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METHOD FOR LEAK DETECTION AND LOCATION FOR GAS NETWORKS

METODA WYKRYWANIA I LOKALIZACJI NIESZCZELNOŚCI SIECI GAZOWYCH

Leak detection in transmission pipelines is important for safe operation of pipelines. The probability of leaks may be occurred at any time and location, therefore pipeline leak detection systems play a key role in minimization of the occurrence of leaks probability and their impacts. During the operation of the network there are various accidents or intentional actions that lead to leaks of gas pipelines. For each network failure, a quick reaction is needed before it causes more damage. Methods that are used to detect such network failures are three-staged-: early identification of leakage, an accurate indication of its location and determine the amount of lost fluid. Methods for leak detection can be divided into two main groups: external methods (hardware) and internal methods (software). External leak detection methods require additional, often expensive equipment mounted on the network, or use systems that could display only local damage on the pipeline. The alternative are the internal methods which use available network measurements and signalling gas leakage signal based on the mathematical models of the gas flow. In this paper, a new method of leak detection based on a mathematical model of gas flow in a transient state has been proposed.

Keywords: leak detection; network simulation; transient state

Wykrywanie nieszczelności w rurociągach przesyłowych jest bardzo ważne dla bezpiecznej eksploatacji rurociągów. Nieszczelność gazociągu może wystąpić w dowolnym momencie i miejscu, dlatego systemy wykrywania nieszczelności odgrywają kluczową rolę w ograniczeniu strat gazu. Podczas eksploatacji sieci występują różne czynniki prowadzące do uszkodzenia gazociągów. W przypadku każdej awarii sieci wymagana jest szybka reakcja, zanim spowoduje ona więcej strat. Metody stosowane do wykrywania awarii sieci to: identyfikacja wycieku, lokalizacja wycieku i określenie ilości straconego gazu. Metody wykrywania nieszczelności można podzielić na dwie grupy: metody zewnętrzne (sprzęt) i metody wewnętrzne (oprogramowanie). Zewnętrzne metody wykrywania wycieków wymagają, często kosztownego sprzętu, który może wykrywać i lokalizować tylko lokalne uszkodzenia w rurociągu. Al-

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ternatywą są metody wewnętrzne, które wykorzystując dostępne pomiary wybranych parametrów sieci oraz modele matematyczne przepływu gazu wykrywają i lokalizują nieszczelności. W niniejszym artykule zaproponowano nową metodę wykrywania nieszczelności opartą na matematycznym modelu przepływu gazu w stanie nieustalonym

Słowa kluczowe: wykrywanie nieszczelności, symulacja sieci, stan nieustalony

1. Introduction

(Bilman & Iserman, 1981; Stuart et al., 2003) show the methods of leak detection can be divided to external and internal leak detection systems. Leaks detection system of the gas pipelines should comply to leak detection, alarm generation, leak localization and estimation of the flow rate of leaking medium. (Stowikowski, 2007; Furness & Reet, 1998) show that in the external methods the detection is done from outside the pipe through application of specialized sensors or visual observation of the area and, if possible, sensing with portable detectors of transported medium, also the use the helicopters can give faster leak detection but less accurate information. External methods utilize various additional devices installed on the network and are expensive. Hence, the metering around the whole gas network becomes infeasible. Other types of methods, that examine the presence of methane (network inspections by foot or control from the air), do not allow for permanent control of the entire network (Pergam-Suisse, 2007). Additionally, during chilling winters, the area of gas leaking to the surface can vary significantly from the actual location of the leakage. In this case, the external leakage detection methods either cannot detect or incorrectly indicate the location of leakage. The methods, that are cheaper to implement and allow for simultaneous control of the entire network, are the internal methods.

2. The internal method of leakage detection

The internal leak detection is based on measurements and analysis of flow parameters (mainly pressure and fluid flow rate/velocity, sometimes temperature and density). (Turner, 1991; Muhlbauer, 1996; Daniel et al., 2005) show the main category of internal leak detection in pipelines is known as computational pipeline monitoring (CPM). (Liou, 1996; Farmer et al., 1991) show volume or mass balance method of leak detection, also known as line balance, this method is based on measuring the discrepancy between the input and output product volumes or mass of a particular pipeline segment. The most sensitive, but also the most complex and costly leak detection method, the basis of these methods is modelling in the real time the phenomena inside a pipeline with the use of suitable mathematical models (Slowikowski, 2007) and comparison of the values calculated from the model with values acquired from the real pipeline (Kowalczuk & Gunawickrama, 2002). When the differences between the measured and calculated values are high than allowable acceptable value, the alarm is generated and procedures of leak localization are activated. In internal methods, processing of data involves the appropriate use of information collected by measurements, which are used for the calculation of tested network. Depending upon the method used, the calculations may relate to test changes of the flow, pressure drop or change of speed. Each of these parameters may change in the event of a leakage. For transmission networks, the situation is little more complicated because of the variable nature of gas flow. When we have to deal with the transmission networks, the flow of transient parameters (pressure, flow) vary as a function of distance and time. Therefore, in the case of these networks first we have to examine whether the change of parameters is associated with the real changes taking place on the network or it is actually a result of leakage. The easiest way to discover it, is to perform dynamic network simulation based on available measurements (Osiadacz et al., 2012). Method using such simulations is described in this paper.

3. Characteristics of the model

A modified version of SimNet TS Gas application has been used for simulation (Fluid Systems, 2015). This modification allows to adapt the program according to the requirements of the detection of leakage in the gas network. The described simulator uses a model of transient gas flow described by differential equation of the parabolic type, which is solved by generalized node method. The mathematical model of unsteady gas flow in the pipeline was presented in (Osiadacz, 1990).

Leakage detection algorithm is based on comparison of measured values with values obtained from the simulation model of the pipeline (Kotyński, 2015). Prior to the leakage detection, the identification of the model should be performed. Identification can be made based on three values: linear drag coefficient λ, compressibility factor 'z' and the gas density 'ρ'. The coefficient 'λ' is burdened with the highest uncertainty and greatly affects the pressure drops along the pipeline.

The transmission networks have mainly dealt with the situation where the flow is from the rough pipes for which $\lambda = \lambda(\varepsilon)$. Research literature (Prandtl, 1956; Walden, 1983) shows that the absolute roughness of steel pipes for use in transmission networks can take values over a wide range (from 0.045 mm to 3.0 mm). Modification of friction factor of each pipe is performed repeatedly in an iterative process to find the value for which the difference between the pressure values measured and obtained as a result of the simulation at different points of the network, will be as minimum as possible. Besides modification factor 'λ', identification of model can also be done based on the modification of the compressibility factor 'z' and the gas density 'ρ'. Depending on how they are determined, by calculating the capacity of the pipeline or converting the flow from real conditions to normal, we can get different results. Any difference between the values obtained from the model and the values of measurements may affect the accuracy of leakage detection. It can be noticed that the model used in the gas network has 3 degrees of freedom.

They are dependent on the method of determining the coefficient 'λ', compressibility factor 'z' and the gas density 'ρ'. A suitable method for determining these values permits precise identification of the model.

To calculate the capacity of the pipeline or conversion flow to normal conditions, we use the average value of the density of gas in the section of the pipeline calculated from the equation of state:

$$\rho = P/(zRT) \tag{1}$$

where:

ρ — gas density [kg/m^3],
P — gas pressure [Pa],
z — compressibility factor [-],
R — gas constant [J/(kg K)],
T — gas temperature [K].

For the simulator, isothermal gas flow is considered. Given that the compressibility factor '*z*' is dependent on pressure and temperature, the density value can be determined in three ways:

1) The average pressure is determined on the basis of the pressure values, at the edges of the pipeline. High pressure will be served to this pattern:
2)

$$p_{average} = \frac{2}{3} \cdot \left(p_1 + \frac{p_2{}^2}{p_1 + p_2} \right) \tag{2}$$

where:

p_1 — the pressure at the beginning of the pipe [Pa],
p_2 — the pressure at the end of the pipe [Pa].

The compressibility factor is computed on the basis of the average value of the pressure and temperature. On behalf of these values, density is, then, calculated.

3) As in the first case, it defines the average pressure value. Then, on each end of the pipe for the actual pressure and temperature values at certain point, calculate the value of the compression factor. The arithmetic mean value and then density are calculated based on the two values of "*z*".
4) In the last case, the values of '*z*' and current density for actual pressure are subsequently determined on each end of the pipe. Then, the average density is calculated as the arithmetic mean of the two calculated values.

The differences in gas density are presented in the Table 1 with the following characteristics:

p_1 – pressure at the beginning of the pipe = 6 MPa,
p_2 – pressure at the end of the pipe = 4 MPa,
L – length of pipe = 100 km,
D – internal diameter of pipe = 0,4 m,
T – gas temperature = 5°C = 278,15 K,
Q – flow rate ~210 000 m^3/h.

TABLE 1

The differences in gas densities

Way of calculating	Density value (kg/m^3)	The mass of gas in the pipeline (kg)
1) Density ($p_{average}$)	39,47	~496000
2) Density ($z_{average}$)	39,39	~495000
3) Density ($\rho_{average}$)	39,08	~491100

Differences in the density determination reach almost 1% and can significantly affect the process of leakage detection. The wrong way of determining the density can lead to omission or error in the evaluation of small leaking. The identification in this case, consists in selecting such a method for calculating the density to obtain the smallest possible difference between the measured values and calculated values.

2.2. Principles of leakage detection

After identifying the model, we can switch to the process of leakage detection. The presented algorithm requires the measurement of flow, pressure and temperature at entry and exit points of the pipeline.

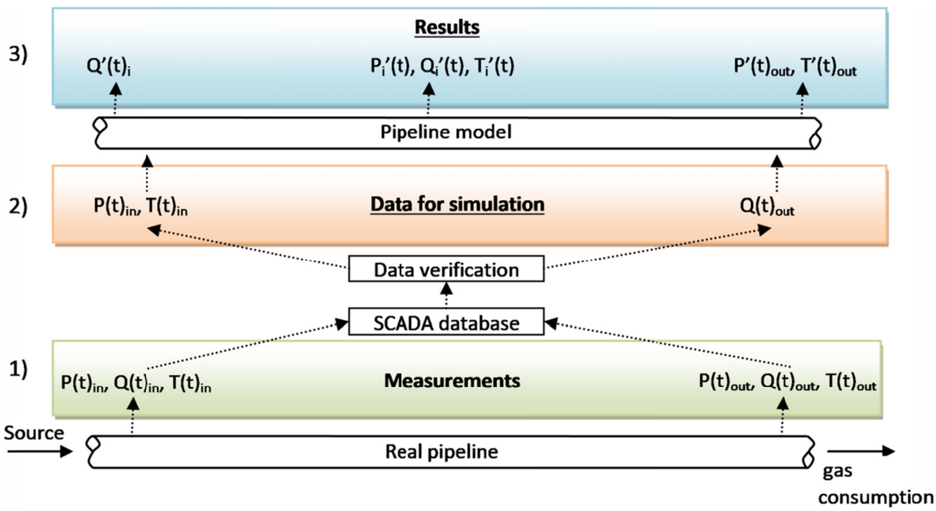

Fig. 1. The data for the simulation

Figure 1 shows the stages of the procedure (step 1, 2, 3) used in the algorithm to detect leakages. In step (1) the measurement results are recorded at $x = 0$ and $x = L$. The values of pressure, flow and temperature are recorded at different points in specific time. Data from the measurements get to the database of the SCADA system. Verification of the data excludes fat measurement errors. Therefore, the processed data is used in step (2) to simulate the tested network. The result of the simulator calculations in step (3) are flow and the pressure at the input and temperature at the output of the examined time points. The resulting data is then compared with the values of the measurements to validate the computational model. Two values were defined (Osiadacz & Kotyński, 2011; 2012):

$$e_{Q_{\max}} = \max_t \left| Q(t)_{in} - Q(t)'_{in} \right| \tag{3}$$

$$e_{P_{\max}} = \max_t \left| P(t)_{out} - P(t)'_{out} \right| \tag{4}$$

where:

$e_{Q_{\max}}$ — Maximum absolute value of the difference in flow during identification of the model at the input between measurement and simulation (flow deviation) [m^3/h],

$e_{P_{\max}}$ — Maximum absolute value of the difference of pressure at the output during identification of the model, between measurement and simulation (pressure deviation) [kPa],

$Q(t)_{in}$ — The measured value of the flow at the entry point at the time 't' [m^3/h],
$Q(t)'_{in}$ — The value of flow at the entry point at the time 't' obtained from the simulation [m^3/h],
$P(t)_{out}$ — The measured value of the pressure at the exit point at the time 't' [kPa],
$P(t)'_{out}$ — Pressure at the exit point in time 't' resulting from simulations [kPa].

The difference in values (3 and 4) are compared with the values of the uncertainty of measuring instruments. If the uncertainty of measuring instruments is greater than the calculated values of the differences, then, in place $e_{Q_{\max}}$ and $e_{P_{\max}}$ we insert the uncertainty of measuring instruments.

Figure 2 shows the principle of the algorithm to detect leakage. After the identification of the model, the flow measurement data are downloaded to the simulator and compared with the obtained simulation results. When the pressure difference between the measurement and simulation on the output exceeds $e_{P_{\max}}$, then, we find a leakage in the pipeline.

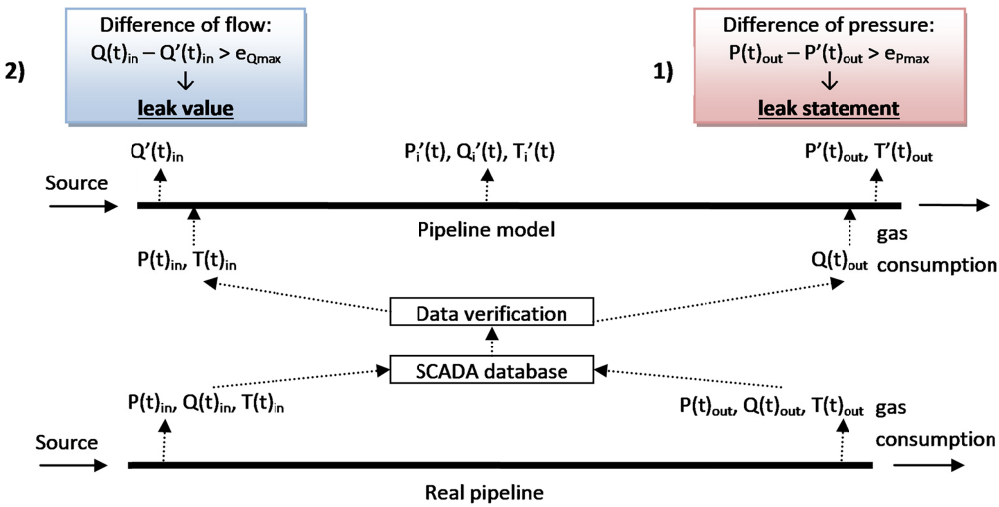

Fig. 2. The algorithm for calculating measurement uncertainty

The algorithm is mainly based on the comparison of pressure, instead of flow, since tests have shown that it is related to more effective leakage detection. The values of the differential flow on the input can be the estimated value of the leakage. Until the time of the leakage difference of the flow value is less than or equal to the $e_{Q_{\max}}$ value. At the time of the gas leakage from the network difference flow is increasing rapidly and oscillates around the leakage value. In the proposed algorithm, the following criteria for determining the value of the leakage was set:

$$Q_{leak} = \frac{\sum_{i=1}^{k}\left|\left(Q(t)_{in} - Q(t)'_{in}\right)\right|}{k} \tag{5}$$

where: k — the number of measurements for which $\left|\left(Q(t)_{in} - Q(t)'_{in}\right)\right| > e_{Q_{\max}}$

After determining the leakage and its value, the last step is to allocate the leakage spot. In the proposed algorithm, the allocation of leakage is carried out at specific points and is done in an iterative process. The method of generalized node used to solve partial differential equations describing the flow of the gas pipeline must be divided into discretization sections of fixed length, which play an important role in the localization process. At the end of each interval discretization, the actual location of the leakage is searched. The shorter the intervals of discretization, greater the computational effort and may increase the calculation errors. The steps of locating leaks in proposed method was presented graphically in Figure 3. In this example, the pipeline has been divided into 8 compartments discretization. It is assumed that the actual leakage is at the end of the third section and was marked with a green circle.

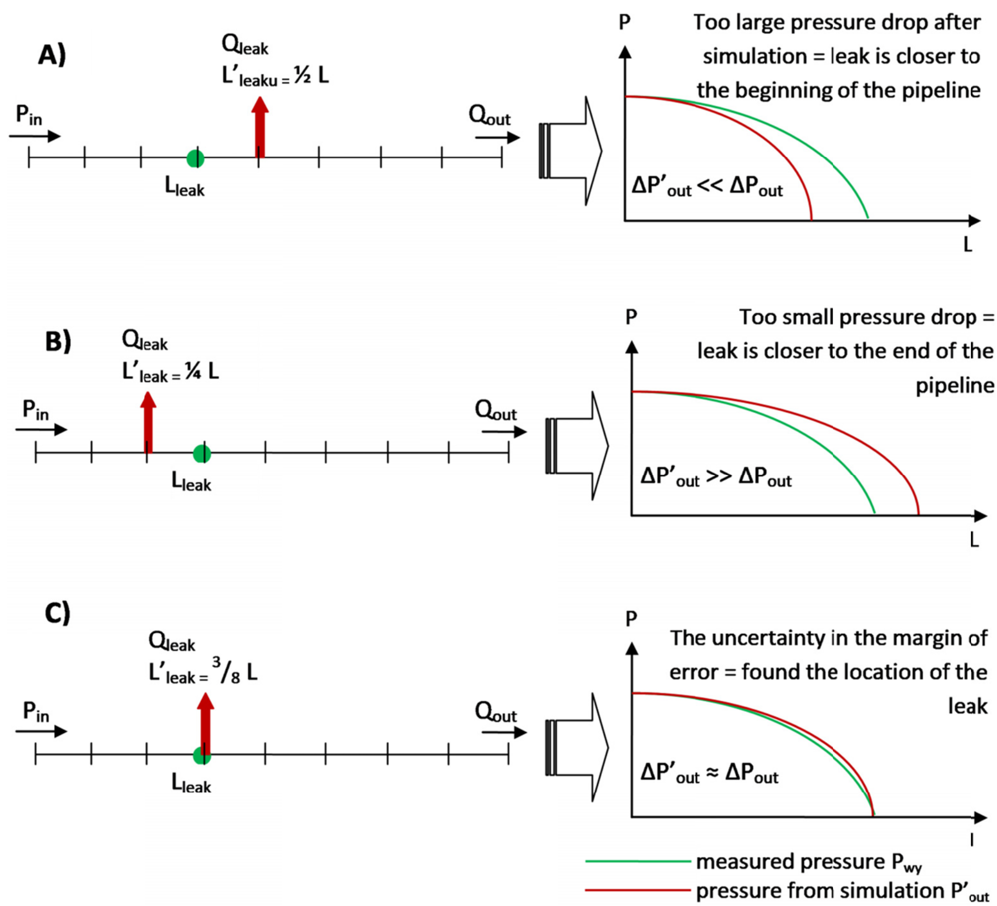

Fig. 3. The principle of the location of the leak

In the first step of the algorithm (Fig. 3A), we assume that the additional gas consumption corresponding to the leakage of the value obtained from the criterion (equation 5) is located at $x = ½\,L$ – at the end of the fourth interval discretization.

Under this assumption, we perform simulation and compare the output pressure of the gas pipeline between simulation and measurement. If the pressure difference is negative (pressure that results from the simulation [red line graph] is smaller than the value obtained from the measurement of the pressure [green line graph]), it means that the actual site of leakage is closer to the beginning of the pipeline. If pressure difference has positive value (pressure at the end of the pipeline simulation is greater than the measured value) it means that obtained information on a real leak is located closer to the end of the pipeline. In a variant 3A, we get negative value of pressure differential, as in the graph on the right shows that the pressure from the simulation at the end of the pipeline (P'_{out}) is less than the measured (P_{out}). In order to locate leakage, we use the deviation of the pressure as a criterion. Lower pressure drop corresponds to smaller values of the flow. In our case, a reduction in pressure drop is the adoption of a shorter segment, through which the gas is escaping through the leakage. We take this situation by assuming that the leakage is closer to the beginning of the pipeline. In the second step (step B) repeat the procedure for searching for leaks in the mid-section defined by the points $x = 0$ and $x = ½\,L$, that is, a quarter of the length of the pipeline – at the end of the second compartment discretization. If after simulation pressure differential has positive sign (Figure 3B), it means that the pressure drops in the assumed location of leak turned out to be too small. In the next step, we repeat the procedure so divide the pipeline in half between the points $x = ¼\,L$ and $x = ½\,L$. New point is located 3/8 the distance from the starting node of the pipeline. Division is repeated until receiving the pressure difference between the measurement and the result of the simulation is less than the assumed uncertainty.

3. The test results of the algorithm for the case of a single pipeline

In order to check the correctness of the algorithm, high pressure gas pipeline in the national transmission system were selected, which previously had leaking. The pipeline was properly metered and measured data was recorded in the SCADA system as hourly intervals. Verification of the model was based on archival data, which included measurements of pressure, flow and temperature. The geometrical dimensions of the pipeline are shown in Table 2 and the change of load and pressure over time is expressed in figures 4 and 5.

TABLE 2

The lengths and diameters the tested pipeline

Parameter	Gas pipeline
Length (km)	93,7
Pipeline diameter	DN500

3.1. The limits of uncertainty of flow and pressure

The simulation of tested gas pipelines was made with hourly time step, the same as in the case of recorded data from the SCADA system. Each pipeline was divided into 30 intervals of discretization for high accuracy of the location of leakage algorithm (approx. 2-3 km). In the present case, the value of the output pressure obtained from the simulation differed from the

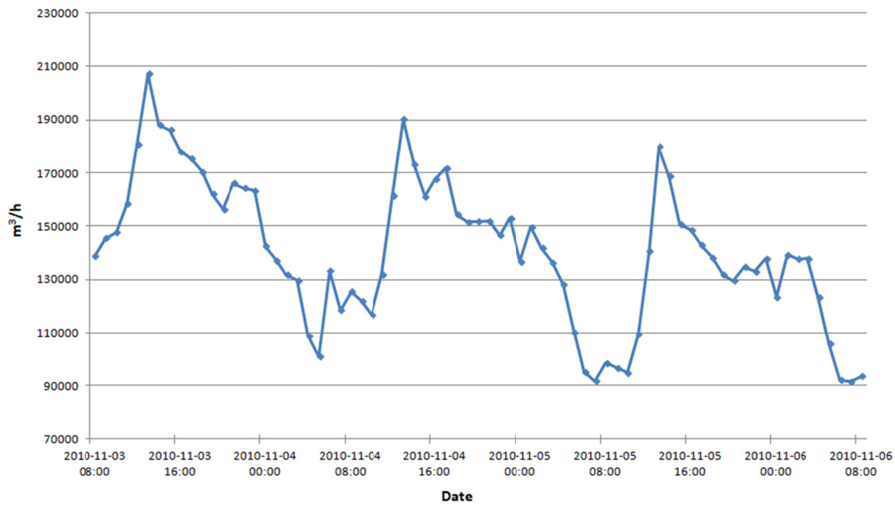

Fig. 4. Change of gas consumption in time in gas pipeline

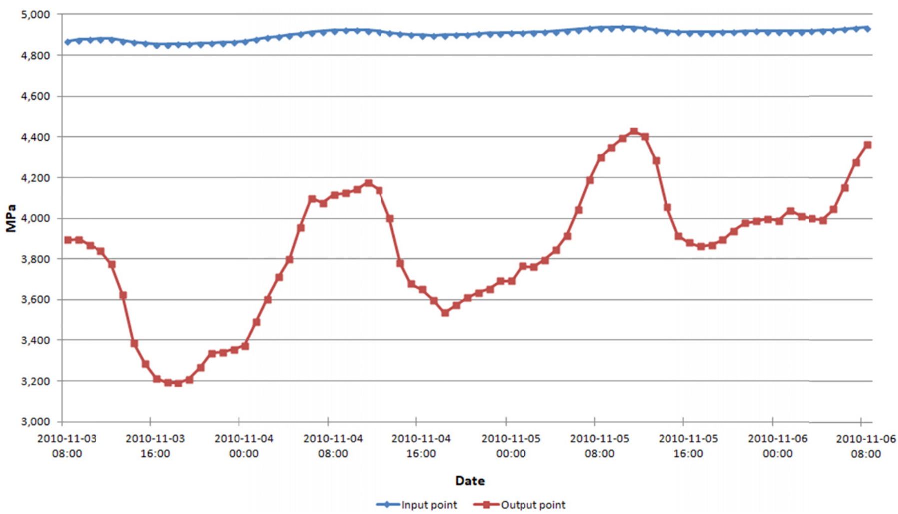

Fig. 5. Change of pressure in time in gas pipeline

values measured by more than 1.5% in relation to the measurement which indicated a need for identification of the model from the leak detection point of view. The iterative process of model identification for pipeline was made by changing the friction coefficient of the pipe. Description of the identification process has been presented in the previous part of article. Deviation of pressure between the results of simulation and measurement results after identifying for the pipeline does not exceed 0.25% of the measured pressure. The relative uncertainty of measurement of flow rate was 0.5%. The limits for the uncertainty of simulation results of flow and pressure established after the test are presented in Table 3.

TABLE 3

Limits uncertainty of flow and pressure

Gas pipeline
$e_{Q_{max}}{}^{I} = \pm 1040\ m^3/h$
$e_{P_{max}}{}^{I} = \pm 11$ kPa

Exceeding these ranges of uncertainty will be interpreted as the occurrence of a leakage on the pipeline. The first step in the detection of leaking in the proposed algorithm is to compare pressure values obtained as a result of simulation and obtained from the measurements. Figure 6 shows the deviation value for the pressure of the gas pipeline in the test period. By dotted lines have been marked uncertainty limits of simulation results of pressure established during the identification. The exceeding of the uncertainty range limit by the value of the difference pressure means the occurrence of a leakage. In figure 6, we obtain a negative value for the difference pressure, so pressure value measured at the end of the pipeline was smaller than the value obtained from the simulation. The larger pressure drop was the result of increased flow caused by a leakage on the pipeline.

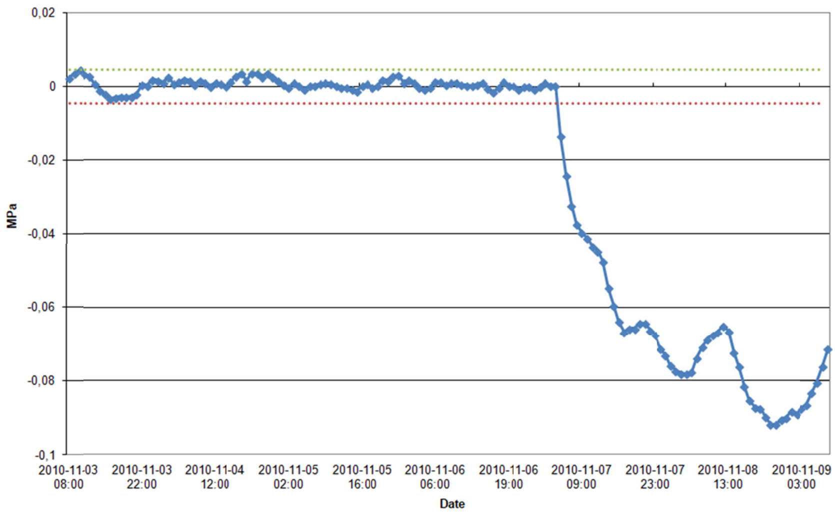

Fig. 6. The difference in pressure at the end of the gas pipeline

When the actual leakage of the pipeline occurred the range $e_{P_{max}}{}^{I} = \pm 11$ kPa was exceeding by the deviation of the pressure. The value of deviations in pressure $e_P{}^{I}$ is –14 kPa and increases at the subsequent moments of time. The negative pressure deviation value is the result of higher pressure drops obtained from measurements at the end of the pipeline as compared to the values obtained from the simulation. The simulation calculations do not take into account the leakage causing increased flow and the associated higher pressure drop.

The data for the pipeline show the correct response of algorithm on the occurrence of leakage. In order to reduce the time required to detect a leakage we can also use the flow value. It is less accurate in comparison to the pressure due to the lower flow measurement accuracy and the necessity of converting its value to normal conditions, but much faster react to any change in the pipeline, for example, such as the occurrence of leaks. We calculated it at each time as the difference between the flow at the inlet pipeline and the resulting measurements obtained by the simulation. Figure 7 shows the measured flow at the input (red line), flow rate obtained from the simulation (green line) and the deviation of values listed above (blue line). Axis scale on the left side of the graph refers to a flow value measured and obtained from the simulation, and the scale axis on the right shows the discrete value of the flow deviation, which is interpreted as a leakage from the pipeline at any given time.

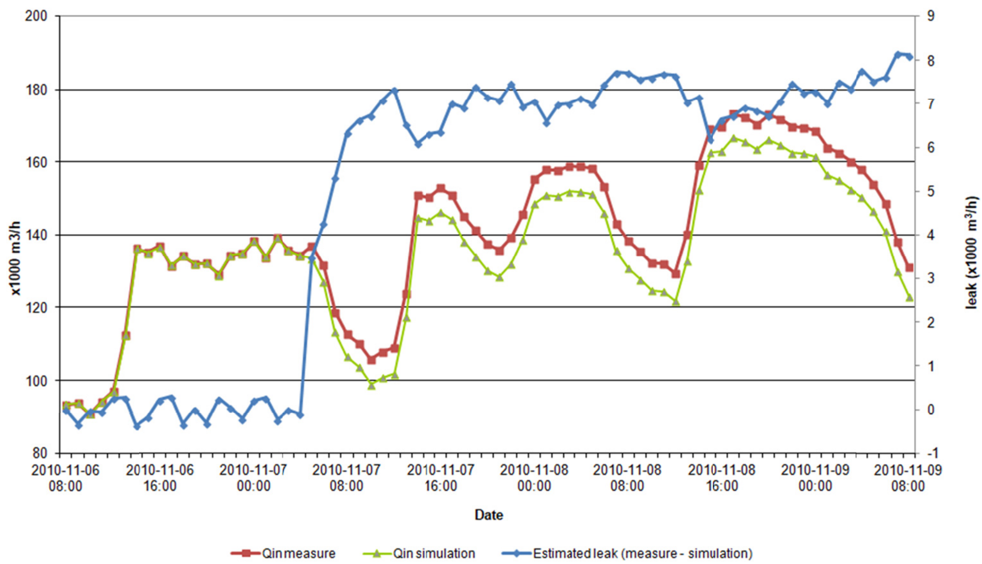

Fig. 7. Estimating the value of leak

At the time of the leakage, when the pressure deviation value exceeded the range of uncertainty, the difference in flow rates measured and obtained from the simulation also rose sharply as shown on Figure 8.

Thick dashed red line is showing estimated value of leakage in the network. As we can see the value of the deviation rate in the next time step after the leak increased rapidly and maintained an upward trend in the subsequent moments of time. A few hours after the leakage occurred deviation of flow value starts to stabilize. According to the criterion of determination of the leak, leakage rate was 6800 m^3/h.

Please note that the responding time of the occurrence of leakage is estimated here and greatly depends on the adopted time step. For smaller values of the time step can be more accurate measurements and quickly get information about the sudden changes in the measured parameters.

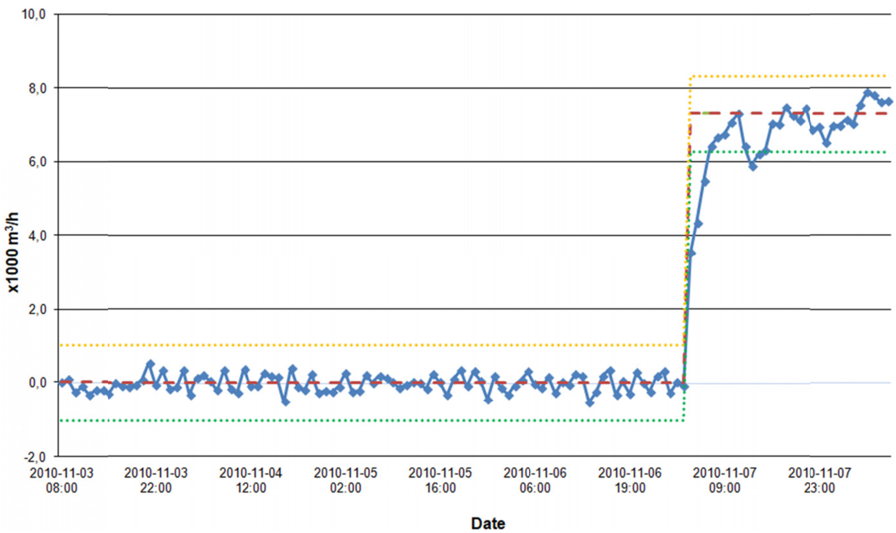

Fig. 8. Deviation of flow as a result of leak

3.2. Estimation of leakage

In the proposed algorithm, the value of the leakage is estimated on the basis of the input deviation of flow of the gas pipeline between the measurement and the simulation value. The estimated value of the leakage is calculated from the moment of exceeding the value of the flow deviation by allowable value of measurement uncertainty of flow. In the case of leakage detection in real-time simulation the estimated value of leakage will be modified in each time step. The more measurements will be available, the more accurately we will be able to determine the value of the leakage. Table 4 shows the calculation of the leak for proposed criteria for the pipeline since the inception of leaks until the pipeline repairing.

The red values which differ from the real value by more than a leakage measurement uncertainty are shown in Table 4. The actual value of the leak was about 7300 m^3/h, while the value of expected uncertainty was $e_{Q_{\max}}{}^{I} = \pm$ 1040 m^3/h. The minimum valid value of leakage, taking into account the measurement uncertainty is thus 6260 m^3/h. We can see that 15 measurements deviate significantly from the actual value of the leakage. However, the estimated value of the leakage is known from the beginning time of a leak.

3.3. Determining the location of leakage

Allocation of the leakage point is the last step of this process. In the case of the proposed algorithm, the accuracy of location is dependent on the accuracy of the estimate of the leak and the adopted length of intervals of discretization of the pipeline. As has been previously presented, the accuracy of estimating the value of the leak has been very good. The length of the discretization interval is resulted from the division of the pipeline for 30 sections. The number of sections was assumed to obtain a small value of the error location. Figure 9 illustrates the principle of locating leaks.

TABLE 4

The estimated value of the leak on the pipeline in the following time series

Time	2010-11-07 05:00	2010-11-07 06:00	2010-11-07 07:00	2010-11-07 08:00	2010-11-07 09:00	2010-11-07 10:00	2010-11-07 11:00	2010-11-07 12:00	2010-11-07 13:00	2010-11-07 14:00	2010-11-07 15:00	2010-11-07 16:00	2010-11-07 17:00	2010-11-07 18:00	2010-11-07 19:00
Uncertainty flow between measurement and simulation	3,541	4,353	5,465	6,414	6,641	6,744	7,063	7,306	6,415	5,879	6,19	6,296	7,038	7,011	7,487
Leak value [×1000 m^3/h]	**3,541**	**3,947**	**4,453**	**4,943**	**5,283**	**5,526**	**5,746**	**5,941**	**5,994**	**5,982**	**6,001**	**6,026**	**6,103**	**6,168**	**6,256**
Time	2010-11-07 20:00	2010-11-07 21:00	2010-11-07 22:00	2010-11-07 23:00	2010-11-08 00:00	2010-11-08 01:00	2010-11-08 02:00	2010-11-08 03:00	2010-11-08 04:00	2010-11-08 05:00	2010-11-08 06:00	2010-11-08 07:00	2010-11-08 08:00	2010-11-08 09:00	2010-11-08 10:00
Uncertainty flow between measurement and simulation	7,232	7,123	7,449	6,858	6,945	6,515	6,973	6,986	7,144	7,018	7,542	7,874	7,801	7,606	7,641
Leak value [×1000 m^3/h]	6,317	6,365	6,425	6,448	6,473	6,475	6,497	6,518	6,545	6,563	6,601	6,648	6,689	6,721	6,752

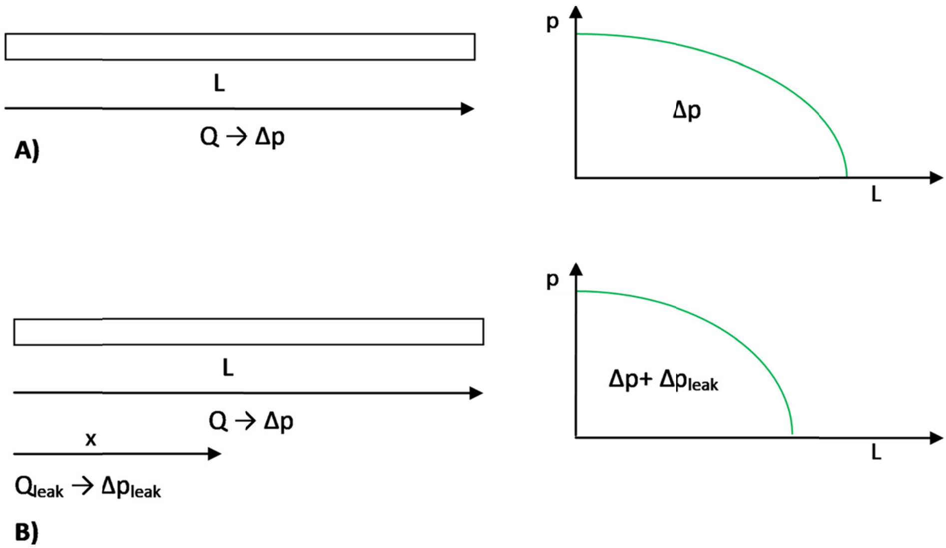

Fig. 9. The principle of the location of the leak

Figure 9 A shows a situation without leakage on the pipeline. The gas flow causes a decrease in pressure along the pipeline. Figure 9 B introduced additional load on the network, which causes additional pressure decrease across the network. In real network, where the leak occurred, we will have to deal with the situation B. We will not know the estimated value and location of the leak, but the measurements will tell us about a larger pressure drop than would result from the loads of the pipeline. Using data from the measurements in simulation concerning the load (no load from unknown leakage) and the supply pressure we get a graph of pressure as in the case A. Task for location algorithm is to minimize the pressure difference at the end of the pipeline between the measured pressure and obtained from simulation calculations, assuming that the decision variable is the distance from leaks to the starting node (distance *x*). Finding locations is, therefore, an iterative process, and the proposed method, start the search in the middle of the pipeline.

$$x_1 = L/2$$

Please note that, in case of an odd number of intervals of discretization, if the designated location is not located at the end of any interval, we must accept that its end, which is the closest. At this point, we assume that the additional load is equal to the determined value of the leak that had previously been estimated on the basis of uncertainty of flow and for such data the simulation is performed. Further searching for leaks are graphically shown in figure 10.

The blue line in figure 10 shows the deviation of pressure at the end of the pipeline between the measurement, during which the leak occurred and simulation, during which the leakage is not assumed. It is therefore a result corresponding to the situations shown in figure 9. At the start in the middle of the pipeline which is the 46.8 kilometre (rounding to the end of the adopted discretization interval) was assumed the leak of value 7000 m^3/h. Deviation value for the simulation of leakage in the middle of the pipeline is shown by the red line. Compared to the first variant of the simulation we obtained a smaller deviation value after the leak. Still, its value exceeds

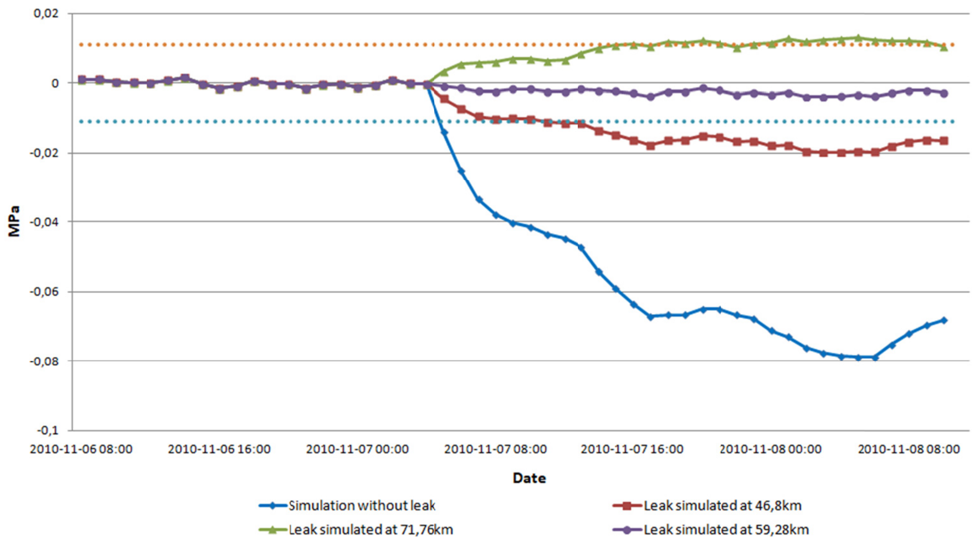

Fig. 10. The difference in pressure between measurement and simulation

the limits of measurement uncertainty (orange and blue dashed lines). The value of deviation pressure at the location of the leakage were also shown in Table 5. The values that go beyond the established allowable deviation are marked with red line.

Pressure deviation at the end of the pipeline for the leak originated in the 46.8 km accepts negative values, so established location of the leak caused too low pressure drop. Leakage, that caused additional pressure drop, must be positioned closer to the end of the pipeline, results in greater pressure loss by the flow. This can be described as follows:

$$e_P = P(t)_{out} - P(t)'_{out} < -e_{P_{\max}} \rightarrow \textit{the leak is closer to the end of the pipe}$$

$$e_P = P(t)_{out} - P(t)'_{out} > e_{P_{\max}} \rightarrow \textit{the leak is closer to the beginning of the pipeline}$$

$P(t)_{out}$ — pressure of the measurement [kPa],
$P(t)'_{out}$ — pressure of the simulation [kPa].

Another location for leakage in pipeline, was searched according to the equations:

$$x_2 = x_1 + \frac{L - x_1}{2} \tag{6)}$$

and

$$x_{i+2} = \frac{x_{i+1} + x_i}{2} \quad \text{for} \quad i = 1, 2, \ldots, n \tag{7)}$$

The new projected location of the leakage including discretization sections of pipeline is 71.76 kilometres. Deviation determined by such assumptions is shown in figure 10 by green line. This time the deviation has adopted positive values and continue beyond the scope of uncertainty in pressure.

TABLE 5

Pressure deviation at different leaks locations

Time	2010-11-07 03:00	2010-11-07 04:00	2010-11-07 05:00	2010-11-07 06:00	2010-11-07 07:00	2010-11-07 08:00	2010-11-07 09:00	2010-11-07 10:00	2010-11-07 11:00	2010-11-07 12:00	2010-11-07 13:00	2010-11-07 14:00	2010-11-07 15:00	2010-11-07 16:00	2010-11-07 17:00	2010-11-07 18:00
A pressure deviation for simulation without leakage	0,000	0,000	**–0,014**	**–0,025**	**–0,033**	**–0,038**	**–0,040**	**–0,042**	**–0,044**	**–0,045**	**–0,047**	**–0,054**	**–0,059**	**–0,063**	**–0,067**	**–0,067**
Pressure deviation for leak simulated at 46,8 km	0,000	0,000	–0,004	–0,007	–0,010	–0,010	–0,010	–0,010	**–0,011**	**–0,011**	**–0,012**	**–0,014**	**–0,015**	**–0,016**	**–0,018**	**–0,016**
Pressure deviation for leak simulated at 71,76 km	0,000	0,000	0,003	0,005	0,006	0,006	0,007	0,007	0,006	0,007	0,008	0,010	0,011	**0,011**	0,011	**0,012**
Pressure deviation for leak simulated at 59,28	0,000	0,000	–0,001	–0,001	–0,002	–0,002	–0,002	–0,002	–0,002	–0,002	–0,002	–0,002	–0,002	–0,003	–0,004	–0,002

Time	2010-11-07 19:00	2010-11-07 20:00	2010-11-07 21:00	2010-11-07 22:00	2010-11-07 23:00	2010-11-08 00:00	2010-11-08 01:00	2010-11-08 02:00	2010-11-08 03:00	2010-11-08 04:00	2010-11-08 05:00	2010-11-08 06:00	2010-11-08 07:00	2010-11-08 08:00	2010-11-08 09:00	2010-11-08 10:00
A pressure deviation for simulation without leakage	**–0,067**	**–0,065**	**–0,065**	**–0,067**	**–0,068**	**–0,071**	**–0,073**	**–0,076**	**–0,078**	**–0,079**	**–0,079**	**–0,079**	**–0,075**	**–0,072**	**–0,070**	**–0,068**
Pressure deviation for leak simulated at 46,8 km	**–0,016**	**–0,015**	**–0,015**	**–0,017**	**–0,017**	**–0,018**	**–0,018**	**–0,020**	**–0,020**	**–0,020**	**–0,020**	**–0,020**	**–0,018**	**–0,017**	**–0,016**	**–0,016**
Pressure deviation for leak simulated at 71,76 km	**0,012**	**0,012**	**0,011**	0,010	**0,011**	**0,011**	**0,013**	**0,012**	**0,012**	**0,013**	**0,013**	**0,012**	**0,012**	**0,012**	**0,012**	0,011
Pressure deviation for leak simulated at 59,28	–0,002	–0,001	–0,002	–0,003	–0,003	–0,003	–0,003	–0,004	–0,004	–0,004	–0,003	–0,004	–0,003	–0,002	–0,002	–0,003

Another approximation of the leak x_3 falls to 59.28 km. Deviation adopted for such locations is presented by violet line. In figure 10 and Table 5 it can be seen that the deviation value is already within the limits of the uncertainty of measurement of pressure. Location of leakage in this point corresponds to the actual flow in the network. Detected place for the location of the leakage is with an error equal to 3.12 km, because such value has been adopted during the identification as the length of the interval discretization. For a gas pipeline, actual leak was located at a distance of 57.30 kilometres from the start of the pipeline. Error for that location was 1.98 kilometer. From the data presented in Table 5 shows that directly after the leakage, and for the next few hours, deviation pressure does not exceed the limit of uncertainty equal to 11 kPa. Detecting leakage in real time could be considered that the location is correct. Exceeding the permissible deviation value for the location started after five hours. When examining different locations of leakage, and comparing the deviation of these options, it is clear that at the location of the leakage at 59.28-kilometre absolute value of the deviation per unit time is smaller than the others. The criterion of the minimum absolute deviation value allows to find the correct location of the leak.

TABLE 6

Summary of data and the results of the algorithm for the test gas pipeline

Parameter	**Gas pipeline**
Length (km)	93,7
Pipeline diameted (DN)	500
Leak value (×1000 m^3/h)	7,3
Leak size (% flow	5%
Estimated leak value (×1000 m^3/h)	6,75the
The accuracy of estimating a size of a leak (%)	92%
Real location of the leak (km)	57,3
Estimated location of the week (km)	59,28
Accuracy of the estimate of the leak (%)	97%
Leak location error (±km)	1,98
Assumed location accuracy (±km)	3,12

In Table 6, the results of the location using the proposed algorithm to detect leakage are shown. On this basis, it can be stated that the presented algorithm is working properly. The results indicate the possibility of obtaining high accuracy in determining the value of the leakage. No impact of input pressure and rapid changes in the flow of the accuracy of leak location results. The accuracy of the results of the calculations may fall, when the deviation between the measured pressure and the result of simulation during identification will increase. The value of the deviation is, however, dependent on the accuracy of measuring instruments and quality of calibration of flow model in the network. If during the initial stage of identification of the model, we obtain a large deviation then it has later impact on the effectiveness of the algorithm. It is more difficult in this case to distinguish between the actual leakage and the imbalance of the network as a result of transient flow. It is very important therefore, to accurately adjust the model with the measured data and the availability of suitably accurate measurement results. When determining the location of the leakage, the length of adopted discretization intervals of pipes plays an important role. Shorter intervals discretization allow for a more accurate indication of the leak, but increase numerical errors.

4. The results of algorithm for the case of tree structure network

Leakage detection algorithm was also verified on the gas network of the tree structure. Due to the lack of high volatility of parameters over time and a larger number of measurements on the network compared to a straight pipeline, the archival data collected in two days from the SCADA system was used to identify the algorithm. The study of gas network consisted of 124 nodes and 128 pipes with diameters from DN100 to DN250. The total length of the network was 274 kilometres of which pipes with a diameter equal to or greater than DN200 was over 222 kilometres (over 80% of the total network length).

In the case of a single pipeline, the leakage detection was based on comparison of the pressure variations in the output node of the pipeline. In the case of network, there are few output nodes, so it is best to compare the deviation in the nodes where we have the results of measurements. Such a comparison will also determine the approximate location of the leakage. In figure 11, the deviations at several time periods for each node are shown. Red dotted lines indicate the permissible uncertainty of pressure.

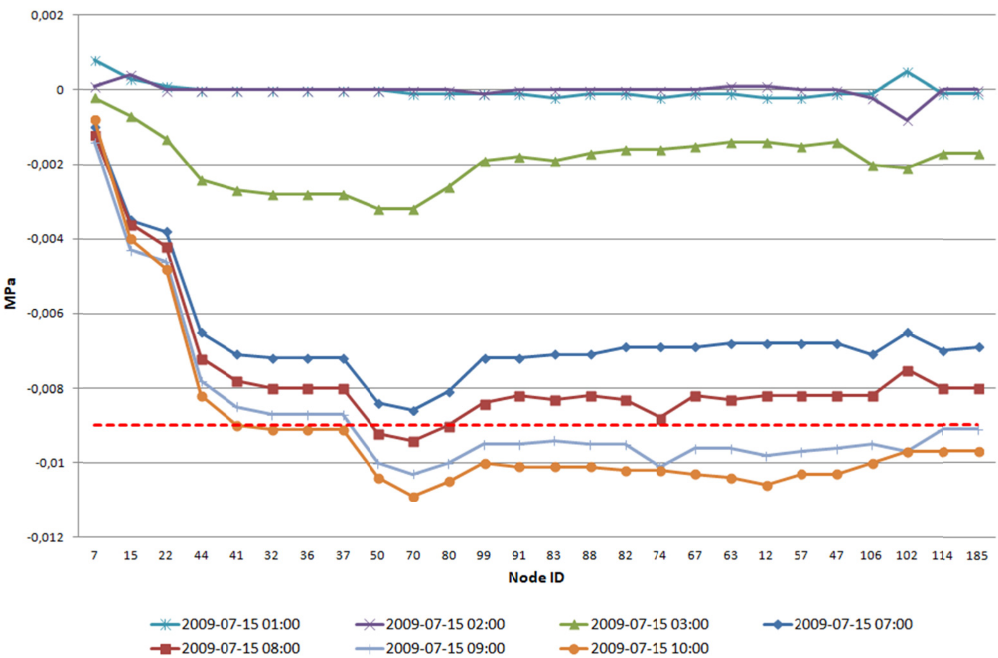

Fig. 11. Pressure difference in the nodes of the network

Figure 11 shows that from 3:00 (line marked with a triangle), the deviation of pressure for most of the nodes begin to slowly decrease until about 8:00 (line marked with a square) while the deviation in the nodes 50 and 70 exceeds the minimum allowable value resulting the uncertainty of measurement of pressure indicating a leakage in the network. The leakage should be somewhere in the neighbourhood of these nodes. The biggest drop in pressure after the leakage is, in fact, the most visible close to the leak. On the section between selected nodes, further stages of locating leaks based on methodology used for a single pipe were conducted. Summary of leakage detection in the network is shown in Table 7.

TABLE 7

Summary of data and the results of the algorithm for the test gas network

Parameter	Value
Length (km)	274
Pipeline diameter (DN)	100-250
Leak value (m^3/h)	870
Leak size (% flow)	15%
Estimated leak value (m^3/h)	850
The accuracy of estimating the size of the leak (%)	98%
Real location of the leak (km)	48,03
Estimated location of the leak (km)	49,37
Accuracy of the estimate of the leak (%)	99%
Leak location error (±km)	2,34
Assumed location accuracy (±km)	2,57

5. Conclusions

The main advantage of the presented solution is the ability to detect leaks on any of the structures of gas networks. Additionally, this method allows the detection and allocation of leakage, without the need to have the network conditions at the leaks, as is required for most of the other internal leakage detection methods. This allows detection of leaks of any value and place of origin. A very important advantage compared to other methods is also possible to detect leaking in transient states. The results obtained for the gas network confirms earlier results obtained from tests on straight pipeline. A more complicated topology of the network does not negatively affect the quality of the location of the leaking. Leakage is correctly located with the assumed accuracy of calculations, and its value is accurately estimated.

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