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# Analytical system of leak detection and localization for long range liquid pipelines

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**Abstract**

The paper deals with analytical, internal methods based on flow and pressure measurements in a pipeline. A set of computer various algorithms of leak detection and localization was developed. Three groups of algorithms were developed and tested: detection of leak occurrence, rough localization and precise localization. The experiments were based on the testing installation consisting of 380 m of PE pipe of 34 mm diameter, tanks, pump, drain valves for leak simulation, flow and pressure transmitters and data acquisition system. The system accuracy is in the range of 0.09 % – 1.45 %.

**Keywords**: long range pipelines, leak detection, pipeline diagnostics.

## System wykrywania i lokalizacji wycieków w rurociągach cieczy dalekiego zasięgu

**Streszczenie**

W artykule przedstawiono analityczne, wewnętrzne metody wykrywania i lokalizacji wycieków w rurociągach, oparte o pomiary ciśnienia i strumienia natężenia przepływu transportowanego medium. Opracowany został zestaw różnych algorytmów detekcji wycieków, wykorzystując metody: gradientowe, rozkładu ciśnienia wzdłuż rurociągu, bilansu strumienia przepływu tłoczonego medium, analizy prędkości medium. Przedstawiono wyniki testów działania algorytmów dla trzech obszarów detekcji: wykrycia wycieku, zgrubnej lokalizacji i dokładnej lokalizacji położenia wycieku. Testy wykonano dla wycieków przeprowadzonych w doświadczalnej instalacji tłocznej, składającej się z rurociągu PE długości 380 m i srednicy 34 mm, zbiorników, pompy oraz zaworów upustowych przeznaczonych do symulowania wycieków, wyposażonej w czujniki ciśnienia i przepływu oraz system akwizycji danych pomiarowych. Na wstępie przeprowadzono badania algorytmów posługując się matematycznym modelem instalacji doświadczalnej z wbudowanymi generatorami wycieków. W następnej fazie wykorzystano dane pomiarowe zarejestrowane na rzeczywistym obiekcie, które zasilały programy z zaimplementowanymi algorytmami detekcji, przybliżając przebieg wykrywania i lokalizacji wycieków do warunków rzeczywistych. Dokładność systemu mieści się w zakresie 0.09 % – 1.45 %.

**Słowa kluczowe**: rurociągi dalekigo zasięgu, wykrywanie wycieków, diagnostyka rurociągów.

## 1. Introduction

No matter how carefully the pipeline is designed and built, there is always a potential of leaks. Pipeline leak detection systems play therefore a key role in minimization of the occurrence of leaks probability and their impacts. The vast assortment of technologies is available today, the background information is presented in Turkowski, Bratek, Słowikowski (2007).

For the purposes of the leak detection and localization systems the following parameters should be permanently measured:

- pressure $p(0,t)$ at the inlet, $p(L,t)$ at the end, end $p(x_i,t)$ at several/a dozen or so points $i$ (generally at the valve stations), at the distance of $x = x_i$ from the inlet of the pipeline (also as well from the pump),
- volumetric flow rate $q(0,t)$ at the inlet and $q(L,t)$ at the outlet of the pipeline,
- temperature $\tau(x,t)$ at the same places that pressure measurement,
- density of the transported liquid $\rho(0,t)$ at the inlet of the pipeline,

where:

$x$ – distance from the inlet of the pipeline (from the pump)
$t$ - time,
$i$ – number of measurement point,
$L$ – total length of the pipeline.

The refresh rate of the measurement results is $T_s$. The instrument data readings are synchronized and fed via communication lines in digital form to the system.

The procedures of leak detections are mainly based on continuous measurements of pressure and flow-rate, measurements of other variables (temperature, density) are only auxiliary.

## 2. Algorithms of detection and localization of leaks for various transients and identifying and filtering the noises

Change of the number of pumps or pumping capacity, switching to another tank at the inlet or outlet station (so opening and closing valves), so all the typical pipeline operations, are the reason of a sudden pressure disturbance at the pipeline inlet and outlet showing transient behavior of the system. Another difficult problem constitutes the simultaneous pumping of two media which have different physical properties (i.e. subsequently gas oil and diesel oil), it changes the pressure distribution along the pipe.

In such situations the process of the leak detection is much more difficult.

At stable pumping of one sort of liquid two methods are suitable for the leak detection and localization: gradient method and pressure wave method. Both are based on the pressure distribution measurements in the pipeline and are widely described in numerous papers, i.e. Beushausen et al. (2004); Gunawikama, (1996); Sobczak, (2001). The first is based on the analysis of the pressure gradient distribution, the second – on the detection of the pressure wave, moving upstream and downstream the leak at the speed of sound at the moment of leak formation.

Moreover, two another methods effective during transients and technological maneuvers were taken into account. First of them, designated **Z**, developed by H. Siebert (Siebert, 2000), using mathematical model of the pipeline, calculates the pressure distribution $p_s(i,t)$ at subsequent metering stations $i$. The values of pressures at the pipeline inlet and outlet are introduced as the boundary values in calculations. The calculated values $p_s(i,t)$ are compared with the measured ones $p_r(i,t)$. The leak detection and localization is identical as in the gradient method:

$$x_w = L(1-\Delta G_P/\Delta G_K)^{-1} \quad (1)$$

where:

$\Delta G_p, \Delta G_k$ - increase of pressure gradients at the pipeline inlet and outlet after the leak occurrence.

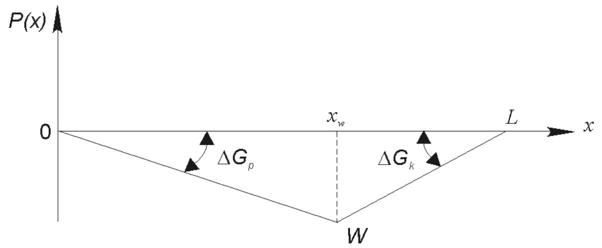


Fig. 1. Distribution of the pressure gradients in the pipeline during the leak occurrence
Rys. 1. Rozkład gradientów ciśniania w rurociągu podczas wycieku

The second method, designated as **W**, takes advantage from the observation, that the sensitivity to the leak is much stronger for the distribution of $w(t)$, than the distribution of $p(t)$.

The method **W** is based on analysis or velocities of the liquid $w(i,t)$, calculated from the mathematical model for the subsequent pipeline segments ($x_{i+1} - x_i$).

In the mathematical model the measured values of pressure $p(i,t)$ are taken into account at all $i$ measurement points.

The analysis of velocity distribution in individual pipeline segments enables the detection of leak existence, determination of the segment $(x_{i+1}$-$x_i)$, where the leak has occurred and, finally, the exact localization of the leak location.

Based on the above mentioned methods, a set of computer various algorithms of leak detection and localization was developed. They can be divided into three groups: identification of the existence of leak, rough approximation of the leak location (segment between measurement points) and precise localization.

The algorithms generate continuously a numerical index (it can be treated as the state of leak tightness of the pipeline) which determines the leak existence after it reaches the determined threshold. The algorithms are denominated as **AB1** and **AB11** (gradient method) **AB2** and **AB21** (so called **Z** method) and **B0** (flow balance method).

Rough approximation procedure AB11_odc (based on the gradient method) indicates the occurrence of the leak and gives information in which segment of pipeline it has happened.

The precise localization procedures, activated after the leak has been detected, calculate the precise leak localization. They are procedures **G1**, **G2**, **G3**, and **I** (based on the gradient method, they use various numbers and modes of evaluation of the measuring points), procedure **V** (detection of the pressure shock wave) and procedure **W** (modeling the velocities of the liquid).

## 3. Preliminary tests of the leak detection and localization algorithms based on the parameters of the physical model

The physical model was built at the Mechanical Faculty of the Bialystok University of Technology. The model consists of a pump, valves, tanks at the inlet and outlet, 380 m of polyethylene pipeline of 34 mm diameter; it is described in details in Ostapkowicz (2007).

The mathematical model used took into account the static and dynamic characteristics of the water flowing through the PE pipe as in the physical model. The pump, valves and receiving tank together with interactions between them was also modeled. The detailed procedure of modeling is described in Sobczak et al. (2007).

The pipe is a typical object with distributed constants. In order to describe the pipeline dynamics for the modeling purposes, the pipeline was arbitrarily divided into 126 sections at $x_i$ points where measuring transmitters were installed on the pipeline physical model. It enabled the direct comparison of the pressure and flow rate values obtained by simulation with the real ones, recorded in the pipeline physical model. Additionally, each pipeline section between $x_i$ and $x_{i+1}$ points was divided into shorter, equal parts $\Delta x_j$.

Moreover, in the mathematical model of the installation, in several places, the models generating leaks were introduced. In such a way an effective tool was obtained which enabled simulations of various states of the system performance both in steady state and during transients and during leak occurrence.

During creation of the model special emphasis was put on the possibility of precise calculation of the liquid flow velocities at particular metering stations (the velocities are not measured at these points) based on the measured pressures at these points and volumetric flow rates at the inlet and outlet.

The structure and the model parameters were carefully verified, to comply exactly with parameters of the physical, experimental installation built and operated by the Bialystok University of Technology.

To verify the mathematical model, the situations which can appear during the pipeline operation at steady state and transients appearing during changes of the pump capacity were simulated using the model. Also the leaks in two points at the distance 115 and 195 m from inlet were simulated at steady state and during transients.

Examples of localization results based on **W** algorithm are presented in Tabs. 1 and 2. In the tables column $q_u$ is the leak rate as percentage of the nominal flow, $x_u$ – leak position (m), $x_{uw}$ – calculated leak position (m), $t_1$ – time between the leak occurrence and start of the leak detection procedure.

Tab. 1. Leak localization in steady state
Tab. 1. Lokalizacja wycieku w stanie ustalonym

| $x_u$ (m) | $q_u$ (%) | $x_{uw}$ (m) | $t_1$ (s) |
|---|---|---|---|
| 115 | 2 | 115.09 | 10 |
| 115 | 5 | 115.08 | 10 |
| 195 | 2 | 195.13 | 10 |
| 195 | 5 | 195.11 | 10 |

Tab. 2. Leak localization directly after the 10 % change the pump capacity
Tab. 2. Lokalizacja wycieku po zmianie wydatku pompy o 10 %

| $x_u$ (m) | $q_u$ (%) | $x_{uw}$ (m) | $t_1$ (s) |
|---|---|---|---|
| 115 | 2 | 115.12 | 12 |
| 115 | 5 | 115.11 | 12 |
| 195 | 2 | 195.12 | 12 |
| 195 | 5 | 195.14 | 12 |

The obtainment of such high precision results from the fact that the simulations were proceeded using only mathematical calculations, without influence of fluctuations and drift of the measuring instruments existing in the physical system.

## 4. Investigation of the efficiency of filtration methods

All the algorithms of leak detection and localization are very sensitive to fluctuations of measuring signals resulting from the instruments noise and systematic errors of instruments. The quality of the measurement data is therefore of the greatest importance.

Before the measuring signals are utilized through the system they have to be filtered to decrease the noise influence on the system efficiency.

The low pass filters and the time averaging of signals for various time constants were investigated. The most effective method was double filtration with time averaging with the time constant 1 s and 10 s. A shorter time constant is used to detect the leak occurrence fast, and the higher – to stabilize measurement results for the purpose of precise leak localization.

## 5. Testing the detection and localization algorithms based on the recorded data

Further tests of the system were carried out basing on the data obtained from the physical experimental installation made of a 380 m long PE pipe of internal diameter $d=34$ mm. In some points there were installed small drain valves for simulations of the leaks.

The experimental facility is equipped with a computerized data acquisition system ensuring recording the data from measuring transmitters and actuators at the rate up to 100 kHz/channel and input resolution equal to 0,02% of the range.

At this stage there were no possibility to gain the data from the real transport pipeline adequate from point of view of completeness, accuracy and sampling rate. The comparison of the real long range pipelines with the experimental facility built in Bialystok, shows essential differences between parameters of the installation itself (material, diameter, length) and between pumped liquids (differences in density and viscosity of the water in the model and crude oil or fuels in real pipelines). However, the physical phenomena occurring during liquid transport is in both cases similar, so the dynamics of the processes induced by the leak (real leak in the real pipeline, simulated leak in the model installation) will be also similar.

## 6. Experiments carried out in the experimental installation

During the experiments the leaks were simulated in the experimental installation with use of drain valves. During these leaks all the data (pressures along the pipe, flow rates at the inlet and outlet, state of the valves) was recorded.

The experiments were carried out at the pump capacity 80 % under steady state conditions. Usually the outlet was throttled. The leaks were simulated at several points and leak rates, the values are given in Tab. 3.

A few methods of leak detection were investigated. These methods can be divided into three groups:

- detection of leak occurrence
- rough localization
- precise localization

The first group of methods gives only the information/alarm that a leek has occurred, rough localization enables determining the segment in which the leak has ocurred (between two measuring points). The third group enables the precise localization of the leak.

The detection algorithms (gradient methods, pressure wave method, pressure distribution and velocity distribution methods) were implemented in the Matlab environment. The programs (group 1 and 2) were continuously fed with the source data recorded at the experimental facility during leak simulations. After the leak detection the programs from the third group (precise localization) were fed with a selected set of data. This approach is similar to the procedure of leak localization in the real system, where the data is collected on-line.

The results of the tests are presented in Figs. 2 and 3. They show the examples of the leak indexes generated by the algorithms of the leak detection and rough localization.

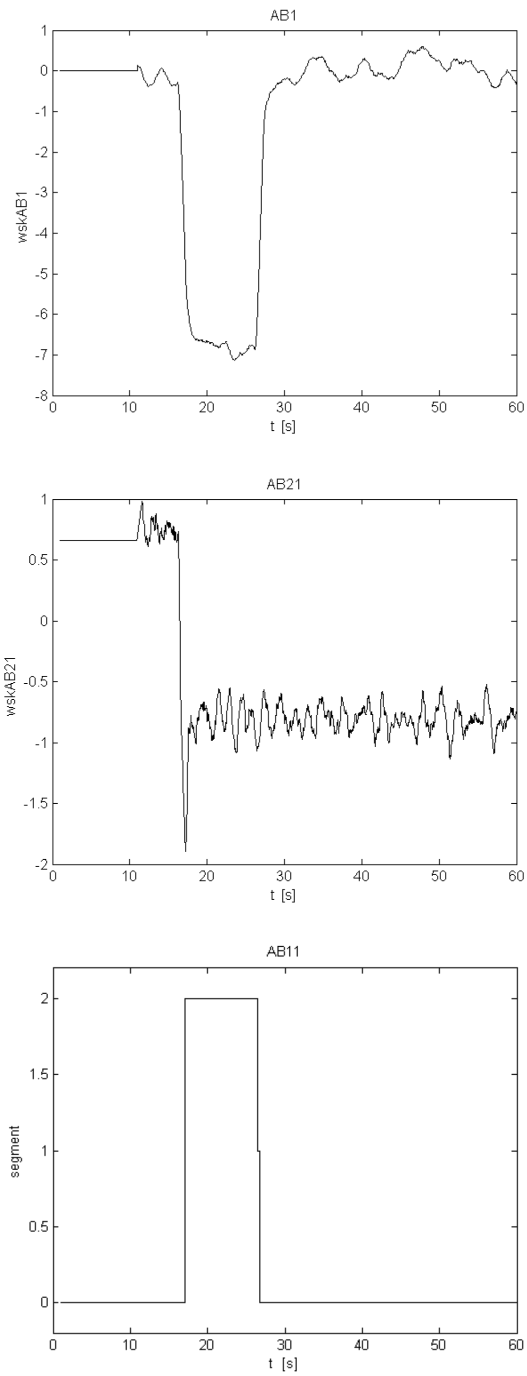


Fig. 2. Indexes of leak detection (AB1, AB21) and the index of rough localization (AB11) for a given set of recorded data. The leak was simulated in the 16th second of data recording

Rys. 2. Wskaźniki wykrywania wycieku (AB1, AB21) oraz wskaźnik zgrubnej lokalizacji (AB11) dla przykładowego zestawu zarejestrowanych danych. Wyciek zasymulowanoo w 16-tej sekundzie rejestracji

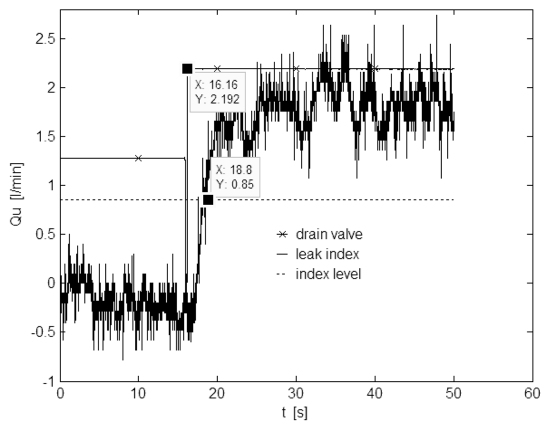


Fig. 3. Leak identification using B0 method. The graph presents the signal of opening a drain valve and values of B0 index for one of the simulated leaks. The delay between the leak occurrence and its identification was ca. 2.5 s

Rys. 3. Wykrywanie wycieku metodą B0. Na wykresie przedstawiono przebiegi stanu otwarcia zaworu upustowego i wskaźnika B0 dla jednego z symulowanych wycieków. Opóźnienie pomiędzy pojawieniem się wycieku a jego detekcją wyniosło około 2.5 s

The results of the localization calculated by the precise localization algorithms with use of the methods: gradient (**G1**, **G2**, **G3**), pressure distribution (**I**) and pressure wave (**V**) are presented in Tab. 3. In the table *Xu* denotes the calculated leak localization. The best results are marked with **bold** characters. Doubtful results are replaced by symbol "**??**". The averaging time was equal to 10 s, the comparative data sample interval equaled 21 s.

Tab. 3. The results of the precise leak localizations obtained with use of various methods

Tab. 3. Wyniki dokładnej lokalizacji wycieku uzyskany przy użyciu różnych metod wykrywania

| nr | Method | | | | leak flow rate | true leak locali-zation |
|---|---|---|---|---|---|---|
| | G1 *Xu* (m) | G3 *Xu* (m) | I *Xu* (m) | V *Xu* (m) | % $Q_n$ | |
| 1 | 104,84 | 111,62 | **113,13** | **113,49** | 2 | 115 |
| 2 | **196,67** | 192,00 | 191,05 | 188,73 | 2 | 195 |
| 3 | **274,75** | 271,28 | 270,25 | 266,67 | 2 | 275 |
| 4 | 104,93 | 113,33 | **113,42** | 112,86 | 4 | 115 |
| 5 | 190,31 | 192,15 | **192,40** | 191,06 | 4 | 195 |
| 6 | 270,26 | 272,84 | **273,15** | 269,02 | 4 | 275 |
| 7 | 152,52 | 152,87 | 152,77 | **155,52** | 8 | 155 |
| 8 | 149,41 | 150,96 | 151,07 | **153,70** | 9 | 155 |
| 9 | 152,09 | 152,43 | 152,32 | **154,48** | 8 | 155 |
| 10 | 148,69 | 150,49 | 150,64 | **153,64** | 9 | 155 |
| 11 | 105,67 | 109,74 | 111,01 | **116,09** | 2 | 115 |
| 12 | 197,11 | **193,73** | 192,90 | 192,42 | 2 | 195 |
| 13 | 277,67 | **273,33** | 272,46 | ?? | 2 | 275 |
| 14 | 107,81 | 112,69 | 112,53 | **113,37** | 4 | 115 |
| 15 | 190,27 | 191,82 | 191,99 | **193,64** | 4 | 195 |
| 16 | 268,93 | 273,03 | **273,23** | 272,55 | 4 | 275 |

The results depend on the filtration parameters, the interval between comparative data samples as well as the time point of algorithms calculations.

For leak detection and rough localization there was used filtration by averaging during the 1 s period in conjunction with comparative data sample window width close to the pipe dynamics loss parameter. It ensured fast reaction to the leak and stable calculation process.

For precise localization higher values of averaging time were used. It did not, however, eliminated the scatter of the results completely.

## 7. Conclusions

- The indexes built and calculated in the algorithms of leak detection show a stable behavior during the leak occurrence. They allow precise distinguishing between the leak and no-leak state. The differences between the index values in leak and no-leak state are in the range from one to two orders of the magnitude. Some of them (i.e. AB21) should be, however, treated only as supplementary or used for calibration of pressure transmitters only.
- The methods of rough localization showed the segment where the leak occurred correctly each time.
- The places of the leak calculated and indicated through the localization algorithms were situated near the true simulated leak, the best theoretical results differed from the real ones of ca. 0,5–1,8 m.
- The instability of the leak detection algorithms was observed for the small rates of leak (2% of actual line capacity). It concerns mainly the V method which sometimes could not cope with the problem and did not give any reasonable results. Much better results were obtained at higher leak flow rates.
- Various principles of leak detection give various precision. It may be expedient to implement in the system several different algorithms functioning concurrently.
- The accuracy of leak localization becomes better when the distance between inlet and leak rises.

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