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STATIC ESTIMATION OF GAS SUPPLY SYSTEMS

Statement of the problem. It is necessary to develop mathematical models and methods for the technical monitoring of functioning gas supply systems to create a modern automated management system. The automatic operation system is required for timely information on the state of the object of management.

Results and conclusions. A new method and model of the steady-state estimation of parameters of the functioning mode of gas supply systems is discussed. The selected scientific approach is based on using energy equivalence. The rapid effectiveness of the developed method in processing information in call centers is provided due to a non-traditional choice of a set of the assessed parameters which are picked by consumers. The practical value of the designed mathematical model and method of the solution of the problem of steady-state estimation is due to the estimated parameters of node pressures being used. As a part of the software complex they are the source information on the condition of the object received by means of manometrical shooting.

Keywords: modeling, automatic operation system, energy equivalenting, systems of gas supply, technical monitoring.

Introduction

Gas supply systems (GSS) of cities are classified as part of housing and community facilities due to their purpose, development trends and operating conditions. They cannot be reliable, cost-effective without automatic operation systems (AOS) being used. Their efficiency is largely due to the quality of algorithm and software programming in processing information about the state of an operation object.

The significance of developing a mathematical apparatus of AOS and consistency of physical laws describing the processes occurring in any transportation systems (as well as GSS) gave rise to a number of studies in domestic and foreign practices which were designed to create a universal methodology for addressing a key problem of technical monitoring which is control of the parameters of the operating mode. There are two factors restraining the use of the results of these studies.

First, such systems generally face the problem of information provision of experimental data about the mode parameters which are at the heart of controlling their state. Due to technological considerations, the most viable way of obtaining experimental data on GSS is manometer filming as data on the consumption of the ultimate product is of greater significance. Insufficient information is currently compensated for by predicting the consumption based on empirical dependencies on climate, meteorological and social factors. The errors incurred in determining the latter put the method to doubt as there are growing requirements for the accuracy of monitoring results.

Secondly, a special consideration has to be made for leaks for which no information about them taking place makes the results of controlling the parameters of their state using mathematical modelling less worthwhile as the model is not capable of detecting thetopological properties of an operation object correctly. All the known methods regard leak monitoring as a separate task which is contrary to the principles of systemic approach.

All of the above gives the assumption that the research to tackle all of these problems is cutting edge and practical.

1. Stages of developing a method of static estimation of GSS

Let us examine how a method of static estimation of the operating parameters of GSS is developed. Static estimation is one of the major problems addressed in technical monitoring. As estimation is a typical reverse analysis problem, in order to solve it, a non-linear variant of the method of weighted least squares is used based on the assumption about the normal distribution of errors. The suggested method is based on the following assumptions:

1. The major experimental data to process in technical monitoring is that of manometric filming, therefore information criterion in OLS should be formed as the total of the differences between the measured and calculated pressure in the nodes of the system.

2. There are known to be two major requirements regarding the parameters being estimated. First, they should be invariant to the commutations in the structure of the system which take place in practice in any kind of manipulations with a multi-purpose reinforcement. Second, the dependency of the values calculated using these parameters to compare the experiments should be clear-cut which proves to eliminate a number of problems associated with a calculating process. Gas consumption choices are proposed as the parameters g_j, $j \in J^n$, J^n are a set of the nodes of consumers' gas appliances. Then the first condition is automatically obeyed. The second one is if the design pressure $h_j^в$ in knot of the consumers' gas appliances is presented as the Bernoulli equation where the hydraulic resistance s_j can be considered equivalent to the entire users' subsystem considering free flow pressure to barometric pressure.

3. In order to provide a universal solution for OLS, a constraint that an inflow should equal the total set of consumers' choices should be taken into account.

2. Formulating and modelling the task at hand

While formulating the problem of static estimation, we will focus on the previously chosen way of solving it, i.e. the method of weighted least squares.

Let us introduce the major terms necessary for formulating a static mathematical model of static estimation. Let us denote a set of the parameters representing a rapidly changing component of the information about the hydraulic system by the vector Z and the components of the vector will be the parameters of the mode [1]. It would be reasonable to assume that a gas flow in pipelines will be isothermic as the focus of the research is a gas supply and distribution system.

Then for the established flow distribution (stationary or static mode) the vector Z will include a vector of the consumption of the transported media at the areas of the system Q with the components q_i ($i = 1 \ldots i_\Sigma$, $i_\Sigma = \{I\}$ is a total of the areas in the system); a vector of knot potentials H with the components h_j ($j = 1 \ldots j_\Sigma$, $j_\Sigma = \{J\}$ is a total of the nodes in the); a vector of knot choices G with the components g_j ($j = 1 \ldots j_\Sigma$).

The rest of the initial information which describes the parameters of the elements of GSS: the length and diameter of the pipes, different regulators and isolation valves with its characteristics change at a much slower pace than the parameters of the mode. The total of the data will be considered previously specified without errors and denoted by the vector D.

A connection between the vectors Z and D are identified using the mathematical model describing the hydraulic processes taking place in the system. We will be employing the following universal model of the identified flow distribution [2—4]:

$$CRQ = M^T \hat{H}, \tag{1}$$

$$KRQ = 0, \tag{2}$$

$$AQ = \hat{G}, \tag{3}$$

where C is a proximity matrix of independent chains (paths) with the dimension $\mu \times i_\Sigma$, μ is a number of independent chains in the design scheme; K is a proximity matrix of the contours (cycles) with the dimension $\nu \times i_\Sigma$, ν is a cyclomatic number of the graph; A is an incidence matrix with the dimension $\omega \times i_\Sigma$, ω is a number of the nodes with a fixed node choice (inflow); 0 is a vector column with all of its components being equal zero; M^T is a transposed matrix of independent chains (paths); R is a diagonal matrix with the dimension $i_\Sigma \times i_\Sigma$ with the elements as follows

$$R_i = s_i \, |Q_i|^{\alpha-1},$$

s_i is a coefficient of hydraulic resistance of the area i; α is a non-linearity coefficient in engineering hydraulics formulas [5].

The symbol «∧» in the model (1)—(3) marks the vectors made up of the elements that will be considered to be the boundary conditions (BC) [4]. The use of the term is explained by the fact that a chose configuration of the model is adapted to an open scheme of presdenting a modelling object with its energy and mass exchange taking place in the nodes.

These nodes will further be referred to as energy nodes (EN) [4], with the total of

$$j_e = j_h + j_g,$$

where $j_h = \{J_h\}$ and $j_g = \{J_g\}$ is a number of the nodes with a fixed (specified) potential or choice (inflow).

There are also energetically neutral nodes where $g_j = 0$ in the system. Let us denote their number as j_0. The total number of the nodes is determined using the ratio

$$j_\Sigma = j_e + j_0.$$

The problem of GS is essential for all EN however it is not important what value a potential or choice (inflow) is fixed for as in any case the models will be dominated either by the equation (1) or (3) or it will be isolated, i.e. the total number of the equations will equal that of the unknowns (components of the vector Q).

Boundary conditions to be fixed are commonly called degrees of freedom in the implementation of the model in mechanics making it obvious that a number of the components of the vector Z is always greater than that of the vector Q. In order to denote degrees of freedom, the vector Y will further be used by calculating its components unknown parameters according to [1]. The other parameters of the mode will be considered dependent and denoted by the vector X.

The current state of GSS in an isothermic flow of the transported media can in practice be controlled using the results of manometric filming so that the composition of telemeasurements for the investigated objects is determined by technological causes and they are the components of the vector H. In fact in practice it is not possible to provide telemeasurements for all the nodes of the system and therefore those that are provided with gauges and communication channels will be denoted as «э». A set of telemeasurements makes up the vector $H^э$, which can be presented as the total of true parameters of the mode $H(Y)$ which are the functions of the degrees of freedom Y and the error vector ξ_H which occur due to the gauge errors, disturbances of teletransmission and inconsistent measurements, i.e.

$$H^э = H(Y) + \xi_H . \quad (4)$$

Let us look at the choice of a set of independent parameters of the mode. i.e. the component of the vector Y. It is obvious that there can be different options and therefore there is a problem of a rational choice of degrees of freedom for which two major requirements [1] are known:

1) the chosen parameters should not be dependent on the switching options of the multipurpose reinforcement;

2) dependency of the component of the telemeasurement vector on them should be made clear.

The analysis of the known methods of estimating node systems suggests that the second condition dominates. It is obeyed for example for electroenergetical systems if a vector of independent variables is only made up of the node strain complexes [1] which are presented using both Cartesian and polar coordinates. This choice option is used almost in all the papers except when for example there are severely unequal measurements, dynamics needs to be taken into account or there are restricting inequalities, it would be more reasonable to make changes to the composition of the vector *Y* and to compute unclear functions and their derivatives. These are the calculation problems faced in the traditional methods. This is not investigated regarding GSS and this is why it is suggested that the node choices (inflows) g_j ($j = 1 \ldots j_e$) making up the vector *G* are accepted as the independent parameters of the mode. The first condition is obeyed automatically if the consumption depends mainly on chronological factors [6]. As for the second condition, the results of the performed research show it possible to design a clear dependence of the telemeasurement vector on *Y* without using the model (1)—(3).

Fixing the degrees of freedom should not be confused with the specification of the boundary conditions. A fundamental difference comes from the meaning of the modelling tasks being solved. In the first case a problem of estimation (reverse analysis) is dealt with where the mode parameters need to be identified which will be as much equal as possible to the telemeasurement vector whose components are determined erroneously. In the second case there is a problem of direct analysis where the boundary conditions are considered credible. The similarity of both problems allows one to consider the flow distribution analysis a particular case of estimation.

The components of telemeasurements are more complex during estimation which is performed based on non-linear and topological observation of a modelling object [1]. For now we will assume that telemeasurements will suffice to build up a base [1], i.e. the condition of topological observation is obeyed. In a qualitative sense, this means that manometric filming takes place for all EN. In practice providing gauges does not seem possible, however it is only necessary when the problem is formalized. The boundary conditions for the implementation of the model (1)—(3) in the estimation are design information which is expected to be sufficient.

It should be noted that leaks are also energy nodes even though there might be no information regarding the location and volumes without dealing with monitoring. This problem cannot be jointly solved with estimation and therefore their algorithmic structuring should be performed.

This is why a condition is put forward that there are no leaks in the system. This way topology of the system as well as the composition of the EN are identified.

For the choice made for a component of the vector of the state of a pipeline system an objective function in the method of the least squares is as follows

$$F = \sum_j \frac{1}{\sigma_j^2} \left[h_j^э - h_j \left(G, Q \right) \right]^2, \tag{5}$$

where σ_j is a dispersion of error of the j-th telemeasurement.

A vague dependency h_j (G, Q) expressed by a flow distribution model (1)—(3) in the studies [5—9] of the methods of solving estimation problems make it necessary to employ linearization of the model with all the calculation problems that come with it. The current studies are presented in [10—13].

In order to tackle these problems two circumstances are suggested to be made use of. First, for the formalization of the problem of estimation the idea of functional (energetic) equivalence of consumers' subsystems (SC) which is presented in [3]. The aim of using equivalence is that the design values of node potentials $h_j^в$ can be calculated not only by means of traditional implementation of the model (1)—(3), but by using Bernoulli's equation connecting the initial node potential of EN with the barometric pressure:

$$h_j^в - h_б = s_j \; g_j^2. \tag{6}$$

In the equation (6) it is assumed that a change in the speed pump and difference in geodesic levels between the nodes of the system consumers are connected to and the location of the equipment consuming a transported media can be neglected.

The suggested method of determining the design node potentials makes use of a well-known fact that the equations of the flow distribution models (1)—(3) that describe the established flow mode are not consistent, i.e. each of the parameters being measured does not depends on all the parameters of the mode but on a few of them [1].

Using the equivalence of CS, it can be made sure that a node potential is not dependent on the components of the vector Q.Assuming the barometric pressure to be known, we transform the objective function (5) in OLS is

$$F = \sum_{j} \frac{1}{\sigma_j^2} \left[h_j^э - h_j^э \left(s_j, g_j \right) \right]^2. \qquad (7)$$

An important factor in (7) is that the initial node potential $h_j^в$ for j-th EN is now immediately (vaguely) dependent on the components of two vectors G and Q and is immediately dependent only on a hydraulic equivalent, CS joined to it and target product g_j it consumes.

This replacement of the mutual connection between the controlled parameters of the mode and degrees of freedom is a massive advantage in the calculation plan as instead of previously unknown number of parameters affecting h_j, there are only two left and they are connected with the ratio (6), i.e. this connection is already clear.

The second factor considered in the suggested statement of the estimation problem is that during the operation of any hydraulic pipeline systems there is normally ongoing control of the transported media via the power supplies.

Assuming the investigated system is transported, i.e. the total flow is equal to the total utflow, the obvious condition is obeyed

$$\sum_{j \in J^{\pi}} g_j = \sum_{j \in J^{\eta}} g_j, \qquad (8)$$

where the upper indices «π» and «η» denote the subsets of EN of power supply and consumers respectively.

There is a reason to assume that keeping record of the linear constraint (8) in (7) is one of ways to come up with a timely solution. In the traditional variant the ocmponent of the vector of independent variables in (5) there would be no point in considering continuity as it does not seem possible to identify a connection between the consumption of the media in the areas.

Considering the conditions (8), the objective function (7) is transformed using the traditional apparatus of the indefinite Lagrange multipliers into the following

$$F = \sum_{j \in J^{\eta}} \frac{1}{\sigma_{j_h}^2} \left[h_j^э - h_j^в \left(s_j, g_j \right) \right]^2 + \lambda \left(\sum_{j \in J^{\pi}} g_j - \sum_{j \in J^{\eta}} g_j \right), \qquad (9)$$

where λ is an indefinite Lagrange multiplier.

The traditional scheme of the implementation of OSL comes down to designing a system of normal equations obtained as a result of equating to zero the derivatives of the objective function according to the initial variables. The initial parameters (9) will be s_j and g_j, however due to (6) only consumers' choices can be considered to be independent variables.

Therefore while finding the conditions of the extremum (9), the objective function is complex in relation to g_j. Equating to zero the derivatives ($\partial F/\partial g_j = 0$) using the components of the vector of independent variables g_j according to (6) we get a system of normal equations

$$\frac{\partial F}{\partial g_j} = 2w_j\left(h_j^э - s_j g_j^{\alpha} - h_{б}\right)\left[-\alpha s_j g_j^{\alpha-1} - g_j^{\alpha}\left(\frac{\partial s_j}{\partial g_j}\right)\right] - \lambda = 0;\; j \in J_H, \qquad (10)$$

where $w_j = 1/\sigma_j^2$ is a weight function of the j-th measurement.

Since s_j should be similar to s_i with the only difference that in the first case they express metric characteristics (length and diameter) of fictional elements of CS and in the second case it is actual pipelines of GSS, it is obvious that they are not dependent on the consumption. Then the derivatives ($\partial s_j/\partial g_j$) can be considered to equal zero and the second member in the square brackets can be neglected (10). s_j being independent of g_j can be explained based on elementary energy considerations.

It should be noted that according to the power supplies, the initial data along with the potentials is also the inflows of the transported media through them into the system resulting in (9) the corresponding constraint dominating through the indefinite Lagrange multiplier.

Considering the meaning of the estimation problem which is the approximation of similar design and measured parameters, it is obvious that the basis of the suggested approach is the fixation of the power of the flows of the transported media using the power supplies.

Since any model of flow distribution is relies on the principle of minimizing dissipated energy in the system, it is clear that no matter what changes there are in the solution of the problem of the estimation of the parameter g_j, the design node potentials $h_j^в$ (g_i) obtained using the model (1)—(3) will be such that s_j should remain almost unchanged. In other words, in (6) s_j is no more than the coefficient of proportionality between the pump loss and consumption.

Hence, the system of normal equations of OSL is as follows

$$\left.\begin{aligned}
&\left(\partial F / \partial g_1\right) = 2(\alpha-1)w_j\,[h_1^э - h_б + s_1 g_1]\,s_1 g_1^{\alpha-2} - \lambda = 0;\\
&\left(\partial F / \partial g_2\right) = 2(\alpha-1)w_j\,[h_2^э - h_б + s_2 g_2]\,s_2 g_2^{\alpha-2} - \lambda = 0;\\
&\qquad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
&\qquad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
&\left(\partial F / \partial g_e\right) = 2(\alpha-1)w_j\,[h_e^э - h_б + s_e g_e]\,s_e g_e^{\alpha-2} - \lambda = 0.
\end{aligned}\right\} \tag{11}$$

The system of non-linear equations (11) could be solved using one of the known methods as it is isolated. The number of the equations corresponds to that of EN and for an extra unknown which is the indefinite Lagrange multiplier it would suffice to include the condition (8) into the system.

However, it is known in advance that the indefinite Lagrange multiplier cannot be constant and should change in an iteration process. In this case its dependency in the initial parameters should be known but as it does not seem possible to identify it in advance, it would make sense to exclude the extra variable λ reducing the dimension of the system of normal equations. As a result of this transformation, the system (11) will be as follows

$$\left.\begin{aligned}
&2\,(\alpha-1)\,[w_1(h_1^э - h_б + s_1 g_1)\,s_1 g_1^{\alpha-2} - w_2\,(h_2^э - h_б + s_2 g_2)\,s_2\,g_2^{\alpha-2}] = 0;\\
&2\,(\alpha-1)\,[w_1(h_1^э - h_б + s_1 g_1)\,s_1 g_1^{\alpha-2} - w_3\,(h_3^э - h_б + s_3 g_3)\,s_3\,g_3^{\alpha-2}] = 0;\\
&\qquad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
&\qquad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\\
&2\,(\alpha-1)\,[w_1(h_1^э - h_б + s_1 g_1)\,s_1 g_1^{\alpha-2} - w_e\,(h_e^э - h_б + s_e g_e)\,s_e\,g_e^{\alpha-2}] = 0.
\end{aligned}\right\} \tag{12}$$

Since the estimated parameters h_j, s_j, g_j for a set of EN are only connected with the equation (6), determining degrees of freedom g_j using OSL comes down to one of the traditional methods (Newton's method).

For the convenience of forming the algorithm, let us present (12) as a matrix:

$$\left[E_{(1)}E_{(d)}\right]\times\left[\Theta_{(1)}\right]\times\left[g_{(1)}\right] = \left[0_{(1)}\right], \tag{13}$$

$$\left[E_{(1)}\right]\times\left[g_{(1)}\right] = g_{\Sigma}^{э}, \tag{14}$$

$$\Theta_j = -w_j h_j^э s_j g_j^{\alpha-1} + w_j s_j^2 g_j^{2\alpha-1} + w_j h_б s_j g_j^{\alpha-1}, \tag{15}$$

where the symbol «*E*» denotes identity matrices. The identity matrix in (13) is square with the size $(J_H - 1)\times J_H$ and has a block structure, i.e. the number of equations of this kind is a unit less than that of EN. The identity matrix in (14) is more convenient to be considered not a column matrix but a line with the number of equations always being one regardless of the number of the sources in the system. The analysis of the obtained model allows us to conclude that it is possible to be numerically implemented as part of software to provide timely solutions in monitoring gas distribution systems.

Conclusions

1. The control of rapidly changing parameters of the mode in gas supply systems is shown to include one of the subtasks of a more complex monitoring of gas supply systems, which is static estimation.

2. A mathematical model and method of dealing with static estimation has been suggested for the first time for a functioning gas supply system based on using energy equivalence.

3. Speed performance of the developed method in processing information in control centers is secured by employing a non-traditional choice of a set of the estimated parameters which are accepted to be consumers' choices.

4. Practical significance of the developed method is that node pressures are adopted as the parameters to be estimated which allow the use of most convenient way of controlling a functioning mode which is manometric filming as the initial information.

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