nodes. The developed approach allows increasing the accuracy of calculations in comparison with the traditional Lobachev-Cross method, especially in normal operating modes. A study of the energy intensity of the ring network revealed potential abnormal situations due to the lack of pressure to overcome frictional resistance. The developed algorithm and software package provide the possibility of modeling the gas-dynamic state of the network, as well as the analysis of emergency scenarios leading to changes in the network topology. Complex analysis of normal, emergency and pre-emergency modes of operation of the gas pipeline system allows to optimize the operation parameters and improve its reliability.

Keywords: Gas pipeline, ring network, hydraulic calculation, flow direction, discrete-continuous method, gas transportation system, energy intensity of the network, modeling of emergency situations, optimization of pipeline systems.

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All over the world more and more attention is paid to the development and implementation of resource-saving technologies, which cover various spheres of the national economy and social structures. An important role is played by the active introduction of ring gas gathering networks at fields, their application in distribution systems, heat supply and other areas with different levels of operating parameters. The ring network architecture increases system reliability, ensuring uninterrupted supply of gas and other resources even in case of failure of individual pipeline sections.

The Republic of Uzbekistan has an extensive and dynamically developing network of gas pipelines, which ensures gas transportation from fields to consumers both inside and outside the country. This

infrastructure is constantly being expanded and modernized in accordance with current needs. In this regard, the Strategy of actions for further development of the Republic of Uzbekistan for 2017-2021 outlined the need to modernize industry with a focus on increasing the technological level of raw materials processing, reducing the energy intensity of the economy and introducing energy-saving technologies. The document also emphasizes the importance of developing information and communication technologies in various sectors, including management of production and engineering systems [1].

To achieve these goals, optimization of pipeline networks operation, consideration of their development prospects taking into account growing urbanization, as well as specification of current loads and identification of hidden reserves are of particular importance. Increasing the efficiency of operation and management of gas pipeline systems largely depends on the correctness of mathematical models of flow distribution used at all stages of design, construction and operation of engineering networks. In addition, organizational and economic modeling methods serve as a basis for improving the efficiency of pipeline systems operation and their controllability.

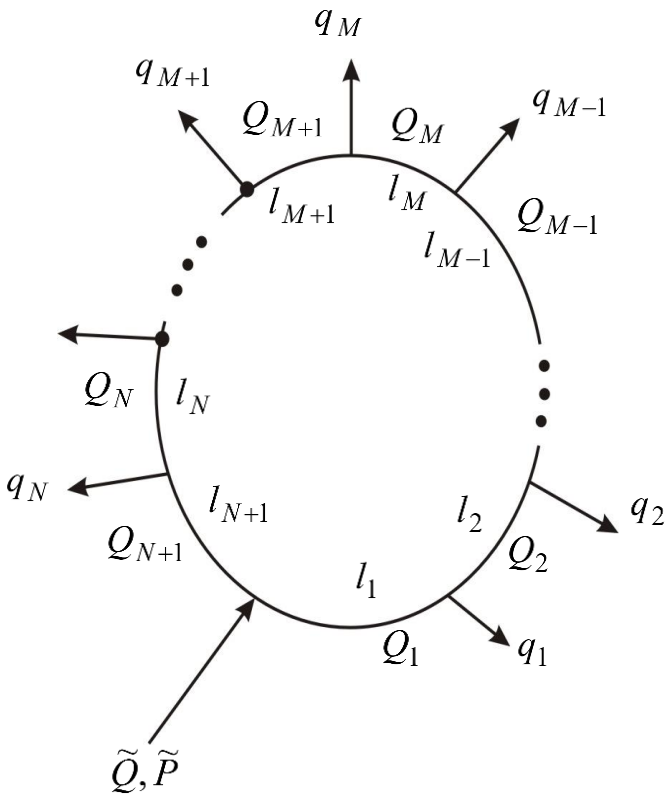


Figure 1. Diagram of a ring network with one inlet and N outlets

One of the key tasks in improving the operation and management of pipelines is the competent design of new and reconstruction of existing utility networks. It is necessary to take into account the optimal number of technological facilities, their location and service areas to ensure the reliability and efficiency of the system in the long term. Let us consider the problem of hydraulic calculation of a ring network with one supply point and several gas extraction points (Fig. 1), which is useful for calculating a network with a limited number of rings. Such a problem is typical for urban distribution network [2,3].

We can imagine a ring network with one gas supply point with intensity $\tilde{Q}$ (>0) and N extraction points with intensities , q_i (<0) $i=1...N$. The diameter of the gas pipeline is the same everywhere and is D . Also the coefficient of friction resistance has the same value λ in the whole network. Let us define the lengths of elementary sections as follows: l_1 - between the points of supply and the first withdrawal, l_2 - between the points of the first and the second withdrawal, ..., l_{N+1} - between the points of N - the first withdrawal and the gas supply. Accordingly, the index i will provide the length (l_i) and gas flow rate (Q_i) on the *i-th* section.

If the gas flow rate at the first section is Q_1 , the value of the gas flow rate at the subsequent sections can be determined by recurrence formula:

$$Q_i = Q_{i-1} + q_i, .i = 2...N+1$$

At the same time, the flow rate will be negative in certain elementary sections.

The problem consists of determining the value of the flow rate Q_1 of the 1st section and the direction of flow in the sections, which are necessary for the hydraulic calculation. Although pressure and gas flow rate are squared in the solutions of the momentum conservation equation, at each elementary section the pressure change is determined according to the flow direction. Therefore, it can be assumed that , $Q_i \geq 0$ $i = 1...N+1$, and the flow direction can be determined through the auxiliary coefficients ς_i . At coincidence of flow directions and increasing numbers of sections (indices) $\varsigma_i = 1$ is accepted, and at the opposite - $\varsigma_i = -1$ (the case of $\varsigma_i = 0$ is excluded, because the zero value of the product $\varsigma_i Q_i$ is provided by the condition $Q_i = 0$ at the section, which represents the boundary of zones with different directions of gas flow). Then the hydraulic formula for i -th section of the ring takes the following form

$$p_{i-1}^2 - p_i^2 = \varsigma_i b Q_i^2 l_i , i = 1...N+1 \text{ . (1)}$$

To keep the generality of the entries, we assume that

$$p_0 = \tilde{p} \text{ and . } p_{N+1} = \tilde{p}$$

Assume that from the feed point to M -th withdrawal node $\varsigma_i = 1 \left(i = 1...M\right)$, and in the remaining sections $\varsigma_i = -1 \left(i = M+1...N+1\right)$.

Then the costs at the sites with $\varsigma_i = 1$ are

$$Q_1, , Q_2 = Q_1 + q_1 \; Q_3 = Q_2 + q_2 = Q_1 + q_1 + q_2 \; ,...$$

$$Q_{M-1} = Q_1 + \sum_{k=1}^{M-2} q_k \; , . \; Q_M = Q_1 + \sum_{k=1}^{M-1} q_k \qquad (2)$$

Similarly, the area gas flow rates are determined under the condition : $\varsigma_i = -1$

$$Q_{N+1} = Q_1 - \tilde{Q} \; , , Q_N = Q_1 - \tilde{Q} - q_N \; Q_{N-1} = Q_1 - \tilde{Q} - q_N - q_{N-1} \; ,...$$

$$Q_{M+2} = Q_1 - \tilde{Q} - \sum_{k=M+2}^{N} q_k \; , . \; Q_{M+1} = Q_1 - \tilde{Q} - \sum_{k=M+1}^{N} q_k \qquad (3)$$

In the presented values of sectional costs, according to the assumption about the values of ς_i , the only unknown quantity is Q_1 . To determine the value of this quantity, let us turn to the mathematical representation of the analog of Kirchhoff's second law (1), summarize the formulas for i -section at : $i = 1...N+1$

$$\sum_{i=1}^{N+1} \left(p_{i-1}^2 - p_i^2 \right) = \sum_{i=1}^{N+1} \varsigma_i b Q_i^2 l_i \; .$$

The left part of this equality, by virtue of the condition $p_0 = p_{N+1}$, takes zero value. Accordingly, the right part of the equality must also equal zero

$$\sum_{i=1}^{N+1} \varsigma_i b Q_i^2 l_i = 0 .$$

Taking into account the values of ς_i from this equality, we obtain a representation of the analog of Kirchhoff's second law:

$$\sum_{i=1}^{M} Q_i^2 l_i = \sum_{i=M+1}^{N+1} Q_i^2 l_i .$$

With increasing the value of M from 1 to $N+1$ the sum from the left part of the equality monotonically increases from $Q_1^2 l_1$ to $\sum_{i=1}^{N+1} Q_i^2 l_i$, and the sum from the right part of the inequality monotonically decreases starting from $\sum_{i=1}^{N+1} Q_i^2 l_i$ to 0. The existence of the solution for M is conditioned by the intervals of change of the values of the sums from the left and right parts of the equality. And the uniqueness of the solution is provided by the monotonic change of the sums depending on the value of M

Let's express Q_i by Q_1

$$Q_1^2 l_1 + \sum_{i=2}^{M} \left(Q_1 + \sum_{k=1}^{i-1} q_k \right)^2 l_i = \sum_{i=M+1}^{N} \left(Q_1 - \tilde{Q} - \sum_{k=i}^{N} q_k \right)^2 l_i + \left(Q_1 - \tilde{Q} \right)^2 l_{N+1} . \quad (4)$$

Let us represent (4) in the form

$$a_M Q_1^2 + 2 b_M Q_1 + c_M = 0 , \quad (5)$$

where the designations used were

$$a_M = \sum_{i=1}^{M} l_i - \sum_{i=M+1}^{N+1} l_i ,$$

$$b_M = \sum_{i=1}^{M} l_i \sum_{k=1}^{i-1} q_k + \tilde{Q} \sum_{i=M+1}^{N+1} l_i + \sum_{i=M+1}^{N+1} l_i \sum_{k=i}^{N} q_k ,$$

$$c_M = \sum_{i=1}^{M} l_i \left(\sum_{k=1}^{i-1} q_k \right)^2 - \sum_{i=M+1}^{N+1} l_i \left(\tilde{Q} + \sum_{k=i}^{N} q_k \right)^2 .$$

The process begins with a check at . $M = 1$

The condition $a_M = 0$ is checked. If it is fulfilled, the quadratic equation passes to the linear equation and there is a case of apparent hydraulic symmetry, when the solution of the problem has the following form

$$Q_1 = -\frac{c_M}{2 b_M} .$$

Involving (2) and (3), the difference of sums is calculated

$$\varphi_M(Q_1) = \sum_{i=1}^{M} Q_i^2 l_i - \sum_{i=M+1}^{N+1} Q_i^2 l_i .$$

If the difference of sums has zero or positive value, then the problem solution stops, because the search has led to the desired result for M and Q_1 . In the first case, the node M is fed unilaterally, and in the second case - from both sides. If $\varphi_M(Q_1)$ has a negative value, the parameter M is increased by one and the process is resumed.

If $a_M \neq 0$, then the positivity of the discriminant of the quadratic equation

($b_M^2 - a_M c_M > 0$) and the positivity of the solution ($Q_{1,2} > 0$) provide the solution of

$$Q_{1,2} = \frac{-b_M + \sqrt{b_M^2 - a_M c_M}}{a_M} .$$

With the help of the obtained values $Q_{1,2}$, using dependences (2) and (3), the value of the difference of sums $\varphi_M(Q_1)$ is calculated. If it is negative, the parameter M is increased by one and the process is resumed. Otherwise, the computational process is interrupted.

The discrete and continuous unknowns M and Q_1 defined in this way must be mutually consistent. If M corresponds to the 1st node, then the condition $0 < Q_1 \leq -q_1$ must be satisfied , if $M = 2$, then the condition $-q_1 < Q_1 \leq -q_1 - q_2$ must be satisfied, etc. That is, in general, the condition $-\sum_{k=1}^{M-1} q_1 < Q_1 \leq -\sum_{k=1}^{M} q_1$ must be satisfied.

After the node number M and the gas flow rate value Q_1 of the first section are determined, it is possible to determine the flow rate values of the remaining sections according to (2) and (3), and the pressure values at the nodal points according to the hydraulic formula (5.3).

The problem has the property of duality and the whole search process can be carried out both clockwise and counterclockwise. The second of these variants of the problem solution can be used when checking the solution of the problem.

The algorithm allows to take into account technological limitations, for example, for the case of setting the lower limits of pressure values in the extraction nodes. This factor determines the only possible abnormal situation when designing a ring network with one extraction node and N extraction nodes, when the potential energy of static supply pressure is not sufficient to ensure the normal operation of the network. If the value of the supply pressure is too small, a similar abnormal situation occurs in the very process of calculating the nodal pressures (a negative number is formed under the radical).

Such abnormal situations can be eliminated by increasing the supply pressure values, which requires a second invocation of the algorithm.

Repeated references are also necessary to determine optimal section diameters when sections have different diameters and resistance coefficient. In this case, modification of the algorithm is required to take into account the variability of the coefficient in formulas (1).

According to the above material, a computational algorithm is constructed, a software package is

compiled and a computational experiment is conducted, the results of which confirm our research

The developed method of discrete-continuous search for the flow direction in a ring system of gas pipelines with a single supply node and a limited number of extraction nodes, unlike the well-known Lobachev-Cross method, provides the possibility of obtaining an accurate solution to the design problem under normal operating conditions.

The study of energy intensity of the ring gas pipeline network with one supply node allowed to reveal the occurrence of non-standard situations associated with the deficit of energy potential pressure to overcome the resistance due to friction forces within the network.

Based on the proposed mathematical models and the method of discrete-continuous search for the flow direction, an algorithmic solution and a software package have been developed to calculate the gas dynamic state of a ring gas pipeline system with a single supply node, as well as to simulate emergency scenarios leading to the transition of the network to the beam structure. Complex analysis of normal, emergency and pre-emergency modes of operation of the gas pipeline network allows to determine the optimal parameters of the system functioning, ensuring its stability and efficiency.

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