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LEAKAGE DETECTION FROM LIQUID TRANSMISSION PIPELINES USING IMPROVED PRESSURE WAVE TECHNIQUE

DIAGNOZOWANIE NIESZCZELNOŚCI W RUROCIĄGACH PRZESYŁOWYCH CIECZY Z WYKORZYSTANIEM ZMODYFIKOWANEJ METODY OPARTEJ NA DETEKCJI FAL CIŚNIENIA*

This paper deals with leak detection in liquid transmission pipelines. It focuses on improving the efficiency of a method based on negative pressure wave detection. A new algorithm for pressure wave monitoring has been proposed. The algorithm is aimed to precisely capture the corresponding characteristic points in the signal sequence of negative pressure waves caused by leakage. It uses median filtering of the calculating deviations of pressure signals measured along the pipeline. Adaptive alarm thresholds with reduced margins, based on statistical analysis of the calculating deviations of pressure signals, were used. Additionally, the algorithm is supported by a set of functions base on the calculation of the cross-correlation of the deviations which represent pressure signals from neighboring transducers. The developed technique has been tested on a physical model of pipeline. The pipeline is 380 meters long and 34 mm in internal diameter, and is made of polyethylene (PEHD) pipes. The medium pumped through the pipeline was water. Tests proved, that the proposed solution is sensitive to small leaks and resistant for false alarm (occurring disturbances). It is also capable of localizing the leak point with satisfactory accuracy, without significant delay.

Keywords: *pipelines, leak detection and location, pressure wave detection.*

Artykuł dotyczy zagadnień diagnozowania wycieków z rurociągów przesyłowych cieczy. Skupia się na polepszaniu skuteczności metody opartej na detekcji fal ciśnienia. Zaproponowano nowy algorytm do monitorowania fal ciśnienia. Algorytm jest ukierunkowany na precyzyjną identyfikację charakterystycznych punktów na przebiegach sygnałów ciśnienia reprezentujących fale wywołane przez zaistniały wyciek. Działanie algorytmu jest oparte o filtrację medianową residuów wyznaczanych dla sygnałów ciśnienia mierzonych wzdłuż rurociągu. Zastosowano adaptacyjne progi alarmowe, obliczane na podstawie analizy statystycznej. Dodatkowo, algorytm wspomagany jest przez wykorzystanie zbioru funkcji korelacji wzajemnej pomiędzy obliczanymi residuami reprezentującymi sygnały ciśnienia z sąsiednich przetworników pomiarowych. Zaproponowane rozwiązanie zostało przetestowane na fizycznym modelu rurociągu, którym tłoczono wodę. Rurociąg ma 380 m długości, średnicę wewnętrzną 34 mm i został wykonany z rur z polietylenu (PEHD). Wyniki badań udowodniły, że proponowane rozwiązanie jest wrażliwe na małe wycieki i odporne na fałszywe alarmy (występujące zakłócenia). Pozwala na zadawalająco dokładną lokalizację wycieku, bez znaczących opóźnień czasowych.

Słowa kluczowe: *rurociągi, wykrywanie i lokalizowanie wycieków, detekcja fal ciśnienia.*

1. Introduction

Even if properly designed, built and serviced a liquid transmission pipeline is exposed to the risk of leakage. In order to minimize the effects and risks caused by leakages, leak detection systems (LDS) are installed in pipelines. The purpose of such systems is to detect, locate, as well as determine the magnitude of leakage. Most popular leak detection systems are developed with the use of diagnostic methods which are based on measurements of internal flow parameters (flow rate, pressure and fluid temperature). In the literature such diagnostic methods are called *indirect (analytical, internal) methods* [1, 3, 9].

The implementation of leakage diagnosis process is a rather complex issue. Existing leak detection methods, whose review can be found in [3, 9], alone do not ensure the execution of all diagnostic tasks. Particular methods are useful only in reference to specified operation state of the pipeline and the characteristics of leakage. Therefore, the elaboration of an effective and reliable leak detection system requires the use of at least several internal methods working concurrently. Such methods are activated by suitable synchronization algorithms which are used to detect a steady or unsteady (transient) state of pipeline operation, as it is mentioned in [9].

In the case of liquid transmission pipelines operating under steady-state conditions, detection and location of leakages can be quite effective with the use of the method based on negative pressure wave detection. At present, thanks to many advantages, it is one of the most widely used methods. However, quite often it proves to be not enough effective. Therefore, a solution to improve the effectiveness of this method has been proposed.

An important element of research into new solutions of leak detection is their verification. The optimal solution would be to conduct such verification using an existing pipeline. In the case of the developed solution, a physical model of a pipeline was used, with water as the pumped medium. An extensive research program with simulated leaks was conducted on the pipeline. The following were taken into account: changes of the operating point of the pipeline, different location and size of simulated leaks, and the way of their increasing (sudden and slow). Carrying out such research program on a real pipeline would be connected with high costs and would suspend its normal exploitation.

The obtained results showed, that the developed solution (algorithm) gives the possibility to improve the effectiveness of the method based on negative pressure wave detection. In particular, it relates to the following elements: improving the level of detecting leakages and

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** the accuracy of pressure wave front identification, and thus, the accuracy of leakage location.

The developed solution (algorithm) can be applied to existing pipelines, as one of the elements of LDS system, and will be co-responsible for the detection and location of leakages. Two types of transmission pipelines: liquid (including crude oil and its products) and gas are taken into account.

2. The method based on negative pressure wave detection

2.1. Description of leakage phenomenon

Assuming that a tight pipeline operates under stationary conditions, pressure and flow rate along the pipe have stabilized values, with low levels of fluctuations.

Example signals of pressure and flow rate in the pipeline without and with leakage are shown in Figure 1a and 1b. The signals are measured at the inlet and outlet, and in the case of pressure, additionally at several points along the pipeline. According to Figure 1a, the state without leakage is represented by period “A”. Indexes “0” in the marking of individual pressure signals indicate their average values in this period. The end of this interval determines the beginning of leak.

Occurrence of leakage changes pressure in the pipeline. At the beginning, a sudden pressure drop takes place in the leak point. Afterwards the pressure drop propagates in both directions of the pipeline in the form of a negative wave. Such a front of wave can be recognized in the pressure signals as a characteristic impulse. In case of sudden leakages (whose flow rate reaches the nominal value in short time after the moment of their occurrence) negative pressure waves have clearly visible fronts. For slowly increasing leakages where pressure changes are milder, fronts of waves have a smoother shape. Behind the front of a wave, the longer is the distance from the leak point, the smaller is the pressure drop in the pipeline (Fig. 1a). The observed pressure drops depend on the size of leakage, its position, and flow conditions.

Some time after the occurrence of leakage flow conditions in the pipeline are stabilized. As it is shown in Figure 1a, such new steady-state conditions are represented by period “C”. Average values for individual pressure signals in this period (marked with “1”) are different from those before the leakage.

Apart from changes in the pressure, the occurrence of leakage results also in the changes of flow in the pipeline. Compared to the state before leakage, the flow rate in the section from the inlet to the leak point is increasing, and the flow rate in the section from the leak point to the outlet is decreasing (Fig. 1b).

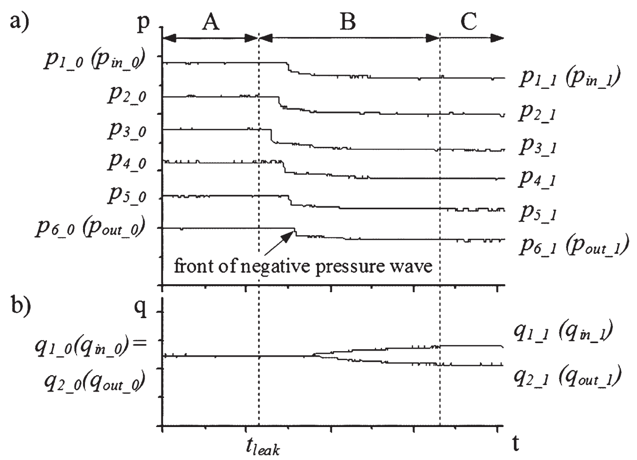

Fig. 1. Signals in the pipeline before and after the occurrence of leakage: a) pressure, b) flow rate; where: t_{leak} – the beginning of leakage

It should be noted that the relationship between changes in the pressure and flow take specific values for various pipelines. Also, one should remember that changes in the pressure and flow can be caused by many other phenomena, not directly related to leak.

2.2. General characteristics of the method

The monitoring of the above described phenomenon of pressure wave propagation is the essence of the method based on pressure wave detection. The method is aimed at detecting and locating leakages. In practice, it is concerned with a single leakage.

The method is based on measurements of pressure signals in pipelines. The analysis of such signals is carried out in order to detect the fronts of propagating pressure waves, considering the fact that such waves at first appear in measuring points located closest to the leakage point and then, with certain delay, in more distant points [8, 9].

The localization of leakage is realized by means of determined moments $t_{wav}(z_n)$. These are moments of detection of pressure wave fronts passing through individual measuring points z_n (see the graph in Figure 2). Knowing the order of the passes of pressure wave fronts through individual measuring points and the distance between the points, it is possible to find the leak point as the intersection of straight lines A-C and C-B, according to the relation (1). The relation is defined as a location formula.

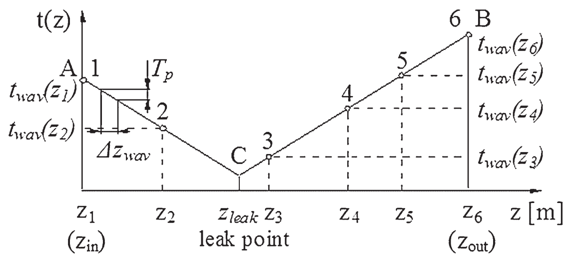

Fig. 2. Detection of pressure waves passing through individual measuring points in relation to time

$$z_{leak} = \frac{a_k}{a_p + a_k} \cdot l + \frac{t_{wav}(z_{in}) - t_{wav}(z_{out})}{a_p + a_k} \tag{1}$$

where: $a_p = 1/c_p$, $a_k = 1/c_k$ – slope coefficients of the straight lines A-C and C-B;

c_p, c_k – average velocities of pressure waves in the sections: $0 < z < z_{leak}$, $z_{leak} < z < l$;

l – length of the pipeline (distance between outermost pressure measurement points z_{in} and z_{out});

$t_{wav}(z_{in})$, $t_{wav}(z_{out})$ – determined moments of pressure wave fronts reaching the points of coordinates $z_{in} = 0$, $z_{out} = l$.

It should be added that in addition to the standard solution offered by the method, techniques of assessing the shape of the pressure wave are used. This way of diagnosis has the additional possibility of estimating the size of the leak. The estimation is based on the analysis of the observed wave amplitude when attenuation on a given section of the pipeline is known. These types of techniques, however, are not of interest to this study.

2.3. Requirements, advantages and disadvantages of the method

The method is relatively inexpensive and easy to use. It can even be applied with the use of only two pressure sensors placed at the inlet and outlet of the pipeline. In this variant, the velocities of pressure waves c_p and c_k, taken into account in the formula (1), respectively in the form of slope coefficients a_p and a_k, must be estimated basing on analytical relationships, i.e. according to (2), given in [4]. A better solution is to use more than two pressure sensors, located at regular intervals along the pipeline. This solution reduces the time of detection and improves the accuracy of location of the leak. In this case pressure waves velocities c_p and c_k, taken into account in the formula (1), are determined empirically, with much greater accuracy. Such assessment is made by measuring the delay of a wave passing between given pressure measurement points on a given section of the pipeline, when the distance between the points is known.

$$c = \frac{1}{\sqrt{\rho\left(\frac{1}{K} + \frac{d}{E \cdot e}\right)}} \tag{2}$$

where: c – velocity of pressure wave,
ρ – liquid density,
K – liquid's modulus of elasticity,
E – modulus of elasticity for pipe material (Young's modulus),
e – pipe wall thickness,
d – inside diameter of pipe.

An important requirement of the method concerning measuring instrumentation and the components of telemetry system is precise time synchronization when measuring pressure at various points along the pipeline. It is also required to use relatively short sampling period of the signals. The sampling period T_p determines the minimum error Δz_{wav} allowed when tracking the location of a pressure wave front (Fig. 2). Depending on the length of the pipeline, the sampling period should be tenths, hundredths or even thousandths of a second.

One should emphasize the speed with which the method works. With non inertial pressure transducers located every few kilometers, detection and location of leaks takes usually a few seconds. Referring to Figure 1, the detection and location of leakage usually does not go beyond the period "B". Such result would be difficult to achieve by means of other methods. For example, the gradient method, which is described in [7], requires the use of measured data related to the period "C", which significantly extends the time of diagnosis.

It must be remembered, however, that if a leak is not immediately detected (e.g. due to a temporary crash or shutdown of the LDS) there will be no other possibility of detection with this method.

Despite undoubted advantages of the method, its effectiveness is often not satisfactory. In practice, it is possible to detect only large leakages (about 1 % of the nominal flow rate – according to information in available studies or even about 3÷5 % – according to information provided by pipeline operators) and locate them not very accurately (ranging from several hundred meters even up to dozens of kilometres).

2.4. Problems to solve

The implementation of the method poses a basic problem with detection of pressure waves propagation as a result of the occurrence of leakage and the exact identification of the front of wave passing through the measuring pressure points z_n.

When detecting pressure waves one should be aware of false alarming and the possibility of miss alarming. The difficulty in identifying the front of negative pressure wave consist in a correct capturing of characteristic points on signal profiles, which mark the beginning of the observed pressure change impulse. These points represent the moments $t_{wav}(z_n)$. The accuracy with which the moments $t_{wav}(z_n)$ are captured, has a major impact on the precision of leak location, according to the formula (1). The level of difficulty in identification of a wave front is essentially determined by its shape and amplitude. These parameters, which characterize the profile of pressure wave propagation, are dependent on the location of the leak, its size and the way it is increasing (which, in turn, depends on the development of damage to the pipeline). The easiest to diagnose are those pressure waves whose fronts are clearly visible and which occur as a result of sudden leakages (whose flow reaches the nominal value in short time after they occur). In leakages increasing slowly, due to the milder character of pressure changes, wave fronts have a smoother shape, which makes their identification difficult and for leakages increasing very slowly the identification may not be possible at all. It is necessary that negative pressure waves on the analyzed signal profiles were characterized by a sufficiently large amplitude in relation to the level of pressure fluctuation, occurring disturbances and measuring noises and the range of sensor accuracy.

Various signal processing methods are used in order to identify the pressure wave front together with moments $t_{wav}(z_n)$. According to [2], the following can be mentioned: fast difference algorithm, Kalman filter, wavelet transform, correlation analysis, and others. An important feature of such methods should be the elimination of noise from the pressure wave signal while retaining its original characteristics. In practice, however, it appears that these techniques show satisfactory performance only for large leaks and with high level of disturbance and noise in the case of small leaks (even less than 2 % of the nominal flow rate), they prove to be rather ineffective [2].

A solution that would improve the effectiveness of the method based on negative pressure wave detection should involve:

- detecting possibly smallest leaks in possibly shortest time,
- locating leaks with high accuracy through more precise determination of moments $t_{wav}(z_n)$,
- extending the applicability of the method to slowly increasing leaks,
- obtaining high level of resistance for false alarms in states with no leakage.

It should be also noted that pressure wave propagation can be also accompanied by other flow phenomena whose impact may change the way it develops. These can include: flow disturbances, multiphase flow, incomplete filling of the pipe, lack of continuity of the stream. Negatively conditioned pressure wave propagation may indicate the presence of changes in the wave velocity, attenuation level and wave front distortion. Thus, when required, the standard solution of the method with the use of the equation (1), should be subjected to an appropriate adjustment.

Additionally it should be also remember that pressure waves caused by a leak may have a strong resemblance to pressure transients, which may be a consequence of technological operations, such as: opening and closing of valves, starting and stopping of pumps, or change of the operating point of the pipeline. It is therefore necessary to use algorithms that reliably differentiate the occurrence of a leak from the other operational cases, as noticed by [9]. These types of algorithms, however, are not of interest to this study.

3. Characteristics of the developed solution

The proposed solution takes into account the previously defined requirements for improving the effectiveness of the method based on negative pressure wave detection. It involves the use of pressure signals p_n from measuring transducers located at the inlet and outlet and a few extra points along the pipeline. The number of all pressure transducers is equal to j. The solution includes a procedure for detecting and locating the leakage. Its key element is an algorithm that is designed to detect the leakage by means of detecting the phenomenon of pressure wave propagation and to provide information about the development of the phenomenon, i.e. to determine moments $t_{wav}(z_n)$. Then, on the basis of the moments $t_{wav}(z_n)$, the leakage is localized according to the formula (1). The algorithm operates in a continuous cycle and generates diagnostic results each time it receives the signals p_n with a sampling period T_p. It is based on the analysis of variables Δp_n that correspond to measured pressure signals p_n. The variables Δp_n represent deviations (residua), calculated as [3, 8]:

$$\Delta p_n{}^k = p_n{}^k - \overline{p}_n{}^k , \qquad (3)$$

where: $p_n{}^k$ – the value of the measured pressure signal in the moment k,

$\overline{p}_n{}^k$ – the reference value in the moment k.

The reference value $\overline{p}_n{}^k$ is calculated by applying filtering based on a recursive filter (4) and referred to as *a recursive averaging with fading memory (exponential smoothing)*.

$$\overline{p}_n{}^k = (\alpha \cdot \overline{p}_n{}^{k-1}) + ((1-\alpha) \cdot p_n{}^k) \qquad (4)$$

where: $\overline{p}_n{}^{k-1}$ – the reference value in the moment $k-1$ resulting from the applied sampling period T_p,

$p_n{}^k$ – the value of the measured pressure signal in the moment k,

α – filter correction factor $0 < \alpha < 1$.

In the existing approach adopted by the author [8], a wave front was detected through the detection of variables Δp_n exceeding the assumed alarm thresholds Th_n marked as "nom" (Fig. 3a). Due to disturbances and measuring noises the alarm thresholds Th_n were set with quite large margins. On the one hand, it prevented the generation of false alarms in states without leakage. On the other hand, it resulted in delays in the detection of wave fronts, which were detected only in the moment $t_{wav}{}^{I}(z_n)$. The wrongly determined moments $t_{wav}{}^{I}(z_n)$ caused, in turn, errors in the location of leakage. With so large alarm threshold margins it was often impossible to detect small leaks, even the sudden ones, not to mention those slowly increasing.

The essence of the proposed solution is an improved way of determining the moments $t_{wav}{}^{II}(z_n)$ (Fig. 3b). For this purpose the algorithm shown in Figure 4 has been elaborated. The algorithm contains the following main elements:

a) median filtering of the variables Δp_n which results in the variables Δpf_n,
b) new way of setting alarm thresholds Thf_n which involves lowering the margins,

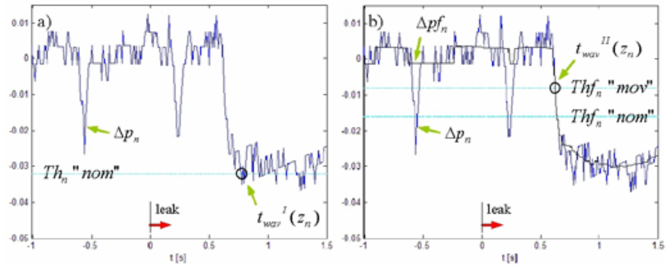

Fig. 3. *Way of determining the moments $t_{wav}(z_n)$ corresponding to front of pressure wave: a) existing approach, b) proposed approach*

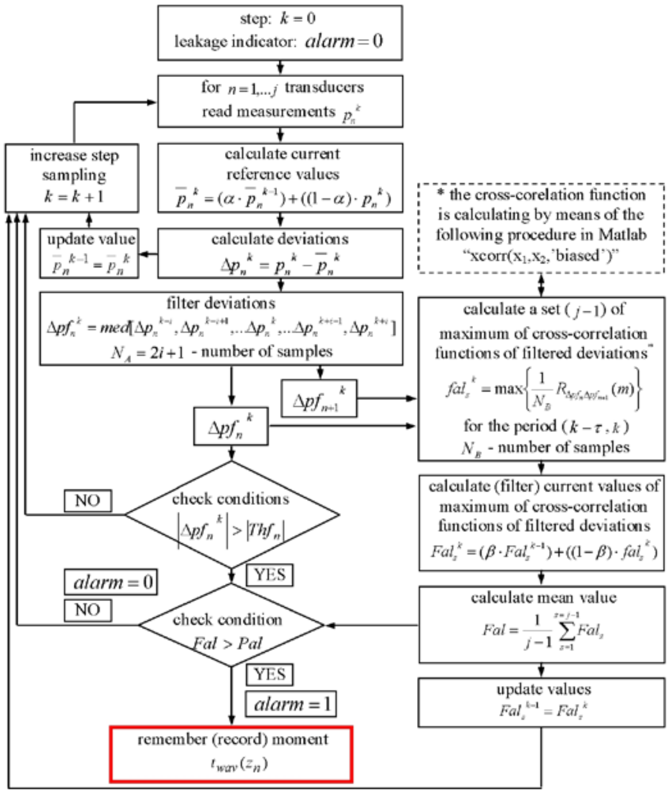

Fig. 4. *Algorithm for leakage detection, with determination of moments $t_{wav}(z_n)$*

c) the calculation of additional function Fal.

Regarding a) Median filtering is particularly useful when the analyzed signal is used for time synchronization. This type of problem occurs in the case of analysis aimed at detecting pressure wave fronts. Median filter is particularly well suited for the removal of impulse noise or disturbance that is characteristic of pressure measurements. At the same time the filter retains signal slope and properly follows its trend. The median filter is implemented using a movable window with the length of $N_A = 2i + 1$ of the input signal samples. The longer is N_A, the longer the impulses which the median filter is able to „delete".

Regarding b) The applied adaptive alarm thresholds Thf_n are calculated on the basis of statistical analysis of variables Δpf_n. In Figure 3b, which shows changes of variable Δpf_n, one can observe a standard alarm threshold marked as "nom". Its value is determined so that it prevents an occurrence of an alarm without leakage. The alarm threshold with lowered margins was marked as "mov". Lowering the margins of alarm thresholds Thf_n helps to improve the accuracy of wave front detection together with its moments $t_{wav}^{II}(z_n)$. In this way it is possible then to enhance the precision of the location of leakage.

Regarding c) The use of lower margins for alarm thresholds can cause false alarms in states without leakage. The possibility of such a situation is taken into account here as a normally occurring state. Therefore, to reliably recognize the states of leakage, the algorithm is further supported by the determination of additional function Fal. This function is the medium value of a set of functions $\{Fal_s\}_{s=1,...,j-1}$ (where j denotes the number of all used pressure transducers) base on the calculation of the cross-correlation of the variables Δpf_n. Particular functions Fal_s in the set are calculated according to a sensitive algorithm presented in [5, 6]. The functions Fal_s are the result of filtration of the functions fal_s, based on a recursive filter, referred to *as recursive averaging with fading memory (exponential smoothing)*. The individual functions fal_s are the maximum values of the cross-correlation function corresponding to the correlation of the variable Δpf_n representing the given measuring point with the variable Δpf_{n+1} which represents the neighbouring measuring point along the pipeline. Cross-correlation functions are calculated with the time shift $k-\tau$. The shift value τ is determined using the velocity of the pressure wave propagation and taking into account the distance between the pressure measuring points that correspond to the variables Δpf_n and Δpf_{n+1}. If the function Fal exceeds its alarm threshold Pal, the occurrence of leakage is confirmed.

4. Verification of the developed solution

4.1. The test stand

The above presented solution has been put through experimental tests. They were conducted on a test stand with a physical model of a pipeline (Fig. 5). The medium pumped through the pipeline was water.

Fig. 5. The pipeline

The pipeline is 380 meters long and is made of polyethylene (PEHD) pipes which are 34 mm in internal diameter and 40 mm in external diameter. It consists of three sections each of which is over one hundred meter long. The sections: 0÷140 m, 140÷280 m and 280÷380 m, are joined with the use of special connectors which have the same diameter as the pipeline. The model pipeline is equipped with standard measuring devices: two electromagnetic flow meters (at the inlet and outlet), six pressure transducers and two thermometers. The pressure transducers are located at 1st, 75th, 141st, 281st, 335th, and 378th meter of the pipeline. They are connected to a PC equipped with a 12 bit A/D converter. In order to simulate leakages, manually operated valves with exchangeable orifices with holes of different diameters were used.

4.2. Test conditions

Before each simulation of leakages the pipeline operated under steady-state conditions. The test simulations included varied leakages: from very fast opening of the valves to slow. The results presented in this work were obtained for the following settings of the operating point of the pipeline: inlet pressure $p_{in\_0} \approx 5.7$ bar, outlet pressure $p_{out\_0} \approx 2.2$ bar, nominal flow rate $q_{in\_0} \approx 95$ l/min, temperature of pumped water ranging from $18°$ C to $22°$ C. Leaks sized 1–10 % of the nominal flow rate q_{in_0} were simulated at selected points, located between the first and the last three pressure sensors, about coordinates: 155, 195 and 235 m. Three experiments were performed for each leakage value. Measured signals were sampled with the frequency of $f_p = 100$ Hz. Such a choice of the frequency value resulted from the velocity of pressure wave propagation in the pipeline, taking also into account the wave front tracking error and the location of the measuring pressure points.

4.3. Results of tests with simulated leaks

An important element of this research was to compare the diagnosis of simulated leaks obtained by means of the existing algorithm, with the results obtained using the developed algorithm.

An appropriate choice of the alarm thresholds Th_n and Thf_n was a crucial element for proper operation of both compared algorithms. The choice was based on the statistical analysis of individual variables Δp_n and Δpf_n in states without leakage. The stabilized values of measured pressure signals with certain levels of fluctuations and noises resulting from the pumping (the flow) of water trough the pipe and the measurement of signals correspond to such steady states of the pipeline operation. Other additional disturbances were not simulated.

The performed analysis consisted of a series of experiments where, for each experiment in the same length of time window, the following statistical parameters were determined: "min" – the minimum value of the variable, "mean" – the average value of the variable and "std" – the standard deviation for the variable. Then the average value "μ" and the standard deviation "σ" of the distributions "mean" and "std" obtained for each experiment were determined. The results of this analysis are presented in the form of Table 1.

The analysis of the results led to the choice of the average values "μ" of the standard deviations "std" for the calculation of the alarm thresholds Th_n and Thf_n. The value of each threshold was determined by the following formulas:

$$Th_n = -b \times \mu(std)\{\Delta p_n\} \quad and \quad Thf_n = -b \times \mu(std)\{\Delta pf_n\} \qquad (5)$$

where: b – a coefficient determined experimentally.

When determining the value of individual alarm thresholds Thf_n it was assumed to use identical values of coefficients b (Table 2). Standard alarm threshold values Thf_n, denoted as "nom", were de-

Table 1. The statistical parameters of the variables Δp_n and Δpf_n

variables		Δp_1	Δp_2	Δp_3	Δp_4	Δp_5	Δp_6
–	min	–0.03682	–0.09311	–0.02935	–0.02645	–0.06246	–0.02769
μ	mean	–0.00004	–0.00004	–0.00002	–0.00003	–0.00003	–0.00003
	std	0.00522	0.00461	0.00427	0.00487	0.00520	0.00597
σ	mean	0.00042	0.00038	0.00035	0.00034	0.00034	0.00035
	std	0.00078	0.00067	0.00056	0.00070	0.00067	0.00066
variables		Δpf_1	Δpf_2	Δpf_3	Δpf_4	Δpf_5	Δpf_6
–	min	–0.01630	–0.01091	–0.01300	–0.01377	–0.01428	–0.01356
μ	mean	0.00044	0.00025	0.00023	0.00011	0.00012	0.00017
	std	0.00253	0.00273	0.00267	0.00317	0.00312	0.00330
σ	mean	0.00051	0.00045	0.00040	0.00040	0.00041	0.00044
	std	0.00037	0.00037	0.00035	0.00047	0.00043	0.00043

Table 2. The values of the alarm thresholds Th_n and Thf_n

alarm thresholds	Th_1	Th_2	Th_3	Th_4	Th_5	Th_6
b=20.5	–0.1069	–0.0946	–0.0875	–0.0999	–0.1067	–0.1224
b=6.5	–0.0339	–0.0300	–0.0277	–0.0317	–0.0338	–0.0388
b=5.0	–0.0261	–0.0231	–0.0213	–0.0244	–0.0260	–0.0298
alarm thresholds	Thf_1	Thf_2	Thf_3	Thf_4	Thf_5	Thf_6
"nom" b=6.5	–0.0165	–0.0177	–0.0174	–0.0206	–0.0203	–0.0214
"mov" b=5.0	–0.0127	–0.0137	–0.0134	–0.0159	–0.0156	–0.0165

termined in such a way that if they exceeded the observed minimum values of the variables Δpf_n they would not trigger the alarm in states without leakage. This situation was obtained for the value of coefficients $b = 6.5$. Then the alarm threshold values Thf_n with reduced margins, marked as "mov", were set with the assumed value of coefficients $b = 5.0$.

Certain problems occurred when determining the value of individual alarm thresholds Th_n. They resulted from large differences between the observed minimum values of individual variables Δp_n. Assuming absence of false alarms in states without leakage and the use of the same values of coefficients b would mean that the value of the coefficients should be as high as $b = 20.5$. This, in turn, could mean that many leaks would not be detected. Hence, in order to compare the accuracy of both algorithms in detecting pressure wave fronts, but ignoring the possibility of false alarms, when determining the alarm thresholds Th_n the same values of coefficients $b = 5.0$ were used as for the alarm thresholds Thf_n.

A similar statistical analysis was carried out in order to determine the alarm threshold Pal. Its value was equal to $Pal = 0.0000115$.

For both algorithms, the following parameter values were used: $\alpha = 0.995$, $\beta = 0.900$, $N_A = 35$, $N_B = 25$ and $\tau = 0.25$ sec. The values were determined experimentally.

When localizing simulated leakages, the velocities of pressure waves c_p and c_k (respectively in the form of slope coefficients a_p and a_k) taken into account in the formula (1) were determined on the basis of two subsets of data: the initial ${}^{(p)}\{z_n, t_{wav}(z_n)\}_{n=1,2,3}$ – for the first three sensors and the final ${}^{(k)}\{z_n, t_{wav}(z_n)\}_{n=4,5,6}$ – for the other three sensors, using the least-squares approximation method.

An influence of changes in the density of pumped medium on changes in the velocity of propagation of pressure waves, resulting from changes in temperature, was not taken into account. Such problem was ignored as the range of temperature changes of water pumped through the pipeline was small and did not cause significant changes in its density. For many liquids, such as crude oil and its products, small temperature changes can cause significant changes in density, and therefore in the velocity of pressure waves.

In addition, an algorithm which, basing on the determined order of the passes of pressure wave fronts through individual measuring points z_n (where: $n = 1,..., j \geq 2$ and outermost pressure measuring points z_1 and z_j are located at the inlet and outlet of pipeline, and therefore $z_1 = z_{in}$ and $z_j = z_{out}$) adjusts subsets of

Table 3. Times of detection "RT" and errors of localization "LE" of simulated leakages obtained by means of the existing algorithm "I" and using the developed algorithm "II"

leakages		sudden				slow(1)					slow(2)				
z_{leak}	q_{leak} [%]	I		II		valve [s]	I		II		valve [s]	I		II	
		RT [s]	LE [m]	RT [s]	LE [m]		RT [s]	LE [m]	RT [s]	LE [m]		RT [s]	LE [m]	RT [s]	LE [m]
155 [m]	1.0	1.52	47.5	1.94	67.8	3.5	–	–	2.13	26.9	6.3	–	–	2.47	57.7
	1.5	0.98	26.0	1.15	30.2	3.9	1.91	-13.3	2.03	-8.7	5.0	3.06	50.1	3.17	58.8
	2.0	1.09	11.1	1.18	-2.9	5.7	2.58	18.3	2.52	16.0	7.1	2.42	-18.8	2.61	-4.4
	2.5	0.75	0.2	0.91	2.1	3.8	1.51	6.1	1.66	14.9	7.8	2.35	23.7	2.38	10.4
	3.0	0.86	1.7	1.03	-1.1	4.0	1.70	-18.7	1.84	-14.8	7.0	2.42	38.9	2.37	-3.4
	3.5	0.85	-1.3	1.01	-0.2	3.8	1.39	11.9	1.49	16.8	8.7	2.28	31.4	2.42	23.6
	4.0	0.75	2.5	0.90	-3.5	5.6	2.23	2.8	2.35	2.8	8.8	3.04	-14.3	3.15	0.2
195 [m]	1.0	2.54	-27.2	1.04	14.5	3.9	–	–	2.45	41.2	10.0	–	–	3.15	-32.5
	1.5	0.79	4.5	0.94	3.4	4.8	1.64	-1.1	1.76	9.3	8.2	1.77	137.4	1.85	13.3
	2.0	0.76	-1.5	0.92	-3.9	5.1	1.82	-2.6	1.90	5.7	9.1	1.61	54.2	1.71	0.1
	2.5	0.72	-3.8	0.84	-7.0	5.2	1.72	10.1	1.77	-7.6	8.8	2.34	32.0	2.23	16.1
	3.0	0.72	-4.6	0.86	-3.3	5.1	2.21	-14.2	2.26	-14.4	8.2	1.99	-9.1	2.00	-5.6
	3.5	0.69	-0.3	0.84	-3.9	5.2	1.91	20.9	1.94	1.4	7.6	1.97	14.3	1.96	22.1
	4.0	0.65	-1.7	0.81	1.1	3.8	1.21	5.1	1.31	0.8	8.6	1.49	-7.9	1.61	14.7
235 [m]	1.0	2.71	-49.2	1.01	34.1	4.3	–	–	1.74	-7.9	8.3	–	–	1.74	-7.9
	1.5	0.88	-9.7	0.96	-3.2	5.0	2.10	-22.3	2.01	-5.2	8.8	2.53	48.2	2.45	-5.0
	2.0	0.70	33.4	0.94	-5.2	4.3	1.78	34.8	2.13	-22.3	7.6	1.44	-14.3	1.43	-3.6
	2.5	0.66	17.0	0.93	-2.7	5.0	2.04	-19.1	2.01	-17.6	8.6	1.92	4.2	1.98	-3.1
	3.0	0.68	0.4	0.96	-5.8	3.7	1.94	-9.9	2.01	-1.2	8.9	2.32	-11.9	2.27	9.0
	3.5	0.80	-6.0	0.95	-5.3	3.9	2.11	0.9	2.26	1.7	9.9	3.22	-14.0	3.54	9.1
	4.0	0.58	-5.1	0.91	0.9	4.5	1.70	-5.8	1.78	6.3	9.2	2.11	-10.5	2.17	-31.0

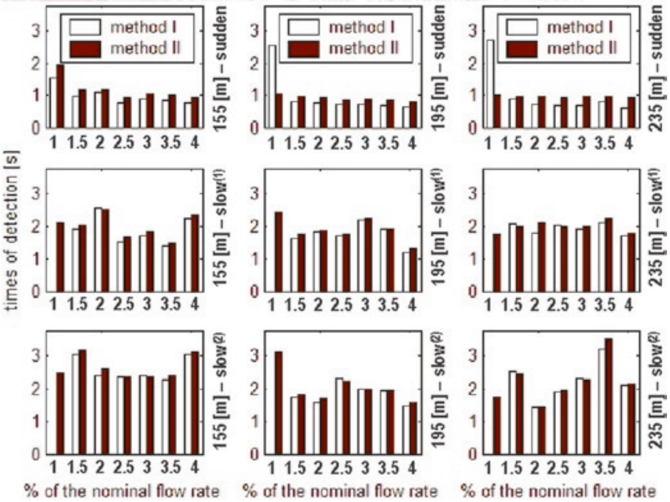

Fig. 6a. Times of detection of simulated leakages obtained by means of the existing algorithm "I" and using the developed algorithm "II"

data: $^{(p)}\{z_n, t_{wav}(z_n)\}_{n=1,\ldots,j-r}$ and $^{(k)}\{z_n, t_{wav}(z_n)\}_{n=j-r+1,\ldots,j}$ which are used for estimation of the velocities of the pressure waves c_p and c_k, taken into account in the formula (1). Otherwise, if a given subset contains only data from a single measuring point z_1 or z_j, it means that the leak place is located only behind a single pressure sensor from the beginning or the end of the pipeline. Then estimation of the pressure wave velocities c_p or c_k is performed analytically using the formula (2).

Table 3 shows the times of detection and the results of location of the simulated leakages, sudden and slow, obtained for the compared algorithms. The results are also shown in the form of diagrams in Figures 6a and 6b. Leakage detection time is defined here as the time from the occurrence of leakage to the moment when the last piece of information necessary to detect and locate the leakage is obtained. The leakage location results are given in the form of errors, i.e. the difference between the determined and the actual place of the leakage. For sudden leakages, which were simulated with the total time of opening the valves from 0.15 to 0.30 seconds, the results refer to average values obtained from three experiments. For slow leakages, the results refer to single experiments, with different total times of opening the valve labelled "slow$^{(1)}$ and "slow$^{(2)}$". The table, additionally, provides the total time of opening the valves for slow leakages, labelled "valve", which ranged from 3.50 to 10.00 seconds.

Additionally, Figure 7 shows profiles of example functions Fal obtained for leakages of 1.5 % of the nominal flow rate which were simulated in the three selected points along the pipeline.

Analyzing the results, one can observe a significant increase in the accuracy of locating sudden leakages when the developed solution is used. Leakage detection and location accuracy in slow leakages was improved, too.

In addition, it can be seen that the developed algorithm is characterized by similar times of leakage detection to the existing algorithm. This was achieved in spite of the application of the median filter which introduces some delay due to the time window containing N_A samples where the current estimate concerns the central sample.

Moreover, the profiles of the functions Fal signal certain possibility concerning further improvement of leakage detection.

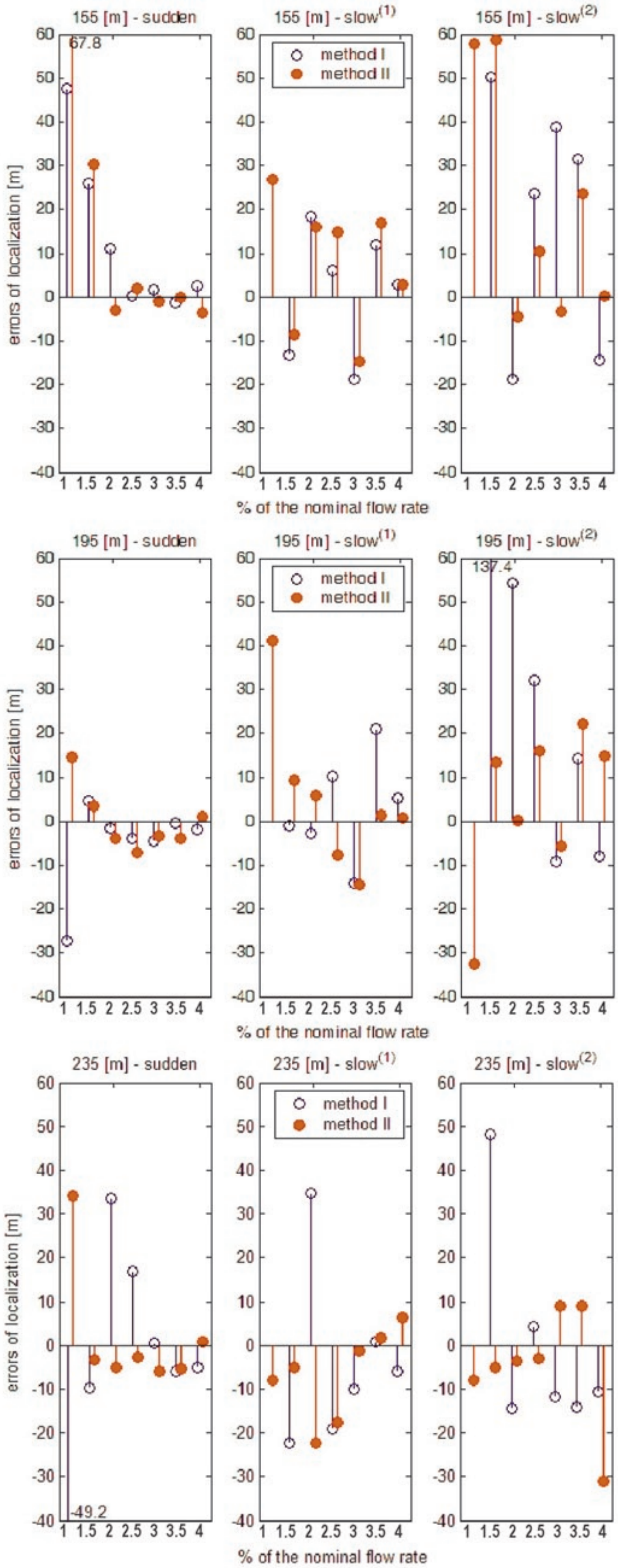

Fig. 6b. Errors of localization (b) of simulated leakages obtained by means of the existing algorithm "I" and using the developed algorithm "II"

5. Conclusion

The solution to improve the effectiveness of the method based on negative pressure wave detection has been developed. It is aimed to

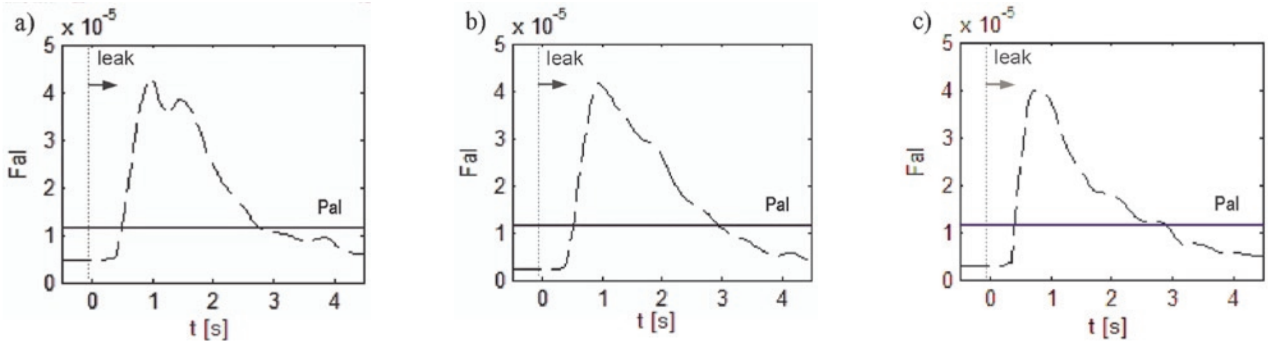

Fig. 7. Functions Fal obtained for sudden leakages of 1.5 % of the nominal flow rate simulated at the points of coordinates: a) 155 m b) 195 m c) 235 m

precisely capture the corresponding characteristic points in the signal sequence of negative pressure waves caused by leakage.

The proposed technique is sensitive to small leaks and resistant to false alarms (occurring disturbances). It is also capable of localizing the leakage point with satisfactory accuracy and without significant delay.

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