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HYDRAULIC ANALYSIS OF SEQUENTIAL WATER WITHDRAWAL FROM A MAIN PIPELINE

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The article presents a detailed step-by-step analytical method for the hydraulic calculation of systems with sequential water withdrawal from a main pipeline through a network of lateral branches. Particular attention is given to the important problem of non-uniform pressure and flow rate distribution among consumers, which arises due to the gradual accumulation of hydraulic losses along the length of the main pipeline. This effect is especially pronounced in long linear water supply and irrigation systems, where remote consumers receive significantly lower water flow rates compared to those located closer to the supply source.

The proposed method is based on the classical Darcy–Weisbach equation for determining frictional pressure losses in pipes, as well as on the empirical Altshul formula for accounting for local resistances and transitional flow regimes.

To verify the analytical model, it was compared with the results of numerical simulations performed in the Ansys Fluent software package, where the finite volume method with a detailed three-dimensional computational mesh was applied. The obtained average discrepancy between the analytical and numerical values of flow rates and pressures was 5–7%, which confirms the sufficient accuracy of the developed simplified model for engineering practice.

In addition to the basic calculation procedure, the study proposes a practical method for system optimization. It consists of the purposeful variation of the diameters of lateral branches in order to compensate hydraulic losses and achieve the maximum possible uniformity of water withdrawal.

The obtained results have important practical significance. They provide design engineers with a reliable tool for the justified calculation and modernization of drinking water supply networks, agricultural irrigation systems, and technical water pipelines, allowing a significant reduction in the risk of water shortage for remote consumers, decreasing failure rates, and improving the overall energy efficiency of the system.

Keywords: *numerical modeling, finite element method, hydraulic calculation, water supply optimization, Darcy–Weisbach equation, irrigation network.*

Eq. 16. Fig. 5. Ref. 16.

1. Problem formulation

The study presented in this work is devoted to the analysis of a branched water supply system. The problem of calculating irrigation or water supply pipelines is a classical problem in the hydrodynamics of distributed systems. The main difficulty lies in the fact that the pressure in the main pipeline decreases due to friction, while at the same time the dynamic head changes because of the decreasing flow rate along the pipeline.

The principal challenge arises from the interdependence of pipeline parameters in different sections. In a conventional pipe without branches, the pressure simply decreases approximately linearly with increasing distance from the supply source (for example, a pumping station) due to friction losses. However, in a water supply or irrigation system the situation becomes significantly more complex.

First, this is associated with the reduction of the flow rate along the length of the main pipeline. After

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each branch connection, the velocity of water in the main pipe decreases stepwise (nonlinearly), since a portion of the fluid is diverted into the branch.

Second, friction along the pipeline walls plays an important role. The dynamic pressure decreases as a result of friction, since the flow velocity itself is reduced. At the same time, friction losses in each subsequent section of the main pipeline become smaller due to the reduced flow rate.

The main difficulty of the problem lies in its nonlinearity. It is impossible to calculate the parameters of the last branch without knowing what occurs in the first one, while the first branch itself depends on the overall hydraulic resistance of the entire system.

In addition, several other factors complicate the analysis. Accounting for losses along the pipeline requires the use of the Darcy–Weisbach equation. It is important to consider that the velocity appearing in this equation changes stepwise after each node of the main pipeline.

Another important aspect is the presence of local hydraulic resistances at the branching nodes. Each branch represents a flow splitting point, which generates additional turbulence and creates extra hydraulic resistance in the main pipeline.

Furthermore, due to the variation of flow velocity and pressure along the pipeline, the flow regime itself may change. At the beginning of the pipeline the flow may be turbulent (with a high Reynolds number), while near the end of the pipeline a transition toward laminar flow may occur.

All these factors make the problem of determining the hydraulic parameters of such pipeline systems rather complex and nontrivial.

2. Analysis of recent research and publications

The problem of ensuring uniform water distribution in engineering networks is a critical aspect in the design of both urban water supply systems and irrigation complexes. The modern approach to solving hydraulic calculation problems is based on the integration of classical hydraulic methods with advanced information technologies and numerical modeling.

The fundamental aspects of the design of closed irrigation systems and specific issues of hydraulic engineering have been previously studied in detail. The key problems and methods for their solution are presented and thoroughly discussed in modern manuals on the design of water supply systems [1, 2].

Particular attention has recently been given to the consideration of the topological structure of networks as a form of a mathematical model [3]. Such an approach makes it possible to evaluate the condition of water supply systems and predict flow distribution already at the design stage [4, 5].

A special role in the analysis of modern water supply and irrigation systems is played by accounting for the non-uniformity of water consumption [6], which directly correlates with the problem of uneven pressure distribution in main pipelines addressed in the present study. The calculation of pressure and flow velocity variations is of great importance for determining the parameters of the future system.

The influence of geometric parameters on flow non-uniformity and pressure drop in collector systems with parallel branches has been investigated in [7]. The complexity of accounting for these parameters makes the use of iterative algorithms particularly relevant, including approaches similar to the method proposed in this paper based on the Darcy–Weisbach equation.

Issues of pressure stabilization and throttling regulation in closed networks were also considered in the works of A. V. Tkachuk [8], where particular emphasis was placed on the calculation of pressure increase required to compensate hydraulic losses.

Considerable attention in modern literature is devoted to the automation of such engineering calculations. Studies [9–11] describe the application of specialized software (in particular the PipeLine software package) for constructing detailed schemes and performing calculations of irrigation system elements.

Operational irrigation management under modern challenges [12], as well as the need to improve resource management efficiency [13], require accurate models of water supply. Collective monographs and conference proceedings [14, 15] emphasize that physical and mathematical modeling represents an indispensable tool for minimizing the risk of flow deficit in remote consumers.

Thus, the analysis of the available literature indicates that the step-by-step analytical method proposed by the authors represents a logical development of existing approaches [1, 2, 16], while its integration with finite-element-based numerical modeling corresponds to the global trend of digitalization in water engineering [7, 8, 10]. Such an approach is consistent with the use of the Ansys Fluent software package for the verification of analytical models through numerical simulation.

3. The purpose of the article

The objective of this study is to develop a methodology for calculating the pressure and water flow parameters in a main pipeline with sequential water withdrawal through a system of lateral branches. The focus of the research is to eliminate the non-uniformity of pressure and flow distribution at distant outlets already at the pipeline design stage.

4. Results and discussion

Before proceeding to the optimization of the mathematical model, it is necessary to build the model based on certain initial data.

The principal scheme of the pipeline to be calculated is shown in Fig. 1.

As input data, we will use the parameters of a real water supply system. This will allow us to construct the mathematical model in a «zero approximation».

The main pipeline has the following initial parameters:

- Nominal diameter: 4" (DN 100), internal diameter $D_1 \approx 101{,}6$ mm=0,1016 m,
- Length of one segment between take-offs L_{seg}=100 m,
- Nominal diameter of take-offs: 1" (DN 25), internal diameter$D_2 \approx 25{,}4$ mm=0,0254 m,
- Length of each take-off L_{otv}=100 m,
- Number of take-offs (line number) N=20,
- Minimum number of consumers – 10.

As the working fluid, we will use water at a temperature of ≈ 20 °C. Then, for the given fluid, we take the value of absolute roughness Δ=0,05 mm=0,00005 m (Nikuradse equivalent roughness). Initial pressure in the main line$P_{in} \approx$ 4 atm=405300 Pa, initial flow velocity in the main lineV_{in}=1,5 m/s.

The pressure at the outlet of each take-off (at the point of consumption) is considered fixed for all take-offs (for example, due to installed pressure reducing valves, regulators, or open discharge at the same level) and equals $P_{out} \approx$ 1 atm=101325 Pa.

Building a mathematical model that takes into account all possible variable parameters is practically impossible.

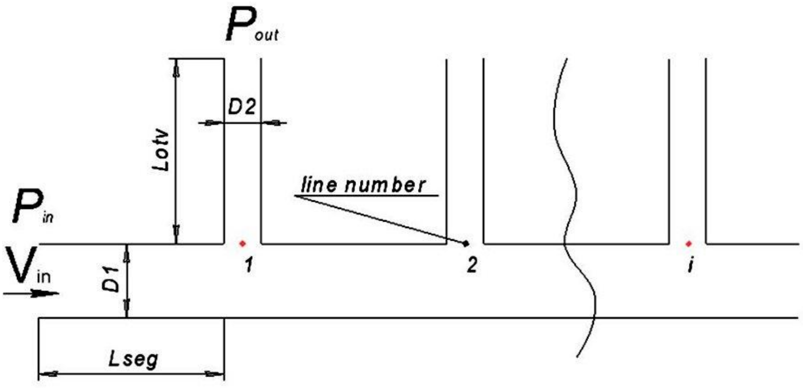

Fig. 1. Schematic Diagram of the Main Pipeline

Therefore, we will introduce certain simplifying boundary conditions and assumptions that will allow us to construct an adequate mathematical model without losing the influence of the main factors.

The main assumptions of the model are considered to be:

- Flow – fully developed turbulent regime ($Re >$ 4000on all sections);
- Pressure losses are caused exclusively by friction losses along the length;
- Local hydraulic resistances (tees, inlets/outlets, fittings) are not taken into account (model simplification);
- The temperature of the fluid and the properties of water are constant along the entire route;
- The pipeline is horizontal (the influence of elevation differences is absent). There is no inflow or withdrawal of fluid at any other points except at the calculated take-offs.

These data and assumptions make it possible to perform a sequential iterative calculation from the first take-off to the last one, determining at each step the new flow rate in the main line, velocity, Reynolds number, friction factor, pressure losses on the section, and the residual flow rate through the next take-off.

The total initial flow rate will be equal to:

$$Q_{total}=\mathrm{V}_{in} \cdot \frac{\pi D_1^2}{4}, \tag{1}$$

All pressure losses are calculated using the Darcy–Weissbach formula:

$$\Delta P = \lambda \cdot \left(\frac{L}{D}\right) \cdot \left(\frac{\rho V^2}{2}\right), \tag{2}$$

where: λ – coefficient of hydraulic friction (friction factor), L – length of the section (m), D – internal diameter (m), ρ – density of the fluid (kg/m^3), V – average flow velocity (m/s).

The friction factor λ is determined using the simplified empirical Altshul formula (for turbulent regime in engineering calculations):

$$\lambda = 0{,}11 \cdot \left(\frac{\Delta}{D} + \frac{68}{Re}()^{0{,}25}\right) \tag{3}$$

where: Δ– absolute roughness of the wall (m), $Re = \frac{V \cdot D}{\upsilon}$ – Reynolds number.

The flow rate through the pipe

$$Q=\mathrm{V} \cdot \frac{\pi D^2}{4}. \tag{4}$$

Sequential calculation algorithm:

As defined earlier, the calculation using the system of equations (1)–(4) is performed iteratively from the first take-off to the last one. Let us denote: i – number of the node / take-off ($i = 1,2,3,\ldots$), Q_i– flow rate in the main line immediately before the i-th take-off, V_i – velocity in the main line before the i-th take-off, V_i – absolute pressure at the node before the i-th take-off, Q_{otvi}– flow rate through the i-th take-off.

Initial values (i = 0 or at the entrance to the first segment):

$$Q_0 = Q_{total} = V_{in} \cdot \left(\frac{\pi D_1^2}{4}\right), V_0 = V_{in,}\, P_0 = P_{in} \tag{5}$$

For each take-off $i = 1,2,3,\ldots$ the following steps are performed:

Update the flow rate in the main line after the previous take-off:

$$Q_i = Q_{i-1} - Q_{otv\{i-1\}} \tag{6}$$

Determine the new velocity in the main line:

$$V_i=4 \cdot \frac{Q_i}{\pi D_1^2}, \tag{7}$$

Calculate the Reynolds number and the friction factor:

$$Re_i = \frac{V_i \cdot D_1}{\upsilon}, \tag{8}$$

$$\lambda = 0{,}11 \cdot \left(\frac{\Delta}{D_1} + \frac{68}{Re_i}\right)^{0{,}25} \tag{9}$$

Now calculate the pressure loss over the main line segment to the next node:

$$\Delta P_{segi} = \lambda_i \cdot \left(\frac{L_{seg}}{D_1}\right) \cdot \left(\frac{\rho V_i^2}{2}\right), \tag{10}$$

The pressure at the current node (before the take-off) will be:

$$P_i = P_{i-1} - \Delta P_{segi} \tag{11}$$

Then the available pressure drop across the take-off is:

$$\Delta P_{otvi} = P_i - P_{out} \tag{12}$$

Calculate the velocity in the take-off (using the Darcy–Weisbach formula for the take-off):

$$V_{otvi} = \sqrt{\frac{2 \cdot \Delta P_{otvi} \cdot D_2}{\rho \cdot \lambda \cdot L_{otv}}} \tag{13}$$

The flow rate through the current take-off will be:

$$Q_{otvi}=\mathrm{V}_{otvi} \cdot \frac{\pi D_2^2}{4}. \tag{14}$$

Then proceed to the next take-off ($i \to i + 1$), returning to the updated main line flow rate. In other words, we repeat the iterative calculation procedure steps (6) through (14).

The calculation stops when at least one of the following conditions is met:

1. $\Delta P_{otvi} \leq 0$ (there is not enough pressure to draw flow),
2. Q_{otvi}becomes less than the minimum allowable consumer flow rate.

If Q_i becomes negative or close to zero, this indicates that the supply limit has been reached. Subsequent take-offs will no longer receive the full required water supply.

Numerical Analysis.

The performed numerical calculations have shown that, with the given initial data, water withdrawal is possible only from the first 12 take-offs (see Fig. 2). When moving to the next (13th) take-off, the computed flow rate transitions to negative values, which means that water withdrawal becomes physically impossible at that point.

In addition, a significant variation in the flow rates through the individual take-offs is observed. This indicates a markedly non-uniform water withdrawal along the pipeline.

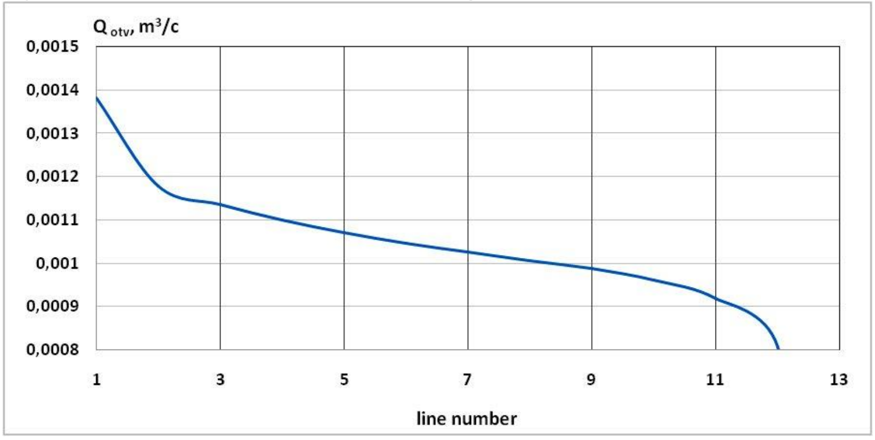

Fig. 2. Dependence of flow rate at take-offs on the take-off number

As mentioned earlier, achieving uniform water withdrawal is one of the optimization parameters. The most likely approach to optimization is to adjust the diameters of the take-offs in order to keep the variations in flow rates Q_{otvi} within 10–15% across all take-offs. However, this approach requires setting the take-off diameters to specific values that are not multiples of standard pipe diameters (3/4", 1", etc.). Therefore, we selected a different optimization criterion – the minimum flow rate among the take-offs.

For this purpose, the following parameter was introduced:

$$Q_{min} = N \cdot q_{sp} \cdot k \tag{15}$$

where: N – minimum number of consumers per take-off, q_{sp} – flow rate per single consumer (an empirically adopted value of 0,2 liter/s was used), k – coefficient of variation, i.e., an indicator of the simultaneity of consumer demand (empirical values typically range between 0,2 and 0,5).

Thus, the boundary condition we adopt is that the minimum flow rate must lie within a certain interval:$Qotvi_{min_{min}}$

Consequently, it was found that if the diameters of the first 8 take-offs are reduced to 3/4", while the remaining take-offs retain their original diameter of 1", then – for the selected coefficient of variation – not only does water withdrawal become possible at all take-offs, but also a reasonably uniform water supply to all consumers at each take-off is achieved. A noticeable jump in flow rate is observed only at the transition point between pipes of different diameters (fig. 3).

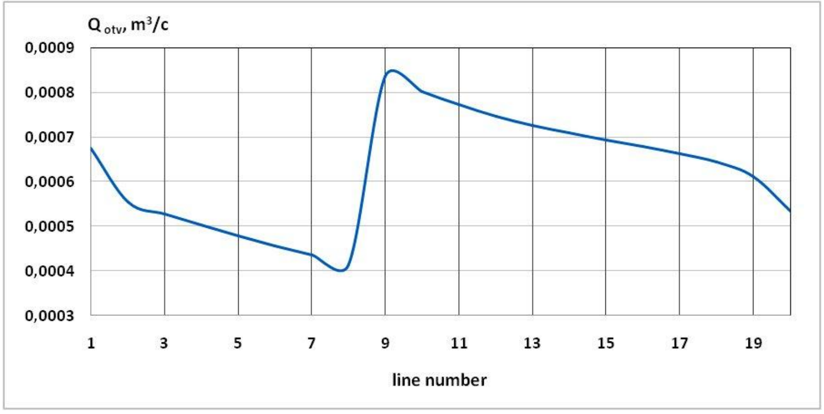

Fig. 3. Dependence of flow rate at take-offs on the take-off number

Thus, the proposed model enables water withdrawal for the declared number of consumers with a level of simultaneous demand sufficient for normal daily household and living activities.

Verification of the obtained calculation results within the framework of the mathematical model was carried out in two ways:

1. Numerical simulations using the finite element method in the Ansys Fluent software package,
2. Direct calculation using a program written in the Python programming language.

Finite element modeling was performed according to the following scheme (fig. 4). Comparison of results was carried out for the initial (non-optimized) model parameters – i.e., before any diameter adjustments or other optimizations were applied.

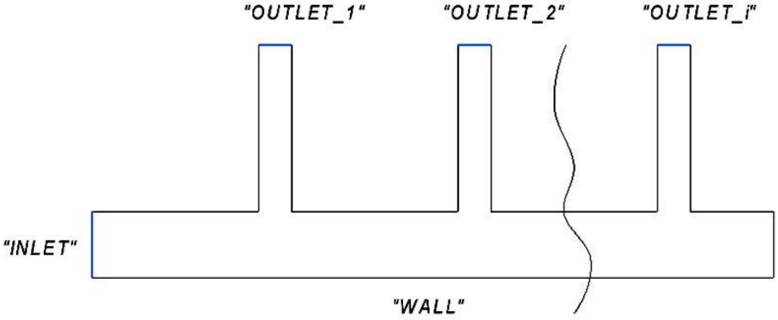

Fig. 4. Principal scheme of modeling in Ansys Fluent

Here, the boundary condition «Inlet» represents the entrance to the main pipeline with the specified initial parameters (pressure and initial velocity). The boundary conditions «Outlet_i» are the outlets of each take-off, where a boundary condition of outlet pressure is set at a level of at least 1 atm. The boundary condition «Wall» corresponds to the pipeline walls with a specified level of absolute roughness.

Mesh refinement was applied near the pipeline walls and at the transitions between pipes of different diameters. Calculation parameters: geometric dimensions – as defined in the initial model; element size – 0,02 m; nodes – 2289277024; elements – 2161868025; number of iterations – 100; wall thickness – 2,5 mm.

To verify the required parameters, the Result Expressions postprocessor was used, in which the following expression was defined:

$$Q = massFlowAve(Velocity)@Outlet\_\mathrm{i} \cdot (\pi \cdot 0{,}0254 \cdot 0{,}0254/4) \qquad (16)$$

where massFlowAve(Velocity)@Outlet_i is the mass-flow-weighted average velocity value at the outlet of the corresponding take-off, and i is the take-off number).

The numerical calculations in Python were performed using a simplified model: without accounting for variation of the friction factor along the pipeline length, instead assuming a constant valueΔ=0,05 mm=0,00005 m.

The performed comparison (fig. 5) revealed that the discrepancy between the analytical calculations and the results of numerical simulation in Ansys Fluent lies within 5–7%. This level of agreement indicates high reliability of the obtained analytical results.

At the same time, the results obtained from the Python calculation showed a significant deviation from the analytical data. This clearly demonstrates the importance of properly accounting for the variation of the friction factor along the length of the pipeline.

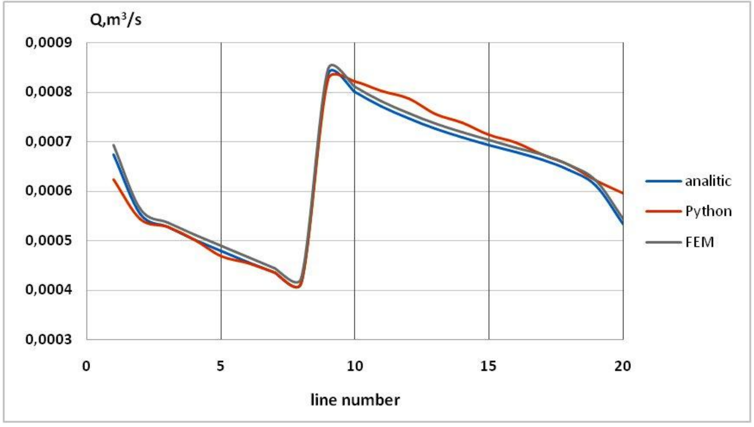

Fig. 5. Comparison of flow rates at the take-offs

The observed differences in results were caused by the following main factors:

- Use of the simplified Altshul formula for calculating the friction factor λ instead of the more accurate Colebrook–White equation. This approximation introduces considerable error, especially for take-offs located farther from the inlet;
- Neglect of local head losses at the junctions (transitions) between the main pipeline and the take-off branches.

5. Conclusion

The developed step-by-step analytical method, based on the iterative application of the Darcy–Weisbach and Altshul equations, provides high-accuracy accounting of hydraulic energy losses along the main pipeline. The created mathematical model enables, through an iterative procedure, the calculation of pressure and flow rate parameters for each take-off along the pipeline, taking into account the variation of the Reynolds number and friction factor in every segment.

The application of this iterative algorithm establishes a reliable foundation for the automation of design processes for closed irrigation and water supply networks. It expands the capabilities of existing information technologies in the water sector [9, 10] and allows engineers to make well-justified selections of network parameters, thereby minimizing both capital and operational costs while ensuring guaranteed service to all consumers.

It has been established that the primary cause of flow deficiency at distant consumers is the progressive pressure drop along the main line. Numerical analysis has shown that, under the given initial conditions (inlet pressure 4 atm, initial velocity 1.5 m/s), effective water withdrawal is possible only from the first 12 take-offs out of the 20 planned. Beyond this point, the pressure becomes insufficient, and the calculated flow rates become negative.

It has been demonstrated that uniform water distribution can be achieved by varying the diameters of the take-off pipes. Specifically, reducing the diameter to 3/4" for the first 8 take-offs while retaining the original 1" diameter for the remaining ones makes it possible to ensure water supply to all 20 take-off points while maintaining the minimum norm of 10 consumers per take-off.

Comparison with finite-element modeling in Ansys Fluent confirmed the high reliability of the analytical method (discrepancy of 5–7%), which is fully acceptable for engineering calculations of water supply systems. The main sources of deviation were identified as:

- the use of the simplified Altshul formula instead of the more precise Colebrook–White equation,
- neglect of local head losses at the tees and transitions.

The proposed methodology allows designers, already at the preliminary design stage, to justify the need to increase take-off diameters or raise the initial pressure in order to guarantee supply to remote consumers. The suggested technique of adjusting the diameters of lateral branches effectively compensates for this pressure-drop effect, ensuring stable and uniform water withdrawal along the entire length of the network. This approach aligns with modern concepts of operational management in irrigation and water supply systems.

The research results can be integrated into specialized software packages for hydraulic calculations, thereby contributing to increased reliability of technical water supply and irrigation systems under conditions of water resource scarcity.

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ГІДРАВЛІЧНИЙ РОЗРАХУНОК ПОСЛІДОВНОГО ВОДОВІДБОРУ З МАГІСТРАЛЬНОГО ТРУБОПРОВОДУ

У статті розроблено детальний покроковий аналітичний метод гідравлічного розрахунку систем послідовного водовідбору з магістрального трубопроводу через мережу бічних відводок. Основна увага приділяється актуальній проблемі нерівномірного розподілу тиску та витрат між споживачами, яка виникає в наслідок поступового накопичення гідравлічних втрат по довжині магістралі. Цей ефект особливо виражений у довгих лінійних системах водопостачання та зрошення, де віддалені абоненти отримують суттєво меншу витрату води порівняно з абонентами, ближчими *до джерела живлення.*

Запропонований метод базується на класичному рівнянні Дарсі–Вейсбаха для визначення втрат тиску на тертя в трубах, а також на емпіричній формулі Альтшуля для врахування місцевих опорів і перехідних режимів течії. Алгоритм має ітеративний характер: на кожному кроці розрахунку визначається падіння тиску на черговому сегменті магістралі між двома сусідніми відводами, після чого коригується витрата через наступну відводку з урахуванням оновленого напору. Процес повторюється до досягнення збіжності всіх витрат і тисків у вузлах системи з заданою точністю.

Для верифікації аналітичної моделі проведено її порівняння з результатами чисельного моделювання в програмному комплексі Ansys Fluent, де застосовувався метод скінченних об'ємів з детальною тривимірною сіткою. Отримана середня розбіжність між аналітичними та чисельними значеннями витрат і тисків склала 5–7 %, що свідчить про достатню точність розробленої спрощеної моделі для інженерної практики.

Окрім базового розрахунку, у роботі запропоновано практичну методику оптимізації системи. Вона полягає у цілеспрямованому варіюванні діаметрів бічних відводок для компенсації гідравлічних втрат і досягнення максимально можливої рівномірності водозабору. Такий підхід дозволяє стабільно забезпечувати проектні витрати всім абонентам навіть за значної протяжності магістралі.

Отримані результати мають важливе прикладне значення. Вони дають інженерам-проектувальникам надійний інструмент для обґрунтованого розрахунку та модернізації мереж питного водопостачання, сільськогосподарського зрошення та технічних водопроводів, дозволяючи суттєво знизити ризик дефіциту води у віддалених споживачів, зменшити аварійність та підвищити енергоефективність систем у цілому.

Ключові слова: *чисельне моделювання, метод скінчених елементів, гідравлічний розрахунок, оптимізація водопостачання, рівняння Дарсі-Вейсбаха, зрошувальна система.*

Ф. 16. Рис. 5. Літ. 16.

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