

# On Leak Localization in the Main Branched and Simple Inclined Gas Pipelines

T. Davitashvili and G. Gubelidze

**Abstract**—In this paper two mathematical models for definition of gas accidental escape localization in the gas pipelines are suggested. The first model was created for leak localization in the horizontal branched pipeline and second one for leak detection in inclined section of the main gas pipeline. The algorithm of leak localization in the branched pipeline did not demand on knowledge of corresponding initial hydraulic parameters at entrance and ending points of each sections of pipeline. For detection of the damaged section and then leak localization in this section special functions and equations have been constructed. Some results of calculations for compound pipelines having two, four and five sections are presented. Also a method and formula for the leak localization in the simple inclined section of the main gas pipeline are suggested. Some results of numerical calculations defining localization of gas escape for the inclined pipeline are presented.

**Keywords**—Branched and inclined gas pipelines, leak detection, mathematical modeling.

## I. INTRODUCTION

FOR the last decades natural gas consumption became very intensive in the many countries of the world and it is expected that natural gas expenditure will increase in the nearest future. For example natural gas consumption in the US is expected to increase 50% during the next 20 years [1]-[3]. Nowadays pipelines become the main practical means for natural gas transportation worldwide [2], [4], but it should be noted that at the same time the gas delivery infrastructure is rapidly aging [3]. The main fault of the outdated pipelines is leak and as a consequence deterioration of environment [2], [5], [6]. For instance methane emissions from leaking pipelines is a serious problem related to the environment as methane is one of the most principal greenhouse gases contributing to climate change [7], [8]. According to the experience of European transit countries the transit of oil and gas causes great losses regarding the ecological situation thus counteracting the intended political and economical benefits [9]. The leaks caused by damage of pipelines are usually very dangerous. Intensive leaks can stimulate explosions, fires and environment pollution, which can lead to the ecological catastrophe. In this case there can be an enormous economical loss. Although it seems that small leaks are not so dangerous,

but in practice it is important to carry out special actions preventing such kind of leaks as well, because the spilled oil or escape gas can damage the corrosion-resistant cover of pipeline and can cause the corrosion processes [10]-[13]. This may outgrow in intensive leaks with above-mentioned results. That is why the determination of damage place in pipelines in time is the significant problem [12], [14], [15]. In pipeline networks that transport gas or oil leaks may occur at any time and location [2], therefore, timely detection of leaks can stop or minimize contamination of environment and leak detection and location is important for the safe operation of pipelines [2], [13]. Pipelines prognostic leak detection systems play a key role in minimization of the occurrence of leaks probability and their impacts on environment [16]. So elaboration the leak detection and location system in a large scale water, oil and gas pipeline system networks is an urgent and sensitive issue of nowadays [5], [9], [15], [16]. That is way a great attention is paid to finding out the new methods and techniques for the leak fast detection and location in the pressurized pipeline and fortunately this process for the last three decades is in progress [1]-[16]. There are many different approaches and techniques for leak detection and location. A spectrum of the methods for detection and location of the leaks in the natural gas pipelines is wide from using trained dogs to advanced satellite based hyper spectral imaging [13], [17]. The methods of leak measurement differ from each other by several features [11]: the determination of the minimum leak value; the precision (fixation) of the leak place; the working regimes (constant, periodic or episodic). At the same time leak controlling methods can be dividing into two types: contact method (directly on pipeline) and remote control method (which implies moving controlling device across the pipeline trace) [5], [9], [12], [13], [15], [18]-[26]. According to the above mentioned classification we can list the following methods: visual method of leak detection – detection of oil and gas on ground surface using painting gases; radioactive isotopes etc.; hydrodynamic method - launching the special material in pipeline; acoustic method and mathematical modeling. Also there are fundamental theoretical and technical methods for leak detection and location in natural gas pipelines and the various methods can be classified into non-optical and optical methods [11]. From existing methods the mathematical modeling with hydrodynamic method is more acceptable as it is very cheap and reliable and has high sensitive and operative features [6], [12], [13], [27]. It is also significant that in this case the defined leak detection placement is possible to control by remote satellite and the earth surface appliances.) This

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article provides the proper methodology for leak detection in horizontal branched (with several sections and branches) pipeline and for leak detection in inclined section of the main gas pipeline. The methodology does not required knowledge of corresponding initial hydraulic parameters at entrance and ending points of each sections of pipeline. The methodology is based on an algorithm describing gas stationary movement in the simple and branched gas pipelines and some results of calculations are presented.

## II. PROBLEM FORMULATION FOR LEAK LOCALIZATION IN BRANCHED PIPELINE

In case of the main gas pipeline's damage first of all the gas expenditure and pressure are altered by gas leakage and initially gas flow has non-stationary character. After some time from the gas leakage (under some conditions), a new stationary state of gas flow is formed in the pipeline. So when there is gas accidental escape from the main gas pipeline it is necessary to study as a non-stationary stage [9], [11] as well a stationary stage of gas flow in the pipeline [5], [13], [16], [18], [28]. We study only large-scale gas leakage problem from the main gas pipeline and we consider this question as a reverse task of hydraulic calculation problem. It is known analytical methods of a large-scale gas escape location determination in the simple section of main gas pipeline when data of the gas pressures and expenditure at the entrance and ending of the gas pipeline are known [12], [29]. But these methods cannot be used for main gas pipelines having several sections and branches and for inclined pipes. The methods offered by us gives possibility first of all detect the placement of the section having accidental gas escape using minimal information (data of the gas pressures and expenditure at the main gas pipeline's entrance and ending points before and after gas escape) then leak localization in the determined section of main pipeline and for leak detection in inclined section of the main gas pipeline.

Thus suppose that there is a complex main gas pipeline having  $n-1$  off-shots, with expenses  $q_k$  ( $k = \overline{1, n-1}$ ) and the pipeline is divided by off-shots on  $n$  simple sections with length  $L_k$  ( $k = \overline{1, n}$ ). If at the entrance of pipeline gas expands in unit of time is  $M_0$ , then at the entrance of the per simple sections the gas expands are calculated in the following way [13],

$$M_1 = M_0 \quad M_k = M_{k-1} - q_{k-1}, \quad k = \overline{2, n}$$

where numbering is performed from the beginning of the pipeline to the ending.

As it is known in case of gas stationary movement in the horizontal gas pipeline exist the following equality [12], [13], [29]:

$$P_1^2 - P_2^2 = \sum_{k=1}^n M_k^2 \beta_k L_k \quad (1)$$

where  $\beta_k = \frac{\lambda_k ZRT}{F_k^2 D_k}$ ,  $P_1$  and  $P_2$  are values of the pressures at the entrance and at the ending of the main gas pipe-line, respectively;  $M_k$ - are expenses of gas in the unit area of pipe-line for unit time in the branches;  $L_k$ - are lengths of simple section  $k$  of the main pipe-line;  $Z$  is a coefficient expressing deviation of natural gas from ideal gas;  $\lambda_k$  is a hydraulic resistance of a gas;  $T$  is an absolute temperature;  $R$  is a gas constant;  $D_k$  are diameters of pipelines;  $F_k$  are areas of branches profile sections.

Suppose that at the entrance of the main gas pipeline in the unit of time through pipe passes  $M_0$  mass of gas, and at the ending of pipeline instant of gas mass  $Mn$  expenditure of gas is  $Mn - Q$ , which indicates that gas with mass  $Q$  is loosen, although the consumers (users) are getting the same mass of gas  $q_k$  ( $k = \overline{1, n-1}$ ) which is conditioned by gas distributive stations (service management).

Let us suppose that gas leakage is placed on the section  $i$  and gas escape is located on the distance  $x$  ( $0 \leq x \leq L_1$ ) from the entrance of the section  $i$ . Also we suppose that accidental gas escape represents additional ramification of the main gas pipeline with expenditure  $Q$  (see Fig. 1).

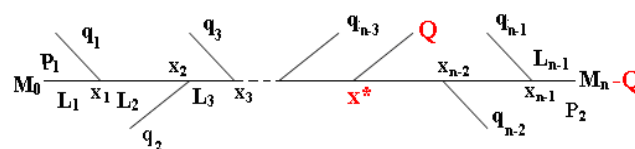


Fig. 1 Schematic map of a branched main gas pipeline

Fig. 1 represents a general scheme of a complex main branched gas pipeline where  $x^*$  is a location of gas escape in the pipeline. It is evidence that expenditure of gas is remained the same in the ramifications located before the section  $i$  but after the section  $i$  instead of expenditure  $M_k$  it will be  $M_k - Q > 0$  ( $k = \overline{1, n}$ ). In analogously of the right side of the (1) let us initiate the following functions  $f_i(x)$ ,  $i = \{1, 2, \dots, n\}$  [13]:

$$f_1(x) = \sum_{k=1}^n [M_k - Q]^2 \beta_k L_k + Q[2M_1 - Q]\beta_1 x, \quad (0 < x \leq L_1)$$

$$f_i(x) = \sum_{k=1}^{i-1} M_k^2 \beta_k L_k + \sum_{k=1}^n [M_k - Q]^2 \beta_k L_k + Q[2M_i - Q]\beta_i x$$

$$i \in (2, 3, \dots, n-1). \quad (0 < x \leq L_1)$$

$$f_n(x) = \sum_{k=1}^{n-1} M_k^2 \beta_k L_k + [M_n - Q]^2 \beta_n L_n + Q[2M_n - Q] \beta_n x, \quad (0 < x \leq L_n)$$

Let us assume that after gas escape  $\bar{P}_1^2$  and  $\bar{P}_2^2$  are values of the gas pressures, at the entrance and ending of main pipeline, respectively (which are obtained by the measuring instruments).

Therefore, analogously of the (1) we have [13]:

$$\bar{P}_1^2 - \bar{P}_2^2 = \hat{f}_i(x) \quad (2)$$

So for detection of the section of accidental gas escape and the point of gas escape in this section we have the following mathematical model (algorithm): first of all it is required to search such kind value  $i_0$  from the sequence  $i = \{1, 2, \dots, n\}$  and then the value of the  $x$  from the interval  $[0, I_{i_0}]$  which will satisfy the (2).

For convenience here and further we are defining some properties of the above mentioned function  $\hat{f}_i(x)$ :

A. Every Function  $\hat{f}_i(x)$  ( $i = \overline{1, n}$ ) Represents Linear Increasing Functions of  $x$ :

$$\text{For as much as } Q[2M_1 - Q] \beta_1 > 0, \quad (i = \overline{1, n})$$

B. The Following Equalities are Correctness:

$$f_{i-1}(L_{i-1}) = f_i(0), \quad (i = \overline{2, n})$$

Indeed, let us consider the cases when  $i = 1, 2$  separately. We will get:

$$f_1(L_1) = \sum_{k=1}^n (M_k - Q)^2 \beta_k L_k + Q[2M_1 - Q] \beta_1 L_1,$$

$$f_2(0) = M_1^2 \beta_1 L_1 + \sum_{k=1}^n (M_k - Q)^2 \beta_k L_k =$$

$$\sum_{k=1}^n (M_k - Q)^2 \beta_k L_k + M_1^2 \beta_1 L_1 - (M_1 - Q)^2 \beta_1 L_1 =$$

$$\sum_{k=1}^n (M_k - Q)^2 \beta_k L_k + Q(2M_1 - Q) \beta_1 L_1 = f_1(L_1).$$

when  $i = 3, 4, \dots, n-1$  then

$$f_{i-1}(L_{i-1}) = \sum_{k=1}^{i-2} M_k^2 \beta_k L_k + \sum_{k=i-1}^n (M_k - Q)^2 \beta_k L_k + Q(2M_{i-1} - Q) \beta_{i-1} L_{i-1} =$$

$$\sum_{k=1}^{i-1} M_k^2 \beta_k L_k + \sum_{k=1}^{n1} (M_k - Q)^2 \beta_k L_k - M_{i-1}^2 \beta_{i-1} L_{i-1} + (M_{i-1} - Q)^2 \beta_{i-1} L_{i-1} + Q(2M_1 - Q) \beta_{i-1} L_{i-1} =$$

$$\sum_{k=1}^{i-1} M_k^2 \beta_k L_k + \sum_{k=1}^{n1} (M_k - Q)^2 \beta_k L_k = f_i(0).$$

when  $i = n$  we have

$$f_{n-1}(L_{n-1}) = \sum_{k=1}^{i-2} M_k^2 \beta_k L_k + \sum_{k=i-1}^n (M_k - Q)^2 \beta_k L_k + Q(2M_{n-1} - Q) \beta_{n-1} L_{n-1} = \sum_{k=1}^{i-1} M_k^2 \beta_k L_k - M_{n-1}^2 \beta_{n-1} L_{n-1} + (M_{n-1} - Q)^2 \beta_{n-1} L_{n-1} + (M_n - Q)^2 \beta_n L_n + Q(2M_{n-1} - Q) \beta_{n-1} L_{n-1} = \sum_{k=1}^{n-1} M_k^2 \beta_k L_k + (M_n - Q)^2 \beta_n L_n = f_n(0).$$

The last fully proofs proper 2.

Using above proved properties of the function  $\hat{f}_i(x)$  we have constructed the numerical algorithm for definition of a placement of the damage section and then the placement of the gas escape in the damaged section which was found by the following [13]. Afterwards it is emplaced the location (number of the section  $i_0$ ) of the gas accidental escape the appropriate distance  $x$  can be defined by solution of the (2) which has the following form [9]. If we have  $i_0=1$  then

$$x = \left[ \bar{P}_1^2 - \bar{P}_2^2 - \sum_{k=i-1}^n (M_k - Q)^2 \beta_k L_k \right] / [Q(2M_1 - Q) \beta_1], \quad (3)$$

If fulfilled the following inequality  $2 \leq i_0 \leq n-1$  then

$$x = \left[ \bar{P}_1^2 - \bar{P}_2^2 - \sum_{k=1}^{i_0-1} M_k^2 \beta_k L_k - \sum_{k=1}^n (M_k - Q)^2 \beta_k L_k \right] / [Q(2M_{i_0} - Q) \beta_{i_0}], \quad (4)$$

and at last if  $i_0=n$ , then

$$x = \left[ \bar{P}_1^2 - \bar{P}_2^2 - \sum_{k=1}^{i_0-1} M_k^2 \beta_k L_k - (M_n - Q)^2 \beta_n L_n \right] / [Q(2M_n - Q) \beta_n] \quad (5)$$

On the basis of the numerical algorithm for definition of a placement of the damage section [9] and then formulas (3)-(5) for a placement of the gas escape in the damaged section we

have investigated the pipes with the length 30km. diameter  $D=0.7\text{m}$ , cross section  $F=0.38\text{ m}^2$ , having one, two three, four, five and six ramifications and we supposed that gas escape had happened at varies points of sections. It is important to say that we have investigated the pipelines with sections having radically different length and location of gas escape in the pipeline. Numerical simulations have performed on the base of a reverse task of hydraulic calculation problem when damaged sections leak location was known beforehand. Below some results of calculations for a horizontal branched main pipelines are presented. In this experiment there were two branches. Gas escape was located in the third section and distance from the beginning of the third section was equal to 3000m. (see Fig. 2) The parameters have accepted the following values:  $R=500\text{N m (kg}^0\text{κ)}$ ,  $Z=0.95$ ,  $T=280\text{K}$ ,  $M_0=15\text{kg/s}$ ,  $q_1=2\text{kg/s}$ ,  $q_2=2\text{kg/s}$ ,  $q_3=2\text{kg/s}$ ,  $L_1=10*10^3\text{m}$ ,  $L_2=10*10^3\text{m}$ ,  $L_3=10*10^3\text{m}$ ,  $M_1=15\text{kg/s}$ ,  $M_2=13\text{kg/s}$ ,  $M_3=10\text{kg/s}$ ,  $x^*=3000\text{m}$ ,  $Q=1\text{kg/s}$ ,  $\lambda=0,002$ ,  $\omega=2570$ .

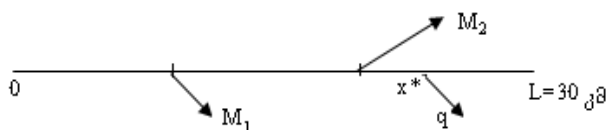


Fig. 2 Gas escape is located in the third section of the pipeline having two branches

The algorithm have defined the number of section correctly and Calculations have shown that distance from the beginning of the third section was equal to 3070m and the error between location of gas known in advance and calculated value was 70m.

In this experiment there were four branches. Gas escape was located in the third section and distance from the beginning of the third section was 3500m (see Fig. 3). The lengths of sections were differ from each other. The parameters have accepted the following values:  $M_0=15\text{kg/s}$ ,  $q_1=2\text{kg/s}$ ,  $q_2=2\text{kg/s}$ ,  $q_3=2\text{kg/s}$ ,  $q_4=2\text{kg/s}$ ,  $L_1=5*10^3\text{m}$ ,  $L_2=5*10^3\text{m}$ ,  $L_3=4*10^3\text{m}$ ,  $L_4=10*10^3\text{m}$ ,  $L_5=6*10^3\text{m}$ ,  $M_1=19\text{ kg/s}$ ,  $M_2=17\text{kg/s}$ ,  $M_3=15\text{kg/s}$ ;  $M_4=12\text{kg/s}$ ,  $X^*=3500\text{ m}$ ,  $Q=1\text{ kg/s}$ .

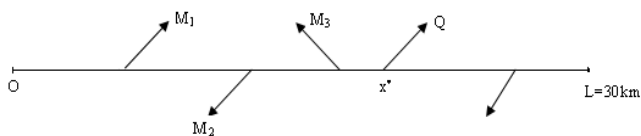


Fig. 3 Gas escape is located in the forth section of the pipeline having four branches

The algorithm has defined the number of section correctly and Calculations have shown that distance from the beginning of the fourth section was 3500m an error was 120m.

In this experiment there were five branches. Gas escape was located in the fourth section and distance from the beginning of the fourth section was 2000m (see Fig. 4). The lengths of sections were differing from each other. The parameters have

accepted the following values:  $M_0=15\text{ kg/s}$ ,  $q_1=2\text{kg/s}$ ,  $q_2=2\text{kg/s}$ ,  $q_3=2\text{kg/s}$ ,  $q_4=2\text{kg/s}$ ,  $q_5=2\text{kg/s}$ ,  $L_1=4*10^3\text{m}$ ,  $L_2=6*10^3\text{m}$ ,  $L_3=5*10^3\text{m}$ ,  $L_4=5*10^3\text{m}$ ,  $L_5=4*10^3\text{m}$ ,  $L_6=6*10^3\text{m}$ ,  $M_1=15\text{kg/s}$ ,  $M_2=13\text{ kg/s}$ ,  $M_3=11\text{kg/s}$ ;  $M_4=7$ ,  $M_5=5\text{kg/s}$ ,  $X^*=200\text{m}$ ,  $Q=1\text{kg/s}$

The algorithm has defined the number of section correctly and Calculations have shown that distance from the beginning of the fourth section was 2090m. The error was -90m.

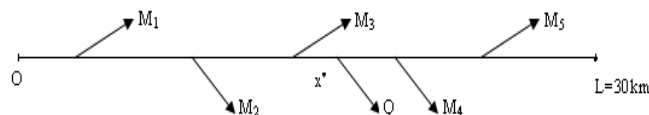


Fig. 4 Location of the gas escape is located in the forth section of the pipeline having five branches

Results of calculations have shown that in all cases number of damaged section was defined correctly and the maximum of error between calculated and previously known of gas escape point did not exceed 200m. in the pipeline with length 30km.

### III. LEAK LOCALIZATION IN INCLINED PIPELINE

On the territory of Georgia (Georgia lies between of the Main Caucasian Ridge and the Lesser Caucasus mountains and territory of Georgia is characterized by the compound orography as Mountain Range forming about 85% of the total land area) there are functioning 4 gas pipelines [30]. The gas pipelines were constructed in the conditions of compound relief, so they are inclined to the horizontal plane. For example North Caucasus – (Transcaucasia) gas pipeline- Grozni-Tbilisi-Yerevan passes from Russia to Armenia through main Caucasus mountain range with the maximum altitude 2400m. South Caucasus pipeline- Baku-Tbilisi-Erzurum (BTC) gas pipeline transports gas from Azerbaijan to Turkey through the territory of Georgia. The BTC pipeline on the territory of Azerbaijan is located almost on the horizontal surface but from the territory of Georgia until to Erzurum the orography is compound. Also it is important to emphases that the territories of Georgia and Turkey are located in the seismic active zone and on the territory of Caucuses there are frequently such kind of phenomenon such are floods, landslides with huge stones and as a consequence with high probability of damage of gas pipelines. So investigation of the question of gas escape localization in the inclined pipes is urgent problem for Caucasus region and for Georgia too.

For the simple inclined main gas pipeline there is the following formula [29]:

$$P_H^2 - P_K^2 \cdot e^{a\Delta z} = M^2 \cdot b \cdot L \cdot \frac{e^{a\Delta z} - 1}{a\Delta z} \quad (6)$$

where  $P_H$  and  $P_K$  –are values of the pressures at the entrance and at the ending of the main gas pipeline, respectively,  $M$ - is expenses of gas in the unit area of pipeline for unit time,  $L$ - is length of a simple pipeline,  $\Delta z$  is difference of heights between

endings of the sloping pipeline, a and b- are known constants [8], [31].

$$a = \frac{2g}{ZRT}, b = \frac{16ZRT}{\pi^2 D^5} \lambda, \lambda = \frac{0.03817}{D^{0.2}}$$

where g is gravitational acceleration. For performing of numerical calculations the parameters have accepted the following values:  $Z=0.9\text{m}$ ,  $D = 0.7 \text{ m}^2$ ,  $R = 287.04 \text{ N} \cdot \text{m/kg.K}$ ,  $T=276\text{K}$ ,

Suppose that an accidental gas escape with intensity q, is located on the distance x from the begging of the pipeline and the gas accidental escape point B represents an additional ramification of the pipeline OA (see Fig. 5).

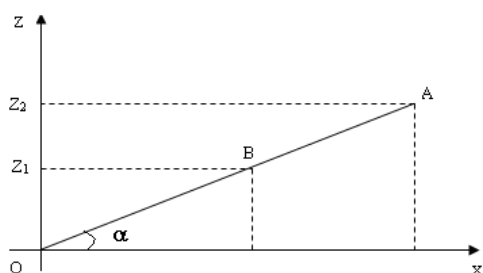


Fig. 5 Inclined by angle  $\alpha$  pipeline OA to the horizontal line OX, with length L. O and A are begging and ending points of the pipeline, B is accidental gas escape point,  $|OA|=L$ ;  $|OB|=x$

Suppose that an accidental gas escape with the intensity q, is located at the distance x from the begging of the pipeline in the point B. We consider that the gas accidental escape point B is a ramification and a simple pipeline is divided by the point B into two simple sections. Then in analogues of the (6) for the sections OB and BA it is possible to write the following system of equations:

$$P_H^2 - P_x^2 \cdot e^{az_1} = M^2 \cdot b \cdot x \cdot \frac{e^{az_1} - 1}{az_1}, \quad (7)$$

$$P_x^2 - P_K^2 \cdot e^{a(z_2-z_1)} = (M-q)^2 \cdot b \cdot (L-x) \cdot \frac{e^{a(z_2-z_1)} - 1}{a(z_2-z_1)}, \quad (8)$$

where we assume that  $z_0 = 0$ ,  $z_1$  and  $z_2$  are vertical coordinates of the entrance, gas escape and ending points of the pipeline, respectively.

From the Fig. 5 it is evidence that

$$z_1 = \frac{z_2}{L} \cdot x = x \cdot \sin(\alpha), z_2 - z_1 = (L-x) \cdot \sin(\alpha).$$

Taking into consideration appropriate equality

$$e^\beta - 1 \approx \beta, \text{ when } 0 < \beta < 1$$

Then (7) and (8) can be rewriting in the following form

$$P_H^2 - P_x^2 \cdot (1 + az_1) = M^2 \cdot b \cdot x. \quad (9)$$

For the second section we have

$$P_x^2 - P_K^2 \cdot [1 + a(z_2 - z_1)] = (M-q)^2 \cdot b \cdot (L-x), \quad (10)$$

Equations (9) and (10) compose the system of equations for defining unknown variables x and  $P_x$ . For defining unknown variable x we get the following quadratic equation

$$\left[ \frac{a^2}{L^2} Z_2^2 P_K^2 + (M-q)^2 \cdot ba \frac{z_2}{L} \right] x^2 + \left[ -P_K^2 a^2 \frac{Z_2^2}{L^2} - (M-q)^2 baz_2 + (M-q)^2 b - M^2 b \right] x - (M-q)^2 bL - P_K^2 (1 + az_2) + P_H^2 = 0, \quad (11)$$

We had investigated discriminant of (11) and for the reasonable values of parameters it was greater-than zero. So (11) has two solutions. In all of tested experiments the absolute value of one root always was greater-than the length of pipeline L, but other one was less than the inclined pipe's length L, which was solution of the (11). In Table I is given some values of the roots (11) and its dependence on the values of gas pressure at the ending point of pipeline.

TABLE I  
 INFLUENCE OF THE PRESSURE ON THE QUADRATIC EQUATION ROOTS

$P_k$	$x_1$	$x_2$
$P_k=1.43 \cdot 10^7$	$1.62945 \cdot 10^5$	$1.3460702 \cdot 10^8$
$P_k=1.44 \cdot 10^7$	$1.22808 \cdot 10^5$	$1.3458845 \cdot 10^8$
$P_k=1.45 \cdot 10^7$	82416.06	$1.34569702 \cdot 10^8$
$P_k=1.46 \cdot 10^7$	41768.79	$1.34551015 \cdot 10^8$
$P_k=1.47 \cdot 10^7$	866.99	$1.34532134 \cdot 10^8$

Table I shows that a value of the root  $x_2$  of quadratic equation is always greater than length of pipeline. Another one is the solution of the problem.

TABLE II

PRECISE AND CALCULATED VALUES (INACCURACIES) OF LEAK LOCALIZATION FOR VARIES RATES OF GAS EXPENSES, PRESSURE AT ENTRANCE AND ENDING POINTS AND GAS ESCAPE

M kg	$P_H H/M^2$ (atm.)	$P_K H/M^2$ (atm.)	q (kg)	precise point of escape km	calcu lated km	drift rate km
2.1	$1.18 \times 10^6$	$7.73 \times 10^5$	0.1	150	152	2
2.1	$1.18 \times 10^6$	$7.9 \times 10^5$	0.1	100	102	2
2.1	$1.18 \times 10^6$	$8.04 \times 10^5$	0.1	50	47	3
12	$1.5 \times 10^7$	$1.5 \times 10^7$	4	100	117	17
12	$1.5 \times 10^7$	$1.5 \times 10^7$	4	150	145	5
12	$1.5 \times 10^7$	$1.5 \times 10^7$	4	50	58	8

Table II shows some results of calculations using for all the experiments the following common values  $L=200\text{km}$ . and  $z_2=300\text{m}$ . There were performed mainly two types of experiments with gas expenditure  $0.13\text{kg/s}$  and  $4\text{kg/s}$ . and the values of the pressure at the entrance and ending points of pipeline were changed. We had known exactly solution of the task when escape was at the point 50, 100 and 150km a long way off the entrance point of pipe. The calculations had shown that maximal inaccuracy with the gas expenditure  $0.13\text{kg/s}$  was 3 km. and with the gas expenditure  $4\text{kg/s}$  maximal inaccuracy was equal to 7km.

If appropriate equality:

$$e^\beta - 1 \approx \beta,$$

is not true then (7) and (8) can be rewriting in the following form

$$P_H^2 - P_x^2 \cdot y = M^2 \cdot b \cdot (y-1) / A \quad (12)$$

$$P_x^2 \cdot y \cdot A - P_K^2 \cdot e^{AL} = (M - q)^2 \cdot b \cdot (e^{A(L-x)} - 1) \quad (13)$$

where  $A = a \cdot \sin(\alpha)$ ,  $y = e^{Ax}$ .

Equations (12) and (13) compose the system of equations for definition of the unknown variables  $y$  and  $P_x$  and after some simple transformation from (12) and (13) we have:

$$y = [A(P_H^2 - P_K^2 \cdot e^{AL}) + M^2 b - (M - q)^2 b \cdot e^{AL}] / q \cdot b(2M - q),$$

Taking into account denotation  $y = e^{Ax}$  then the last equation can be rewriting in the following form:

$$x = 1/A \ln [A(P_H^2 - P_K^2 \cdot e^{AL}) + M^2 b - (M - q)^2 b \cdot e^{AL}] / q \cdot b(2M - q) \quad (14)$$

We had investigated an applicable domain of the (14) and for the reasonable values of parameters expression under sign of logarithm was greater-than zero. Namely if the following inequalities are true

$$\begin{aligned} (P_H^2 / P_K^2) &> e^{AL}, \\ M^2 / (M - q)^2 &> e^{AL} \end{aligned} \quad (15)$$

then for reasonable values of parameters exist exact solution (14) which determines leak location in the inclined pipeline with inclination of  $\alpha$ . We have investigated solution (14) for different values of parameters. Namely in this experiments the following values of parameters were fixed:  $P_H=1.18111 \cdot 10^6$ ;  $M=5,1$ ;  $q=1.2$ ;  $T=276$ ;  $Z=0.9$ ;  $R=287,04$ .

Results of calculations show that when  $P_K=1.18111 \cdot 10^6$ ;  $L=30000$  and  $\sin(\alpha)=0.02$ , then leak's location is  $x=6838,7$ . When  $L=25000$ ;  $\sin(\alpha)=0.04$  and  $P_K=1.024435066 \cdot 10^6$  then leak's location is  $x=18790.1$ . When  $L=25000$ ;  $\sin(\alpha)=0.12$  and  $P_K=9.5690622 \cdot 10^5$  then leak's location is  $x=18695.1$ . When  $L=30000$ ;  $\sin(\alpha)=0.01$  and  $P_K=1.02508942 \cdot 10^6$  then leak's location is  $x=6843.77$  m from the entrance point of the inclined pipe.

#### IV. CONCLUSION

As foreign experience with pipelines shows, the main reasons of crashes and spillages (and fires as a consequence) are destruction of the gas pipes as a result of corrosion, defects of welding and natural phenomena (earthquakes, landslides, floods etc). Also terrorist attacks and sabotage may occur. The probability of crashes for gas pipeline transport rises with the age of the pipelines in service, and with the extent of their network. For example, 250 ruptures, which were accompanied by spillages of the transferred products, occurred every year from 1973 to 1983 in the US pipeline network with a total length of about 250,000km. In West Europe it has been found that 10 – 15 leakages happen every year in a pipeline network of around 16,000km length, resulting in a loss of 0.001% of transferred products. It is obvious that leak detection in gas pipelines has economical, ecological and sociological meaning. Mathematical modelling with hydrodynamic method is very cheap, reliable and high sensitive method for discovering placement of accidental gas escape [31]-[34]. In the present paper in case of gas stationary flow we suggest a new method for discovering placement of gas accidental escape in the main pipeline with several gas offshoots. The algorithm of leak localization in the branched pipeline represents a generalized view of a mathematical model describing gas stationary flow in the simple gas pipeline. For detection of damaged section and then leak localization special functions and equations have been constructed. Some results of numerical calculations for compound pipelines having two, four and five sections are presented. The method offered by us gives possibility first of all detect the placement of the damaged section using minimal information (data of the gas pressures and expenditure at the main gas pipeline's at entrance and ending points before and after gas escape) and then leak localization in the determined section of main pipeline.



We have investigated pipes having one, two three, four, five and six ramifications and we supposed that gas escape had happened at various points of branches. It is important to say that we had investigated the pipelines with sections having radically different length, location of gas escape in the pipeline and sections which was known in advance, (previously, beforehand). Calculations have shown that in all cases number of section was defined correctly and the maximum of error between calculated and previously known point of escape did not exceed 200m.

The calculations had shown that maximal inaccuracy with the gas expenditure 0.13kg/s was 3km and with the gas expenditure 4kg/s maximal inaccuracy was 7km.

For the verification of the proposed method we created quite general test, the manner of the solution had been known in advance. Comparison of the solutions has shown the affectivity of the following method.

Also in the present paper a simple mathematical model (an algorithm) for definition a placement of a gas accidental escape in an inclined section of the main gas pipeline is suggested. The algorithm required knowledge of corresponding initial hydraulic parameters at entrance and ending points of the inclined pipeline. The algorithm is based on mathematical model describing gas stationary flow in the simple gas pipeline. A method and a formula for the determination a location of the gas accidental escape in simple inclined main gas pipeline are suggested. Some results of numerical calculations defining localization of gas escape for the inclined pipeline are presented. The results of calculations on the basis of observation data have shown that the performed simulations were much closer to the results of observation.

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