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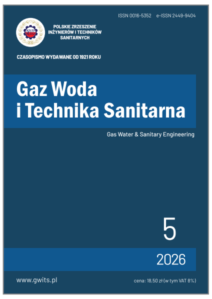
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Gas leakage detection and control

Wykrywanie i kontrolowanie wycieków gazu

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Abstract:
Gas leakage in low-pressure distribution networks remains a significant technical and economic challenge, amplified by pressure fluctuations and aging infrastructure. This study introduces a practical framework for estimating and reducing leakage using pressure-based network analysis. A simplified leakage model relates losses to nodal pressures and pipe characteristics and is integrated with steady-state hydraulic simulations. Leakage reduction is formulated as a constrained nonlinear optimization problem targeting optimal regulator settings and pressure smoothing. Tests on networks of varying size confirm consistent leakage reductions while preserving minimum supply pressure, demonstrating the method's value as an industry-ready decision support tool.

Keywords: gas leakage, leakage modeling, gas network simulation, pressure optimization

Streszczenie:
Wycieki gazu w niskociśnieniowych sieciach dystrybucyjnych są poważnym wyzwaniem technicznym i ekonomicznym, potęgowanym przez wahania ciśnienia i starzejącą się infrastrukturę. Przedstawiono model praktycznego szacowania i ograniczania wycieków gazu z wykorzystaniem analizy sieci opartej na ciśnieniu gazu. Uproszczony model wycieku wiąże straty z ciśnieniami w węzłach i charakterystyką rurociągów. Redukcję wycieków sformułowano jako problem optymalizacji nieliniowej z ograniczeniami, ukierunkowany na optymalne ustawienia regulatora i stabilizację ciśnienia. Testy przeprowadzone na sieciach o różnej wielkości potwierdzają stałą redukcję wycieków przy jednoczesnym zachowaniu minimalnego ciśnienia zasilania, co dowodzi wartości tej metody jako narzędzia wspomagającego decyzje w przemyśle.

Słowa kluczowe: wyciek gazu, modelowanie wycieków, symulacja sieci gazowej, optymalizacja ciśnienia

1. Introduction

Approximately 2–3% of the total gas sent out by Gas Companies is classed as „unaccounted for". This figure is made up of many components, but it is believed that a significant proportion of this is due to small undetected leaks at pipe joints in connection with the conversion of networks to supply natural gas. The reason for this is the potential change in the volume of leakage due to three factors:

- it is necessary to supply natural gas at a higher pressure than manufactured gas for satisfactory combustion,
- natural gas is drier than manufactured gas and could cause leakage as a result of old joints drying out,
- the thermal loss for a given volume of gas in the case of natural gas is more than twice that of manufactured gas.

These factors potentially could result in greater leakage losses, and the industry is taking substantial steps to ensure that leakage is minimised. This leakage loss represents a considerable loss of revenue to each Gaz Company and any reduction in leakage would be extremely beneficial economically [9]. To assist in controlling leakage rates, it is necessary to be able to estimate present leakage rates and quantify the improvements which can be made by a variety of leakage control methods. Since leakage is believed to be directly related to the distribution of pressure in low pressure networks, network analysis programs offer the capability of quantifying leakage in distribution networks [1, 2, 9].

2. Leakage estimation in distribution networks

Medium and low-pressure systems are usually either controlled remotely from a regional centre where set points on particular regulators can be altered to satisfy the current load on the

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network or are individually set to satisfy loading conditions for a specified period of time. In this latter case the experience of distribution engineering is relied upon to ensure that demands will be met, and network restrictions are not violated. In general, this means that the set points are determined so that peak demands are always met. This has the consequence, unfortunately, that networks are working at higher pressures than necessary during off-peak periods of demand, thus of course, inducing higher leakage rates. The main exception to this is where clock or automatic controls are used to reduce pressures at times of low demand.

Network analysis programs are viewed as tools by distribution engineering to compute steady state pressures and flows in networks given the demand loads together with source (regulator outlet) and regulator settings [12]. These settings are usually chosen by experience and a knowledge of a given network's characteristic behaviour [8] and to a certain extent they may be arbitrary but must ensure that the pressures in the network do not fall below a specified minimum at any time. By considering a model to estimate leakage, algorithms can be developed not only to achieve the above but also to reduce leakage rates and to recommend new source settings.

3. Leakage model

In order to estimate leakage rates for various loading levels and governor settings it is necessary to formulate some simple leakage model. The leakage rate at a particular pipe joint will be dependent on many factors associated with that pipe, e.g. pressure of gas in pipe at joint, pipe diameter, age of joint, type of joint and pipe material [3, 5].

Davenport in [4] has formulated a mathematical model which assigns the pipe joint leakages in a network to each node in the network. For large distribution networks the leakage at joints along a pipe is assumed to be equally distributed between the two end nodes of the pipes. The leakage in that pipe is assumed to be:

- proportional to the pressure at that node,
- proportional to the length of pipe (no. of joints).

For a complete network the total leakage:

$$q_{leak} = \sum_{i=1}^{n} q_i \tag{1}$$

where:

q_i – leakage at node *i*.

This leakage model assumes a uniform leakage rate throughout the network, which will only be true if the network is made up of pipes of the same material, same age, sane diameter, and of the same joint type. In most practical cases this will not be true, however, the overall leakage rate determined using this model should be of the correct order of magnitude.

The model outlined above has been used to estimate leakage losses in several low-pressure distribution networks operating under maximum load conditions and conventional governor settings. For an estimated leakage constant of e = 3.5×10^{-5} m^3/h/m/mbar the results shown that for the networks chosen the estimated leakage rate is of the order of 2–3% of the maximum demand.

For a specimen single feed network the estimated leakage rate was calculated as a function of demand loading for a constant source pressure setting. The leakage rate increases with decreasing demand loading. The increased pressure in the network when it is operating below its maximum demand level gives rise to the observed increase in leakage rate. A similar effect can be demonstrated for multi-feed networks. The exact form of the curve will depend on the topology of the network, the total pressure drop across the network and the individual governor settings.

The effect of seasonal and diurnal gas demand variation has a considerable effect on gas leakage rates. The total annual leakage from a gas distribution network could be up to 3% of the total gas send-out, even though the leakage rate estimated at peak demand may only be 2% of the maximum demand loading. Hence by using typical daily and yearly profiles it is possible to estimate total leakage from a particular network, rather than leakage at a given demand level. It is the overall leakage that we wish to minimise, and only by estimation of leakage over a period, can we estimate the effect of strategies for network leakage control.

4. Methods of leakage reduction

The problem of gas leakage at pipe joints can be approached at various levels:

- replacement of mains,
- repair of joints,
- mains reinforcement,
- governor pressure control [11].

Control of leakage is being achieved gradually by mains replacement and system treatment, but the more immediate remedy is the minimisation of system pressures [9].

4.1. Mains reinforcement

To reduce leakage in existing networks to a minimum it is necessary to minimise the pressure in pipes where leakage rates are significant, since the leakage rate is dependent on pressure. If it is known that particular areas or pipes in a network are likely to be susceptible to leakage, then the network must be examined carefully to reduce pressure in this area. If however leakage is believed to be evenly distributed throughout the network, or no specific leakage information is known, then it is necessary to reduce the overall pressure in the network while maintaining the statutory minimum supply pressure in the network.

From network analysis results it may be possible to pinpoint pipes where large pressure drops are occurring or areas of low pressure being fed from a distant source. In these cases, there will be in other parts of the network over-pressurised pipes or areas where leakage rates are greater than they need be. It should be possible to improve on present leakage rates by redistributing the pressure contours for the network, either by strategic upsizing/reinforcement of particular pipes or by the addition of extra sources. The effect of an even pressure distribution throughout the network is to smooth the pressure profile and so reduce leakage. In theory, for minimum pressurisation of a multi-feed network it is necessary to have the highest pressure at the centre of distribution with the pressure minima at the outskirts of the network.

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4.2. Governor pressure control

In a typical multi-feed network, the minimum supply pressure (MSP) in the network, at maximum demand loading, is dependent on the source pressure settings. The MSP can be maintained in the network for different combinations of governor settings and for each combination we can calculate an estimate of the leakage rate for the network. For maximum gas savings it is desirable to operate the distribution network at the optimum governor settings for which the estimated leakage is a minimum while still maintaining the MSP in the network [5, 6, 10].

For a single feed network, it is trivial to determine the optimum governor pressure setting since the minimum pressure in the network, P_{min} is linearly dependent on the governor pressure. For a two-source network the optimum pressure settings can be determined graphically, but for more complex networks the solution must be determined mathematically. Davenport has developed a mathematical optimisation method suitable for multi-feed networks. Singer et al [6] have outlined a similar computer method for the optimal control of networks. Both methods rely on a Newton-Raphson type iterative method, and the complete solution may require more than 10 analyses of the network.

An alternative method for solving leakage minimisation problem has been developed at Warsaw University of Technology (WUT). A governor pressure calculation algorithm has been developed which attempts to smooth the pressure profile of the network thus reducing leakage. In the Warsaw University of Technology we consider solving leakage minimisation problem in two ways. In the first case we consider the following problem:

$$J = \min \sum_{i=1}^{N} P_i \tag{2}$$

where:

N – is the number of nodes

We minimise the sum of pressures over the network in an attempt to reduce the overall pressure distribution and hence leakage rates. In the second case we attempt to minimise the formula that models total network leakage, which is essentially a weighted sum of pressures:

$$J = \min \sum_{i=1}^{N} W_i \cdot P_i \tag{3}$$

where:

$$W_i = \sum_{i=1}^{M} e_{ij} \cdot l_{ij}$$

M_i – represents the number of pipes coincidenced at node i,

e_{ij} – the leakage rate constant for pipe (i, j),

l_{ij} – the length of pipe (i, j).

Thus, the problem of pressure minimisation is a special case of leakage minimisation when the weights Wi are taken as unity.

4.3. Constraints

In low pressure gas networks, the criteria of satisfactory supply is that the minimum pressure in the network should not fall below a prescribed level. Thus for any load node the pressure constraint may be written:

$$p_i^{min} \le p_i \qquad (i = 1, 2, ..., \beta)$$

where:

β – is the number of load nodes in a network.

The limit of pressure at the supply governors of a network depends on the availability of pressure in the medium pressure system, the requirement of not exceeding a specified pressure in the network and finally the ability to maintain adequate supply. Hence pressure limits on governors may be written for a supply node k as:

$$p_k^{min} \le p_k \le p_k^{max} \qquad (k = 1, 2, ..., \alpha)$$

where:

α – is the number of supply nodes in a network and flow limits as:

$$Q_k^{min} \le Q_k \le Q_k^{max} \qquad (k = 1, 2, ..., \alpha)$$

Finally, the network equations themselves are constraints [7]. It means, that:

- the flow equation is satisfied for every pipe,
- I-st Kirchhoff's law is fulfilled for each node,
- II-nd Kirchhoff's law is fulfilled for each loop.

The mathematical problem to be solved is large, sparse, nonlinearly constrained optimisation problem [10]. The optimisation algorithm which has been developed is based on the generalised reduced gradient method (GRG). This approach was found to be generally more suitable than the algorithm which is based on the sequential augmented Lagrangian method. Generally, the problem solved by GRG method is:

$$\min f(\underline{x}) \quad \underline{x} = [x_1 \ \ x_2 \ \ \dots \ \ x_n]^T$$
$$subject\ to \quad h_j(\underline{x}) = 0 \qquad (j=1, ..., m)$$
$$L_i \le x_i \le U_i \qquad (i = 1, ..., n)$$

where: L_i and U_i are the lower and upper bounds on x_i, respectively, the upper and lower bounds are treated as separate vectors rather than being classified as inequality constraints because they are treated differently in determining the step length in a search direction.

Nonlinear inequality constraints can be accommodated by substracting (or adding, as the case may be) the square of slack variables from the inequality constraints thus:

$$h_j(\underline{x}) = g_j(\underline{x}) - \sigma_j^2 = 0 \tag{4}$$

and permitting the bounds on the σ_j's to be:

$$-\infty \le \sigma_j^2 \le \infty$$

An alternate method is to substract (or add) the slack variable itself and make the slack variable nonnegative by adding bounds to the problem:

$$h_j(\underline{x}) = g_j(\underline{x}) - \sigma_j = 0 \tag{5}$$
$$\text{subject to: } \sigma_j \ge 0$$

5. Results

To check correctness of the algorithm five different gas networks were tested. It is not a sufficient number of networks to allow rigorous statistical assessment of the benefits of leakage minimisation by pressure control. However, sufficient results are available to reach positive conclusions on the procedure suitable for industrial application. Table 1 lists the test-gas-network used.

The results of leakage minimisation procedure are the evaluation

Table 1. The test-gas-network parameters
Tabela 1. Parametry testowej sieci gazowej

Test network number	Number of branches	Number of load nodes	Number of supply governors
1	15	9	1
2	120	101	3
3	350	304	4
4	700	608	8
5	1200	960	10

of new supply governor pressures and the corresponding network solution. The investigation have shown that for every system under test there is some reduction in leakage (see Table 2). It cannot be expected, however, that optimisation will result in a large percentage reduction in leakage. What is important is that small reductions in leakage rates represent large sums of money over a period of time.

Table 2. Percentage of peak load for arbitrary and optimum pressure setting
Tabela 2. Procent obciążenia szczytowego dla dowolnego i optymalnego ustawienia ciśnienia

Test network number	Percentage of peak load for arbitrary pressure setting	Percentage of peak load for optimum pressure setting
1	1.69	1.01
2	2.27	1.09
3	2.97	1.50
4	3.91	2.03
5	4.01	2.40

5.1. Multiple local minima

One of the more difficult areas to handle is the situation when it is possible to have more than one solution to the leakage minimisation problem. Nearly all optimisation algorithms are designed to only find a local minimum. It is quite possible to have one, two or many local minima to any given problem. We have not examined in detail all networks to see if more than one solution is possible. However, we had situations, where two valid solutions were obtained, and different governor pressure settings resulted. One solution yielded substantially improved leakage savings compared to the other. It is hypothesised that the larger the network (larger number of controlling governors) the increased likelihood of multiple minima. This is, of course, the situation where leakage minimisation would have the greatest benefit.

There are several possibilities to deal with this situation:

- attempt to find the global minimum; there are a number of techniques around for doing this, though potentially a very large increase in run time can be anticipated,
- accept any local minima that the algorithm arrives at; the danger in doing this is that if there were many local minima to a given problem, then as a network is updated it is quite possible to flip to another local minimum, which could propose a completely different set of governor settings,
- develop a strategy whereby a number of attempts are made to find different local minima from various starting points, and then select the least minimum of this set.

Whatever strategy is adopted, some research effort will be necessary in order to resolve this problem to satisfaction.

6. Conclusions

Leakage minimisation by mathematical procedures of the type described can only be considered as a supplementary measure. The theoretical solutions of gas networks can be developed and extended to include leakage losses as an implicit part of the solution procedure.

Although leakage rates may be higher in medium pressure networks, the pipe length involved relative to low pressure networks is such that these systems can generally be treated or repaired more efficiently than low pressure networks. This is why the investigation was concerned with low pressure networks but much of the theory would apply to medium pressure systems.

As for as engineers using the program are concerned there is the question of data requirements. The bulk of the necessary information consisting of pipe, load and governor data is identical in format to that widely used in the Industry. The only additional data required is the loss constant, the governor pressure limits and the required minimum load node pressure [13].

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