Software for on-line testing of pipeline modeling methods

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Abstract The paper considers the problem of comparative testing of mathematical methods for modeling the pipeline systems. Causes of existence of multiple alternative methods for solving the same problem are shown on the example of flow distribution problems. Many studies proposing new methods or their modifications give, as a rule, one or two numerical examples demonstrating advantages of proposed methods over others, which is surely not convincing. Practice shows that one method can be efficient for one example and fail for the other one. For this reason the issue of comparative testing of the availability and efficiency of computation methods for defining the areas of their preferred application is still open. Defined are the objectives, criteria and capabilities of such testing. The paper gives brief characteristic of the on-line IHCS software as a basic tool for gathering and interpretation of a large array of test examples, as well as techniques and initial results of its application. These results can presumably be used for forecasting the computational intensity of modeling the pipeline systems in specific computing environment using machine learning (ML) methods.

1 Introduction

Pipeline systems (PS) of heat, water, oil, and gas supply include a large
range of facilities developing in time and space that have different purposes, scales, principles of construction, and conditions of operation. Efficient solution of problems associated with their development and operation is of high social and economic value and is directly related to a scope of applying the modern methods of mathematical modeling and computer-aided simulation. For example, methods for flow distribution calculation are widely used at design, operation and dispatching control of PS. As a consequence, methods for calculation and taking into account their industry-specific features are still being developed and enhanced.

A number of methods for flow distribution calculation have been developed both in Russia and abroad that are based on mathematical methods for solving the systems of non-linear equations. They include: Newton method [0-0], a fixed point iteration method [0-0], a secant and chord method [0,0], and an evolution method [0]. Methods for flow distribution calculation differ in the ways of reducing the order of the system of equations; and their efficiency depends both on the number of iterations and on computation intensity of each iteration. Those papers, as a rule, provide one or two numerical examples stressing the advantages of proposed methods over others, but they do not prove their efficiency and availability in the entire variety of computational environment. Practice shows that one and the same method can demonstrate good results in terms of efficiency for one example and not to converge for the other [1]. For this reason the issue of comparative testing the availability and efficiency of calculation methods for defining the areas of their preferred application is still open.

Application of machine learning methods to PS, for example, for forecasting the leakages [0], failures of PS elements [0], water consumption rate [0], etc., are becoming more and more popular today. But such methods need input data on series of ‘learning’ tests for the object the methods are applied to; the more series, the higher the method’s efficiency. Consequently, results of testing the PS modeling methods can be applied for parameterization (‘learning’) of ML methods. Parameterization of ML methods would allow, for example, forecasting the efficiency of PS modeling methods in the specific computational environment.

Robust testing requires some presentable sampling of conditions and parameters of calculations that is difficult to generate, especially if we deal with large-dimensional schemes. Along with brief description of models and methods for solving the flow distribution problems the present paper provides description of IHCS (Internet System for Hydraulic Computations) software [0] (51.isem.irk.ru). This software is, first, intended for modeling the operating modes of multi-loop water and gas supply systems, and of firefighting systems using Internet, and, second, it is rather convenient as it
should not be purchased and installed on users’ PC. It allows testing the conventional methods using two approaches: 1) solution of flow distribution problems using artificially generated schemes; 2) using real schemes developed by the software users.

2 Models of flow distribution and methods for its calculation

A conventional model of steady-state isometry flow distribution in PS includes two analogues of Kirchhoff laws and closing ratios (flow rules) [0]:

\[ \mathbf{A} \mathbf{x} = \mathbf{Q}, \quad \mathbf{A}^T \mathbf{P} = \mathbf{y}, \quad \mathbf{y} = f(\mathbf{x}), \quad (1) \]

where \( \mathbf{A} \in (m \times n) \) is an incidence matrix of \( m \)-nodes and \( n \)-branches of a computational scheme with elements \( a_{ij} = 1 \) if node \( j \) is initial (final) for branch \( i \), and \( a_{ij} = 0 \) if branch \( i \) is not incidental to node \( j \); \( \mathbf{A} = [(m-1) \times n] \) - an incidence matrix formed from \( \mathbf{A} \) by deleting one row; \( \mathbf{x}, \mathbf{y}, \mathbf{P} \) are \( n \)-dimensional vectors of flow rates and pressure drops on branches of the calculated scheme; \( f(\mathbf{x}) \) is an \( n \)-dimensional vector-function with elements \( f_i(\mathbf{x}_i), \quad i = 1, n \), reflecting the pressure drop vs flow rate (flow rules) on the branches of the considered scheme; \( \mathbf{Q} \) is an \((m-1)\)-dimensional vector of nodal flow rates with elements \( Q_j > 0 < 0 \) for inflow (off-take) in the node \( j \), and \( Q_j = 0 \), if node \( j \) is a simple point of branches connection; \( \mathbf{P} = \{\mathbf{P}, \mathbf{P}_n\} \); \( \mathbf{P} \) is an \((n-1)\)-dimensional vector of nodal pressures.

The problem requires determination of vectors \( \mathbf{x}, \mathbf{y}, \mathbf{P} \) at a given matrix \( \mathbf{A} \), vector \( \mathbf{Q} \), known form of \( f_i(\mathbf{x}_i) \) for \( i = 1, n \), and at a given pressure in one of the nodes \( P_n \).

There are numerous methods and algorithms for solving this problem using model (1), but according to monograph [0], methods of loop flow rates (Newton-Raphson Loop Method) [0,0,0] and of nodal pressures (NM) (Newton-Raphson Nodal Method) [0,0,0] were developed first. Both methods are based on the Newton method but with prior reduction of the order of linearized systems of equations.

For example, NM method implies search for solution in the space of nodal pressures and is reduced to organization of the process

\[ \mathbf{P}^{k+1} = \mathbf{P}^k + \lambda \Delta \mathbf{P}^k \]

on each \( k \)-th iteration of which the correction \( \Delta \mathbf{P}^k \) with
account of the step length $\lambda$ is obtained from solution of the system $A(f_x)^{-1}A^T \Delta \mathbf{P}^k = -\mathbf{u}_k^k$, where $\mathbf{u}_k^k = A\mathbf{x}^k - \mathbf{Q}$; $\mathbf{x}^k = \psi(y^k)$; $\mathbf{y}^k = \mathbf{A}^T \mathbf{P}^k$; $f'_x$ is a diagonal matrix of partial derivatives $\partial f_x/\partial \mathbf{x}_i$, $i = \overline{1,n}$ in the point $\mathbf{x}^k$; $\psi$ is a vector-function inverse to $f$ with elements $\psi_i(y_i)$, $i = \overline{1,n}$.

Generalization of the model (1) in the loop form $A \mathbf{x} = \mathbf{Q}$, $B \mathbf{y} = 0$, $y = f(x)$, where $B$ is an $(n \times c)$-matrix of the scheme loops (fundamental cycles of the graph) fixing the selected system of $c$-loops with elements $a_{ij} = 1(-1)$, if branch $i$ is within the loop $j$ and coincides (or does not coincide) with orientation of its bypass, and $a_{ij} = 0$ if branch $i$ is not within the loop $j$.

The flow distribution problem consists in determination of the vector $\mathbf{x}$ under known type of $f_i(x_i)$ for $i = \overline{1,n}$, given matrices $A,B$, and vector $Q$. Computational LM scheme for loop flow rates in this case is reduced to search for a solution in the space of loop flow rates for $x^{k+1} = x^k + B^T \Delta x^k$, where at each $k$-iteration, $\Delta x^k$ is searched for from $(B'^T B) \Delta x^k = -\mathbf{u}_k^k$, $\mathbf{u}_k^k = B f(x^k)$, and $f_x'$ is same as in NM.

For obtaining the guaranteed unique solution of flow distribution problem the requirement of closing ratios monotony shall be observed $y = f(x)$ [1]. But at detailization of ratios the peculiarities of implementation of these methods will depend on characteristics of computing $x^k = \psi(y^k)$ and $f_x'$. The most simple form of $f_i(x_i) = s_i x_i | x_i | - H_i$, where $s_i$ is resistance of $i$-branch, $H_i > 0$ is a developed pump head for the active $i$-branch; $H_i = 0$ in case of the passive $i$-branch (e.g., of a pipeline section). There exist more complicated dependences, where $s_i = s_i(x_i)$. In this case $\psi_i(y_i)$ can be computed iteratively, which, however, will not impact the computing schemes of NM and LM.

3 Automation of testing

Objectives of testing the conventional methods for PS modeling include: 1) getting the data on their efficiency; 2) defining the areas of their preferred application.

Efficiency criteria. Under the methods efficiency we mean the guaranteed solution obtained at a final number of iterations with account of
their speed (time of calculation) versus the problem dimensionality. Variability of computational intensity of methods is closely related to specific computational conditions and can be divided into the following classes of factors.

Topology factor that affects both dimensionality of the problem considered and efficiency of the methods. For example, the number of solvable equations in NM equals the number of nodes $m$, and in LM it is equal to the number of loops $c = n - m + 1$ of the computation scheme. Ratio between the number of nodes and the number of loops for different schemes can vary widely [0]. It should be noted that efforts were made to use advantages of NM and LM simultaneously as well as advantages of their ‘joint’ use for flow distribution calculation, thus changing over from a nodal model to a loop model during computations [0].

Parametric factor. Parameters of PS elements play an important role in convergence of methods. For example, value $s_i$ of the pipeline section resistance depends on its diameter, length, roughness, and on the sum of local resistance coefficients. For objective causes the resistance of different pipeline sections can differ by several orders. Computational practice shows that the higher the variation, the worse conditionality of the coefficient matrix of a system of equations, and the slower convergence of methods [0,0].

Operating Conditions factor. Conditionality of the coefficient matrix indirectly depends on the range of nodal loads, moreover, the value of those loads cannot be lower than the prescribed nodal imbalance $u_i > 0.01$ (for NM case). Stability of computational process also depends on sensitivity of pressures to flow rates in the branches (that, in turn, depend on the branches characteristics) and boundary conditions (specified nodal pressures and flow rates).

Tools. IHCS software allows modeling the hydraulic conditions of water and gas PS operation, and of automatic fire-fighting systems, in the Internet network. It ensures computation of PS with an arbitrary structure (with an arbitrary number and location of sources, pumping stations, tanks, consumption nodes, etc.) and configuration (multi-loop, tree-like, combined ones) with fixed and non-fixed loads. It also allows computations at any time, in any place and for any number of users provided they are connected to Internet and have a standard Web-browser (Microsoft Internet Explorer) with Silverlight plugin. IHCS is used for developing the digital PS models by different companies [0] and can be used by scientific and research institutions, engineers, students and post-graduates. This software is of general purpose and can also be used as a platform for testing different
methods of PS modeling (Fig. 1).

Figure 1. Graphic interface of IHCS.

A library of computational modules in IHCS includes several methods for solving the flow distribution problems: NM, LM, ‘chord’ methods of nodal pressures, and a fixed point iteration method. The library is planned to be extended with enhancement of the existing methods, development and implementation of alternative methods.

Technique. The results of such testing are further demonstrated on the example of a flow distribution problem that are based on the following criteria: 1) availability (workability) is confirmation of convergence from different approximations, including a priori non-typical initial approximation; 2) efficiency implies comparison of time intensity versus convergence.

Methods were tested by comparing the size of computational schemes that were:

- artificially-generated, which allows account of a large number of characteristics (topology, parameters, process, hydraulic, etc.) of PS schemes;
- developed by the software users; until now this testing option was not available for researchers due to labor-intensiveness of generating the representative sampling of computational schemes for real objects.

Results of testing the methods for flow distribution calculation allow generation of ‘learning’ sampling in different computational environment. ‘Learning’ sampling is information on the parameters of a computational scheme and results of the computational experiment that was gathered for ML methods parameterization (‘learning’). Input data in this case shall include, as a minimum, ratio between the number of nodes and the number of loops, range of resistances, and nodal loads. If \( s_i = s_i(x_i) \), then \( x_i = x_i(v_i) \)
at $v_i = 1 \text{ m/s}$ is the prevailing flow rate of medium, for example, in the water supply system. The expected result of forecasting is the number of iterations and/or time of computations that would allow application of the most appropriate method of flow distribution computations in the specific computing environment. In the future, with accumulation of the results of testing, a set of parameters of ‘learning’ information can be expanded for raising the efficiency of ML methods.

*Testing on the generated conditions.* Table 1 presents the results of computational experiments for randomly generated schemes of water supply networks. Conditions for computation: the schemes include nodes (the share of consumers is $\sim 30\%$ that of sources is $\sim 5\%$) and branches ($\sim 5\%$ of pumps, the remaining are pipeline sections). Parameters of pipeline sections: length - from 100 to 1000 m, internal diameter - from 100 to 500 mm; 20 standards of pipes manufactured from different materials (steel, iron, asbestos-cement, polyethylene, reinforced concrete, and glass-reinforced plastics pipes). Network configuration is assumed to be flat, multi-loop, 2-4 branches adjoining each node. The desired imbalance accuracy in the computation methods for the given further indicators is taken to be equal to 0.01: for NM - flow rates in the nodes; for LM - pressure losses in the loops; for CNM - flow rates and pressure losses in the branches; for FPI - maximum correction of flow rate in the branch. Flow rate was measured in l/s, pressure – in meters of water column. Time of computations was measured using appropriate diagnostic procedures of the «.NetFramework 2.0» software. For more vivid demonstration of computation time difference between methods the systems of linear algebraic equations were solved using Gauss-Jordan method without sparsity account (IHCS also supports Kholetsky method with account of sparsity). Fig. 2 presents the graphic interpretation of Table 2 data including arithmetic mean of computation time, e.g., using the empirical formula $t = 2 \cdot 10^{-6} m^{1.7}$, where $t$ is computation time.

**Table 1.** The number of iterations and computation time at different methods

| Method | Number of nodes (loops) of the scheme | Number of iterations (time, sec) |
|--------|---------------------------------------|---------------------------------|
| NM     | 100                                   | 81 (17)                         |
|        | 200                                   | 300 (26)                        |
|        | 300                                   | 400 (361)                       |
|        | 500                                   | 600 (456)                       |
|        | 700                                   | 800 (552)                       |
|        | 800                                   | 900 (648)                       |
|        | 1000                                  | 1000 (744)                      |
|        | 810 (841)                             |                                 |
|        | 820 (930)                             |                                 |
| LM     | 0                                     | 9(1)                            |
|        | 11(1)                                 |                                 |
|        | 12(1)                                 |                                 |
|        | 13(1)                                 |                                 |
| CN     | 0                                     | 6(1)                            |
|        | 8(3)                                  |                                 |
|        | 9(9)                                  |                                 |


Impact of the number of nodes (loops) of computation schemes on the number of iterations in each method is negligible. It must be said that technique of schemes generation does not cover absolutely all the simulated PS, including real ones.

Testing on the real schemes. Fig. 3 shows the graph of results of applying different methods for solving the flow distribution problems for each PS scheme based on some sampling.

Figure 2. Methods convergence curve Notation: 1) NM; 2) LM; 3) CNM; 4) FPI; 5) Mean arithmetic; 6) Empirical dependence.

Problem solution for the schemes without loops and where the number of nodes with specified pressure does not exceed one, the case of using the LM method, unlike others, did not require iterations. Addition of a unified (‘fictitious’) node with specified pressure under availability of several ‘sources’ is a different case, which leads to loops development. This case of LM requires several iterations. The graph also presents the cases when NM requires less iterations than LM when the number of nodes prevails over the loops. In other cases the number of iterations in the methods presented lies within 4-8, the impact of the network scheme dimensionality being negligible.

In the future (as computation schemes are gathered) this method is planned to be extensively used based on different criteria (computation intensity, reliability, etc.) for analysis of comparative efficiency of alternative methods and for identification of areas for their preferred application.
Figure 3. Graph of the number of iterations versus dimensionality growth of calculated schemes of real objects: 1) NM, 2) LM, 3) CNM, 4) FPI. The number of iterations is on the vertical axis.

4 Conclusion

The paper discusses the urgency of applying a new on-line approach for testing different methods of PS modeling using IHCS software designated for computing the hydraulic conditions of water and gas supply systems, and of fire-fighting systems using the Internet network.

It has been shown that this approach allows large-scale testing of the existing and new methods of PS modeling, objective assessment of their availability, and computational efficiency. The first results of such testing and results of the analysis of comparative efficiency of different methods for conventional flow distribution problems of different dimensionality are provided.

It has also been shown that results of such testing would allow identification of preferred areas for application of flow distribution computation methods and justify selection of the best method using machine learning methods.

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