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Oil Product Loss Identification per Pressure Variations in Time at Four Controlled Pipe Cross-Sections

T. E. Mamonova

Tomsk Polytechnic University, Tomsk, Russia
e-mail: mamte@sibmail.com

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Abstract—A loss detection method based on the analysis of pipeline's time-varying hydraulic characteristics is offered. A device for measuring pressure variations at controlled cross-sections is described. The equations for mass flow and loss coordinates calculation according to the method proposed are derived. The method was investigated using COMSOL Multiphysics 3.5 software. The paper shows that both the method and the associated equations are efficient for pipeline loss detection.

Keywords: oil pipeline, sensor of pressure, hydraulic oil pipeline profile, loss in the pipeline

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While mail oil pipeline operation, one of the most pressing and complex tasks is timely loss detection as well as their mass flow and coordinates calculation. One of the most acute problems is pipeline illegal tapping used for oil product stealing as it can lead to heavy economic and ecological expenses. It was established, for example, that about 2.5 mln. RUB are necessary for a pipeline tie-in while ecological damage is almost impossible to assess [1].

Complexity of illegal tapping detection is as follows.

1. Duration of illegal tie-in installation is not great and it can be about a minute or several seconds.

2. The loss flow is considerably small, which results in small pressure variation when they evolve; this event based on used sensors of pressure are often difficult to detect over insufficient sensitivity of the latters.

Loss detection methods used nowadays at oil pipeline linear parts are mainly low-sensitive to intensity variations of occurred losses and are intended for their location detection [3]. Methods applied when there is a possibility to detect a low-intensity loss, for example, an acoustic emission method are expensive.

In the paper we propose a method for mass loss flow and coordinate detection which is based on the analysis of hydraulic characteristics oil pipeline per pressure variations in time at controlled pipe cross-sections. A prototype of the proposed method is a hydraulic loss location method described in [2]. In this method, differential sensors of pressure are used which measure pressure variation at basis segment ends selected close to oil pump stations at the beginning and end of the pipe. The coordinate ξ and flow Q of loss in accordance with the hydraulic location method are calculated

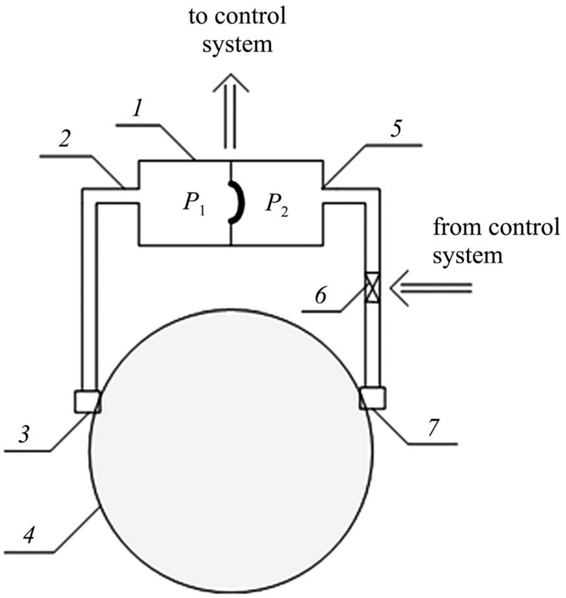

Fig. 1. Scheme of variation measurement device location in pressure time at controlled oil pipeline cross-sections with loss and without it and its hydraulic slopes.

based on formulae [6]:

$$\xi = l \times \frac{|\delta i_2|}{|\delta i_1| + |\delta i_2|}, \quad Q = \frac{|\delta i_1 + \delta i_2|}{\left(\frac{\partial i}{\partial Q}\right)_{Q_0}}, \tag{1}$$

where l is an oil pipeline length [m], i is a hydraulic slope of pipe [m], δi is a variation of hydraulic slope of oil pipeline [m], $\left(\frac{\partial i}{\partial Q}\right)_{Q_0}$ are partial derivatives from the function $i(Q)$ with respect to Q calculated at rated flow Q_0 which can be determined theoretically by differentiation of the formula for hydraulic slope $i(Q)$ dependence or experimentally while studying variations of the hydraulic slope of an oil pipeline section at its capacity variations.

The following can be referred to disadvantages of the hydraulic location method.

1. It is necessary to have prior knowledge of rated or current capacity for oil product pumping for computing loss flow with respect to (1).

2. A high accuracy of differential head variation measurement is required as pressure variation values at ends of the selected basis segments are relatively small.

3. As differential gages to small pressure variation at basis segments ends are limited in sensitivity, the method accuracy is reduced at loss intensity decrease.

The method proposed within the paper is an improved modification of the hydraulic location method as it removes all the listed disadvantages. We study an oil pipeline section located between two oil pump stations with a certain geometric profile operated in a stationary mode without gravity sections, loop lines, and offshoots and its transports a uniform oil product. Special devices are installed at four cross-sections along the oil pipeline which measure pressure variation in time $\Delta P(t)$ at controlled pipe cross-sections. The device for pressure difference variation in time a scheme of which is shown in Fig. 1 is developed by the author and operates as follows [4].

We use an instrument in which differential pressure sensor *1* is used. We have measurement input *2* and controlled input *5*. Measurement input *3* through fitting is connected to pipeline *4*; in this cross-section though controlled valve *6* the controlled input through fitting *7* is connected to the pipeline. When the valve is opened, zero is set in the measurement device; when the valve

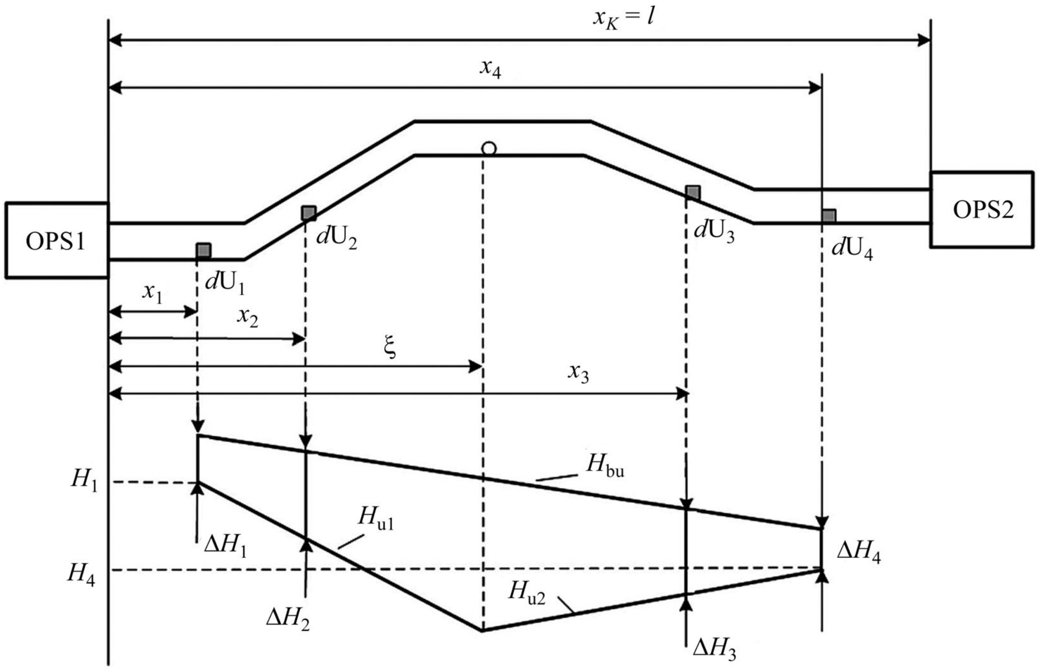

Fig. 2. Scheme of variation measurement device location in pressure time at controlled oil pipeline cross-sections with loss and without it and its hydraulic slopes.

is closed, pressure variation in the controlled pipe cross-section is measured by the measurement input. Measurement occurs in time. We propose a periodic variation of zero device level.

When oil products are transported in pipelines there is a hydraulic noise P_{n} which can be conditioned by vortex formation or fluid flow inhomogeneities close to solid boundaries (vortex noise), elastic structure self-oscillations in fluid or fluid cavitation as it loses strength when pressure is reduced, etc.

When a pressure variation value in controlled cross-sections $\Delta P(t) \geq P_{\mathrm{n}}$ there is either oil product pumping mode change or there is a loss on a controlled oil product section. Based on the readings of the devices above and considering oil product parameters (density and pumping speed) and oil pipeline (hydraulic resistance coefficient and geometrical pipe profile), we can detect loss parameters from the oil pipeline (coordinates and mass flow).

A geometrical method was used for derivation of computing formulae in accordance with the proposed modified method of hydraulic location intended for loss parameter detection. A computing scheme shown on Fig. 2 is used. Here $H(x)$ is a hydraulic characteristic (hydraulic slope) computed according to [5]:

$$H(x) = \frac{P(x)}{\rho g} + z(x),$$

where $\frac{P(x)}{\rho g}$ is a piezometric pipeline profile [m], $z(x)$ is a geometrical pipeline profile [m], $P(x)$ is pressure along the pipeline [Pa], ρ is density of product pumping [kg/m^3], g is gravity acceleration [m/s^2].

It is expected that oil pump stations are set as per coordinates $x_0 = 0$ m and $x_{\mathrm{K}} = l$ m respectively. Along the oil pipeline in cross-sections x_1, x_2, x_3, and x_4 are set devices measuring variations in pressure time at the given pipe cross-sections $\Delta P_1(t), \Delta P_2(t), \Delta P_3(t)$ and $\Delta P_4(t)$; the first pair is set at the beginning of the pipe; the second, at the end so that a site of suspected loss is between the second and third devices.

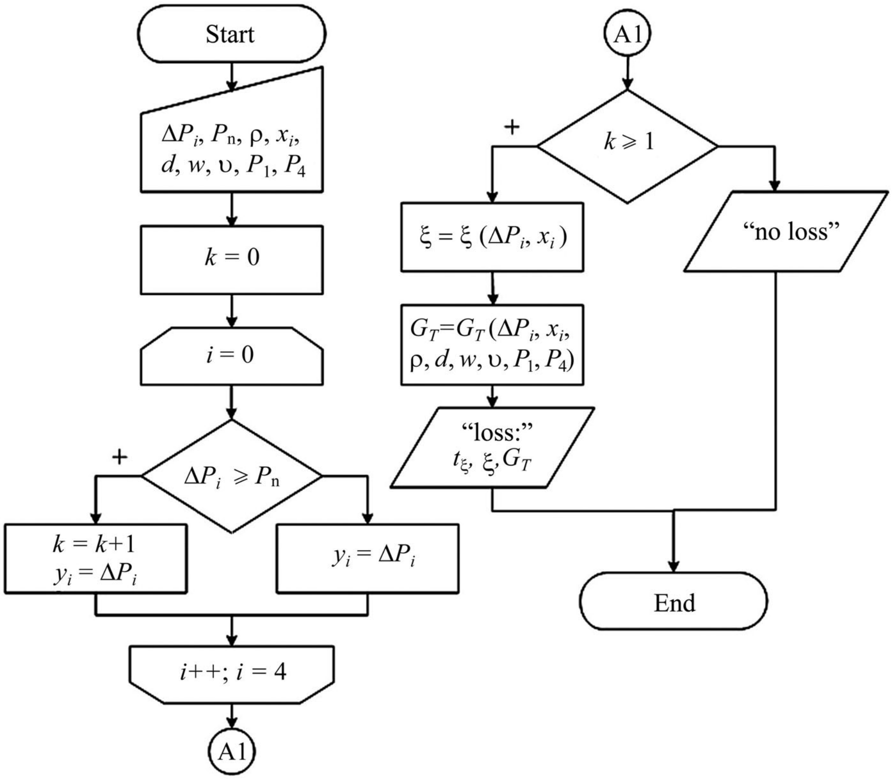

Fig. 3. Information processing algorithm for loss parameters detection in the pipeline.

Formulae for coordinate and mass loss flow detection were received as follows:

$$\xi = \frac{(x_2 - x_1) \times (x_4 \times \Delta P_3 - x_3 \times \Delta P_4) - (x_4 - x_3)(x_2 \times \Delta P_1 - x_1 \times \Delta P_2)}{(x_2 - x_1) \times (\Delta P_3 - \Delta P_4) + (x_4 - x_3) \times (\Delta P_2 - \Delta P_1)}, \tag{2}$$

$$G_{\text{T}} = \frac{\pi \times d^2}{16} \times \sqrt{2 \times d \times \rho} \times \left[\sqrt{\frac{1}{\lambda_1}} \times \sqrt{\frac{P_1 - P_4 + \rho g \times (z_1 - z_4)}{x_4 - x_1} + \frac{\Delta P_2 \times (\Delta P_2 - \Delta P_1)}{x_2 \times (\Delta P_2 - \Delta P_1) - x_1 \times \Delta P_2 + x_2 \times \Delta P_1}} - \sqrt{\frac{1}{\lambda_2}} \times \sqrt{\frac{P_1 - P_4 + \rho g \times (z_1 - z_4)}{x_4 - x_1}} \right], \tag{3}$$

where $P(x)$ is pressure along the pipeline [Pa], P_1, P_4 are absolute pressures in the first and fourth controlled cross-sections [Pa], ΔP_n is difference in pressure time at controlled pipeline cross-sections [Pa], x_n is a coordinate of device location for difference measurement in pressure time [m], z_n is a geometrical pipeline profile represented by pipe height above the horizon at device location sites [m], $n = 1 \div 4$ is a number of devices necessary for difference identification in pressure time, ρ is density of product pumping [kg/m^3], g is gravity acceleration [m/s^2], d is an internal pipe diameter [m], $\lambda = \lambda(\text{Re}, \varepsilon)$ is a pipeline friction coefficient being a dimensionless quantity, $\text{Re} = \frac{w \times d}{\upsilon}$ is a Reynolds number, ε is a relative roughness of internal pipeline surface, w is a speed of oil product pumping along the cross-section [m/s], υ is kinematic oil product viscosity [m^2/s], λ_1, λ_2 is a coefficient before and after loss detection respectively.

We developed an information processing algorithm for loss parameters detection represented in Fig. 3 for testing the method operability and computing formulae (2) and (3).

Table 1. Pipeline and pipeline fluid parameters

Notation	Name	Value	Unit measurement
	Pipeline parameters		
l	length	100	m
d	diameter	0.1	m
S	sectional area	7.85×10^{-3}	m^2
P_1	pressure at the pipe beginning	1	MPa
P_4	pressure at the pipe end	0.7	MPa
	Pipeline fluid parameters		
ρ	density	817	$\mathrm{kg/m}^3$
w	motion speed	1.2	m/s
υ	kinematic viscosity	0.98×10^{-6}	m^2/s
C	sound propagation velocity	975	m/s

Table 2. Simulation experiment results

Geometrical values Pipe profile loss parameters		Packless rectilinear	Packed rectilinear
Specified values in COMSOL Multiphysics 3.5	ξ, m	55	55
	G_{T}, kg/cm	6.46	6.46
Computing values of loss parameters by formulae (1)	ξ, m	56.23	57.08
	Q, kg/cm	–	–
	$\delta\xi$, %	2.24	3.78
	δQ, %	–	–
Computing values of loss parameters by formulae (2) and (3)	ξ, m	55.11	55.14
	G_{T}, kg/cm	6.48	6.33
	$\delta\xi$, %	0.20	0.25
	δG_{T}, %	0.23	0.75

The input data of the presented algorithm are pipeline and pumping fluid parameters, absolute pressure sensor readings, device location coordinates, readings of the devices above, and a level of hydraulic noise for the controlled pipeline section. The counter i is in charge of a counting number of the respondent device, the counter k is responsible for device reading availability higher than the established level of hydraulic noise. If at least at one device there is an increased value of the pressure time variation, then the system will make signals to a loss availability and produce computing data on coordinate and mass loss flow values. The algorithm operates with the periodicity established for variation measurement device operation in pressure time at pipe cross-sections.

Within the offered paper the described algorithm was implemented in MatLab. We made a simulation experiment of pipelines without and with a loss and received pressure difference in controlled cross-sections which we were used for loss parameters computation. It is to be noted that computation in real-time pipelines is used in the program with great time expenses; that was why we made the experiment for the scale pipeline the parameters of which were taken from [5] and represented in Table 1.

Simulation results are in Table 2.

According to the simulation experiment, the maximum error of loss parameters computation on the lines of offered method and formulae corresponding to the method is 0.25% for the loss coordinate and 0.75% for the mass loss flow in the packed rectilinear pipeline. The maximum error of loss parameters computation by the experimental method is 3.78% also for the packed rectilinear.

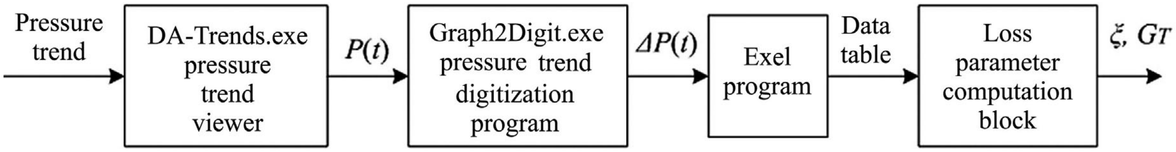

Fig. 4. Data processing algorithm.

We also conducted an experiment on summer diesel fuel transportation pipeline with density $\rho = 860$ kg/m^3. The loss was simulated by turning on the tap and intensity was regulated by a washer d_R of different size. The pipe diameter was $d = 0.530$ m, oil product uptake was made at the site with coordinate $\xi = 125.71 \times 10^3$ m at $d_\mathrm{R} = 10 \times 10^{-3}$ m and $d_\mathrm{R} = 20 \times 10^{-3}$ m.

Coordinates of four pressor sensors location on the pipeline with the loss are specified in Table 3.

All data were processed in accordance with the algorithm represented in Fig. 4.

Loss parameters were computed using formulae (2) and (3). Computation results are in Table 4. Specified values of mass loss flow were computed using formulae [7]:

$$G_\mathrm{T} = \rho\mu\frac{\pi \times d_\mathrm{R}^2}{4} \times \sqrt{2gH_\xi}, \tag{4}$$

where μ is an orifice coefficient (let it be equal to 1), H_ξ is a value of hydraulic head at the site of loss [m].

Error computation of coordinate and the coordinate $\delta\xi$ and mass flow δG_T of the loss are computed by formulae:

$$\delta\xi = \frac{|\xi_p - \xi_r|}{\xi_r} \times 100~\%, \quad \delta G_\mathrm{T} = \frac{|G_{\mathrm{T}p} - G_{\mathrm{T}r}|}{G_{\mathrm{T}r}} \times 100~\%, \tag{5}$$

where $\xi_p, G_{\mathrm{T}p}$ are computed values of the coordinate and mass flow obtained using formulae (2) and (3); $\xi_r, G_{\mathrm{T}r}$ are standard values of the coordinate and mass flow obtained experimentally and using (4).

Table 3. Coordinates of four pressor sensors location on the pipeline with the loss and distance between them

nos.	Pressor sensors location coordinates, m			
	x_1	x_2	x_3	x_4
1	27 339.49	28 139.49	149 636.40	150 480.12
2	27 339.49	28 139.49	143 692.00	150 480.12
3	27 339.49	90 279.93	149 636.40	150 480.12
4	27 339.49	90 279.93	143 864.52	150 480.12
5	90 279.93	91 077.42	143 692.00	143 864.52

Table 4. Loss parameters computation results by the modified method at hydraulic loss location at pressure sensor coordinate variation

Specified values	nos.	Computing values		Computation errors			
		$\xi \times 10^3$, m	G_T, kg/h	Δ_ξ, m	δ_ξ, %	Δ_{G_T}, kg/h	δ_{G_T}, %
$\xi = 125.71 \times 10^3$, m	1	125.627	16.500	83	0.066	2.774	14.394
$d_\mathrm{R} = 20 \times 10^{-3}$, m	2	125.975	22.667	265	0.211	3.393	17.605
$G_\mathrm{T} = 19.74$, kg/h	3	125.758	17.050	48	0.038	2.224	11.539
$\xi = 125.71 \times 10^3$, m	1	125.572	9.023	138	0.110	1.845	16.976
$d_\mathrm{R} = 10 \times 10^{-3}$, m	2	126.032	13.032	322	0.256	3.381	19.913
$G_\mathrm{T} = 10.868$, kg/h	3	125.694	9.813	16	0.013	1.055	9.704

Experimental research results specified in Table 4 pointed that for determination of location and mass loss flow from the pipeline (2) and (3) are applicable in practice.

1. CONCLUSIONS

The offered method for loss determination based on the analysis of hydraulic pipeline characteristics using difference measurement devices in time established at four pipe cross-sections is the best improved modification of the hydraulic loss location method as it allows dynamically locating for a low-intensity loss occurred in the pipeline and computing its parameters. The method is more sensitive to pipe pressure variations as it uses more sensitive devices in pressure time. Device sensitivity is increased by measurement in the same cross-section of the difference pipe in pressure time and displacement from measurement sensitivity from physical values of the differential pressor sensor.

The conducted simulation and practical experiments showed that the offered method and computing formulae obtained in accordance with it are operative.

The offered method can be used in systems of pipeline diagnostics, occurred loss location, and their parameters determination.

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