Remote leakage method in heat supply systems out flow

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Abstract. This paper describes the method of remote sensing of the existence or absence of leaks in functioning heat supply systems developed on the basis of the application of a two-alternative hypothesis. To achieve this goal, we proposed to apply a method for determining the location and volume of leaks, based on the use of energy equivalents. We proposed to check for leakage between static assessments of the state of heat supply systems according to data from a remote manometric survey, with the help of which a simultaneous poll of pressure sensors in the end nodes of the system in question is performed. In the event of sudden changes in the estimated system parameters, it is concluded that there is a leak. If the results of two neighboring evaluations are relatively stable, then a conclusion is made about the absence of leakage. The considered problems are based on mathematical models of flow distribution for a heat supply system. The results of a computational experiment are compared with the results of calculating the parameters in the system based on the results of gauge surveying.

1. Introduction

Work [1] examined in detail the task of static assessment of the state of heat supply systems (SHS) (and for other hydraulic systems [2, 3]) developed on the basis of mathematical models of flow distribution for SHS [4], obtained using functional (energy) equivalent [5].

The problem of determining the magnitude and location of leaks for water and gas supply systems based on energy equivalent equipment is formulated and implemented in detail in [6, 7]. In these works, the problem of the existence of a leak in hydraulic systems was not considered. It is necessary to comprehensively solve three problems of leak diagnostics: its location, its volume, and the fact of the existence of leaks, which will allow for technical diagnostics remotely using metering devices on the system, gauge data and processing information on a computer in real time with using the developed mathematical models, to recreate complete information about the studied object and promptly provide information, for the decision maker, about the presence in the complex system of leaks or unauthorized selections of the target product. As an independent task, ensuring the reliability of hydraulic systems and allowing disconnecting emergency sections and connecting backup ones, it is necessary to consider the backup problem for heat supply systems [8].

Let us consider the problem of fixing the existence of a leak for heat supply systems. First of all, it is necessary to agree that we use the two-alternative hypothesis in assessing the presence or absence of
a leak. Checking for the presence or absence of leakage is supposed to be performed between two static evaluations. The value of the time interval between two evaluations is supposed to be determined practically, depending on the mode of functioning and system features. Such a time interval can be several seconds for extremely important objects (gas supply systems, oil pipelines, etc.) or hours, for new or small systems. In the selected time interval, it is much more likely that one leak can occur, and not several. Therefore, a two-alternative hypothesis was initially proposed, but we are not yet considering a multi-alternative hypothesis, it can be the basis for further developments.

2. Materials and methods
To solve the problem of the presence of an ordinary leak in the SHS, we use the detection theory [9], which assumes a statistical approach to solve it. To detect a natural leak, we apply a scientific analogy. We apply the filtering process of signals arising from the background of noise. In this case, a signal $s(t)$ with an unknown amplitude $\alpha$ is considered to be a leak in the system, which we can fix right after the occurrence of noticeable changes in the operation mode of the SHS (amplitude surge), recorded according to the results of a manometric survey between two state assessments. Here, $s(t)$ is a function of time given to solve the problem.

By noise, we mean relatively stable, having an average amplitude, consumption mode of the target product by users of the hydraulic system. We propose to apply an approach with filtering signals against a background of noise. Leaks comparable in amplitude with such noise will not be significant compared to possible significant leaks, therefore, the proposed approach can be effective for large leaks and, accordingly, SHS accidents that cannot be visually detected promptly.

When solving this problem, the reason for changing the state of the system must be determined. This change can be caused either by a leak or due to an accumulated error (hindrance) of the information recipient of information (dispersion $\sigma_1$) and with random consumption of the target product due to interference in the heat supply system (dispersion $\sigma_2$).

The presence of a leak in the system, as for a statistical problem, must be found using a sample $X_n$

$$X_n = \lambda \alpha S_n + \Xi_n,$$

where $n$ – the sample size; $\lambda$ - the parameter in the binary hypothesis: at $\lambda=1$ leakage occurs with the probability $p_1$, at $\lambda=0$ leak does not occur with the probability $p_2$ ($p_1 + p_2 = 1$); $S_n$ - the multiple possible values of fixed leakage consisting of elements $s_i$; $\Xi_n$ - the multiple values of uncorrelated interference in the heat supply system and in the information receiver, consisting of the elements $\xi_i$.

The most common and, in fact, the most important problem of detecting unknowns is that two parameters are assumed $\alpha$ and $\sigma_j$, having a given range of change $\Delta \alpha$ and $\Delta \sigma_j$. The maximum likelihood method is most rationally used to solve this problem. Hypothesis testing using the maximum likelihood method involves determining the relationship in the form

$$\Lambda(X_n| \alpha^*, \sigma_1^{*'}, \sigma_2^{*'}) = \left( \begin{array}{c} \sum_{i=1}^{n} x_i^2 \\ \sum_{i=1}^{n} x_i^2 - \frac{1}{E} \left( \sum_{i=1}^{n} x_i s_i \right) \end{array} \right)^{n/2} \left( \begin{array}{c} \sigma_2^{*'} \sigma_1^{*'} \end{array} \right)^{-n/2},$$

where: $E = \sum_{i=1}^{n} s_i^2$; symbol "*" is used to indicate the estimated parameters in the system under study.

The ratio $\sigma_2^{*'} / \sigma_1^{*'}(\alpha^*)$ should be compared with a threshold value $C(X_n)$. When the condition is met
\[ \sigma^2 / \sigma^2 (\alpha^*) \geq C(X_n) \]. It is customary to conclude that there is a leak in the system. The converse condition means that the leak does not exist. The threshold value \( C(X_n) \) determined from the relationship

\[ C(X_n) = \left( \frac{g_{21} - g_{22} \Delta \alpha}{g_{12} - g_{11}} \frac{p_1}{p_2} \sqrt{\frac{n}{\sigma^2}} \right)^2, \tag{3} \]

where: \( h_0' = E / 2 \sigma^2 (\alpha^*) \) - the signal to noise ratio.

In relation (3), the value \( g_j \) represents the loss function in the case of making the \( j \)-th decision for the \( i \)-th situation.

The probabilities of situations \( p_1, p_2 \) in (3) are defined as

\[ p(h^* \mid 0) = \begin{cases} 0 & \text{for } h^* < 0, \\ \frac{1}{\sqrt{\pi h^*}} \exp(-h^*) & \text{for } h^* \geq 0. \end{cases} \tag{4} \]

And for \( \lambda = 1 \)

\[ p(h^* \mid 1) = \begin{cases} 0 & \text{for } h^* < 0, \\ \frac{1}{2\sqrt{\pi h^*}} \left( \exp \left\{ -\left( \sqrt{h^*} - \sqrt{h} \right)^2 \right\} + \exp \left\{ -\left( \sqrt{h^*} + \sqrt{h} \right)^2 \right\} \right) & \text{for } h^* \geq 0. \end{cases} \tag{5} \]

where \( h = \alpha^2 E / 2 \sigma^2 \) - the real signal to noise ratio.

Statistical properties when detected by determining the probability of a false alarm using the expression

\[ F = \int_c^\infty p(h^* \mid 0) \, dh^* = 1 - \int_0^c \frac{1}{\sqrt{\pi x}} \exp(-x) \, dx = 2 \left[ 1 - \Phi(\sqrt{2C}) \right], \tag{6} \]

where \( \Phi(\ldots) \) - the probability integral.

The probabilistic leak detection, which is called correct, is determined from the relation

\[ D = \int_c^\infty p(h^* \mid 1) \, dh^* = 1 - \int_0^c \frac{1}{\sqrt{\pi x}} \exp\left\{ -\left( \sqrt{x} - \sqrt{h} \right)^2 \right\} + \]

\[ + \exp\left\{ -\left( \sqrt{x} + \sqrt{h} \right)^2 \right\} \, dx = 2 - \Phi(\sqrt{2C} - \sqrt{2h}) - \Phi(\sqrt{2C} + \sqrt{2h}). \tag{7} \]

In addition to the aforementioned mechanism, which is based on testing a two-alternative hypothesis on the initial sample, it will be necessary to consider a consistent and recurrent analysis procedure in order to consider the decision-making problem in the event of leaks in heating systems.

The proposed approach will quickly detect a leak, eliminate it, thereby increasing the level of security of the system and provide cost savings for its repair. The safety of various systems has been dealt with in a large number of works, for example [10, 11, 12], which can be used by analogy to ensure the safety of hydraulic systems. When performing the study, the works [13 - 26] were used.

Natural leaks are understood to mean leaks arising due to the ageing of the system during its operation or in the event of an accident from a force acting on the system. In practice, unauthorized selection of the environment may also occur due to illegal consumption of the target product from the
system in the personal interest. Such environmental selections using the proposed approach to solving the problem can also be fixed, thereby preventing theft of the target product.

3. Computational experiment results

To confirm the operability of the proposed method, a computational experiment was performed in accordance with the selected design scheme of the SHS (figure 1). Based on the results of a computational experiment, for a leak in node 28 of the SHS, a graph was plotted (figure 2) for the distribution of deviations according to the results of gauge surveys from the calculated values.

![Figure 1. Calculation scheme of SHS.](image)

![Figure 2. The graph of the distribution of deviations according to the results of gauge survey from the calculated values.](image)

In figure 2, in the place of $\sigma_j$, natural $\ln \sigma_j$ logarithm applies. The table below the graph shows the numbers of the system nodes. The greatest likelihood of a leak will be in the node located in the far left upper position of the table. When moving within the table from left to right, as well as from top to bottom, the calculated value of the standard deviation will increase.
4. Conclusions
Based on the results of the research, the following conclusions can be drawn.

1. A method for remote sensing of the existence or absence of leaks in functioning heat supply systems was developed.

2. We propose to apply a scientific analogy, precisely, to apply the process of filtering signals that arise against a background of noise. It is proposed to take a leak in the heat supply system as a signal with an amplitude exceeding the noise level. In this case, by noise, we propose to mean consumer selection of the target product from the system.

3. We propose to implement the developed method for remote checking of leakage in the heat supply system based on the use of flow distribution models, the method of detecting the location and volume of leakage, and static estimation of the current state developed on the basis of the use of energy equivalents.

4. The efficiency of the proposed method is confirmed using the performed computational experiment for the selected design scheme of the heat supply system.

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