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FORECAST OF GAS MASS FLOW RATE IN CASE OF THEINDUSTRIAL PIPELINE RUPTURES

Abstract: *The causes of emergencies on industrial pipelines are given. Industrial pipelines in oil and gas fields are not safe after a long period of operation. Therefore, the risk of emergency-dangerous defects and the possibility of an explosion on gas pipelines are increased. The greatest risk of accidents on industrial pipelines is associated with longitudinal fractures, which can occur both in the main metal of the pipes and in the zone of welded joints, with the formation of corrosive "fistulas" and "guillotine" ruptures.*

The conditional probability of ignition of emergency emissions of hydrocarbon energy carriers taking into account the location of ignition sources was determined.

A method for determining emergency gas losses at a pipeline rupture was proposed. A comparative analysis for the mass flow rate of a gas at a pipeline rupture, depending on the diameter of the pipeline, the initial pressure, time and distance from the damage to the pipes was carried out.

Keywords: *industrial pipeline, probability of ignition, mass flow rate of gas, length of disconnected section, diameter of pipeline.*

Introduction

Ensuring reliable operation of industrial pipeline systems is possible only with the use of organizational and technical measures at the stages of their design, construction and operation.

During the operation of pipelines, it is necessary to monitor the parameters of the work, to diagnose the surface condition of pipelines. Maintenance and repair, fire prevention and protection against explosions, environmental monitoring – these measures are crucial for the safe operation of pipelines.

The accident-free operation of industrial pipelines should guarantee the safety of life and health of workers of this facility and protection of the environment.

Industrial pipelines in oil and gas fields are not safe after a long period of operation. After all, there is a growing risk of emergency-dangerous defects, such as corrosion, and the possibility of an explosion on gas pipelines. In this case, the shock wave in the event of a failure of the main gas pipelines is one of the damaging factors [1].

A shock wave causes the entry to the atmosphere, soil and water of natural gas constituents, which leads to a disruption of the gas balance. It should be noted that sulfur compounds and nitrogen oxides, which cause acid rain, that is capable of falling out at a distance of many hundreds and thousands of kilometers from the point of leakage of hydrocarbon energy carriers, are especially dangerous. The greatest influence is observed in the event of the pipeline's rupture during its operation. It follows that prevention and prediction of the consequences of accidents is one of the top priorities [2].

The analysis of literary sources shows that many scientific works have been devoted to the problem of technogenic safety of objects of the fuel and energy complex, among them, special attention should be paid to the works of Mazur I.I., Ivantsov O.M., Grudz V.Yu, Govdiak R.M., Voronin A.N., Lipskij V.K., Semchuk Yu.M., Vozniak M.P., Askarov G.R., Topilin A.V. and others [1-3, 6- 10].

According to the results of the research, the greatest contribution to the set of emergency situations is made by man-made emergencies. It is, therefore, necessary to use measures for responding, preventing and eliminating the consequences of technogenic emergencies as the most common and threatening [2].

From literature sources devoted to safety issues, it follows that it is necessary to conduct a comprehensive study of factors to predict the probability of accidental emissions of gases in the event of emergencies and their impact on staff and the environment.

The aim of the research is to predict gas emissions from the rupture of an industrial pipeline and the probability of fire of emergency gas emissions and its impact on staff.

The object of the study is an industrial pipeline with a long period of operation.

To achieve this goal, the following tasks were solved: the determination of gas mass flow rate at pipeline rupture, depending on the diameter of the pipeline, the initial pressure, time and distance from the place of its impact on people.

Materials and methods

The largest damage accidents on pipelines occur when longitudinal pipes break down, which can occur both in the main metal of the pipes and in the zone of welded joints during the formation of corrosive "fistulas" and "guillotine" ruptures. Emergency gas emissions can catch fire.

For this, let's define the conditional probability of emergency emissions ignition of hydrocarbon energy carriers taking into account the location of ignition sources.

The conditional probability of emergency gas emissions ignition in the presence of periodically operating sources of ignition is calculated by dependence [4]:

$$P_p = 1 - Q(\tau) \tag{1}$$

where $Q(\tau)$ is the probability of non-ignition of a cloud from sources, the natural logarithm of which is calculated from the following relationship:

$$\mathrm{Ln}\, Q(\tau) = \sum_{i=1}^{I} \sum_{j=1}^{J} A_{ih} \cdot \mu_j \cdot \left[(1 - a_j \cdot p_j) \cdot e^{-\lambda_j p_j d_{ih}} - 1 \right] \tag{2}$$

where:

i – the number of the elementary area in the calculation domain;

j – the number of the ignition source on the elementary area, $j = 1, \ldots J$;

A_{ih} – area of the i-th elementary area, ha;

μ_j – the distribution density of ignition sources, pcs/ha;

a_j – the fraction of the time of activity of the j-th ignition source, that calculated by the dependence:

$$a_j = \frac{i}{(\tau_a + \tau_i)} \tag{3}$$

where:

$_i$ – the time during which the ignition source is active, min;

τ_a – time between the periods of the ignition source activation, min;

p_j – physical potential ignition of the j-th ignition source;

d_{ih} – the time during which the source was in contact with the cloud (it is recommended to accept 60 minutes);

λ_j – activation frequency of the *j*-th ignition source, 1/min, $\lambda_j = 1/(\tau_a + \tau_i)$.

The potential of ignition of the different typical ignition sources is given in table 1.

TABLE 1. *Potential of ignition of the different typical ignition sources*

Ignition source type	Potential of ignition
Switched on burner, Open flame	$p_j = 1$
Electric motors, heat treatment	$p_j > 0.5$
Vehicles, faulty electrical grid	$0.5 > p_j > 0.05$
Electrical equipment, sparks	$p_j < 0.05$
Explosive equipment, radio frequency sources	$p_j = 0$

The probability of non-ignition of a cloud from sources according to (2) is $Q(\tau)$ = 0.01930.

Then the conditional probability of ignition of emergency gas emissions in the presence of periodically operating sources of ignition during the internal transportation of cargos will be equal $P_p = 1 - 0.0193 = 0.9807$.

The results of the calculations indicate a high probability of ignition of emergency gas emissions when the pipeline is ruptured due to the action of negative factors during its operation.

The ignition of accidental gas releases creates a significant danger for maintenance personnel, namely the danger of thermal damage. It should be noted that the current stage of development of oil and gas fields is accompanied by a growing number of technical, environmental and economic problems.

The problem of technogenic safety cannot be solved only by the technical protection means, and requires a comprehensive study of the factors that affect the occurrence of an emergency situation at a certain facility when performing a certain technological process. To do this, it is necessary to forecast the amount of gas loss in the event of an emergency and to carry out measures to ensure the reliability of the operation, and prevent environmental pollution.

The most dangerous accidental damage to the industrial pipeline is the "guillotine" rupture.

The outflow of gas at the rupture of the pipeline to the full cross section is described by differential balance ratios for mass, momentum and energy [5]:

$$\left.\begin{aligned}
&\frac{\partial \rho}{\partial \tau} + \frac{\partial}{\partial x}(\rho \upsilon) = 0 \\
&\frac{\partial}{\partial \tau}(\rho \upsilon) + \frac{\partial}{\partial x}(p + \rho \upsilon^2) = -\lambda \frac{\rho \upsilon^2}{2 d_0} \\
&\frac{\partial}{\partial \tau}\left[\rho\left(e + \frac{\upsilon^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[\rho \upsilon\left(h + \frac{\upsilon^2}{2}\right)\right] = \frac{4\alpha}{d_0}(T_0 - T)
\end{aligned}\right\} \tag{4}$$

where:

ρ – the density of gas, kg/m³;

τ – the time, s;

υ – the mean velocity of gas, m/s;

p – the absolute pressure, Pa;

e – the specific internal energy, m^2/s^2;

h – the specific enthalpy, m^2/s^2;

d_0 – the internal diameter of pipeline, m;

α – the coefficient of heat exchange with an environment, $W/(m^2K)$;

T – the temperature of the pipe wall, K;

T_0 – the ambient temperature, K;

λ – the friction factor.

Known numerical methods for the implementation of the considered system of equations require high costs associated with the preparation of raw data for calculation. Therefore, these methods are not suitable for prediction of accidental losses, as they do not allow to find an operative solution for detecting the scale of product emissions in the event of an accident and conducting urgent measures for the prevention of the environment pollution.

To achieve this goal, we used the method of calculating the mass flow rate of gas at the rupture of the pipeline [4] when the gas flows in industrial pipelines with a diameter of 100 mm to 300 mm, different locations of rupture points from 500 m to 10,000 m. The calculations were carried out in MS Excel.

Results and Their Discussion

For the engineering estimation of the mass flow rate of gas at a pipeline break, it is possible to use the equation of Bell [4]:

$$G(\tau)=\frac{\Gamma G_i}{1+\eta}\cdot\left[\exp\left(-\frac{\tau}{\eta^2\cdot\varepsilon}\right)+\eta\cdot\exp\left(-\frac{\tau}{\varepsilon}\right)\right] \tag{5}$$

where:

$G(\tau)$, G_i – the current and initial mass flow rate of gas (in the moment of rupture), kg/s;

τ – the time that passed from the moment of rupture, s;

Γ – the factor of inertial delay ($\cong$0.5);

η – the mass conservation factor;

ε – the constant of time, s.

The initial mass flow rate is calculated from the condition, that the nature of the gas leakage process is adiabatic at the point of rupture

$$G_i=\frac{p_i A_r\sqrt{k}}{\sqrt{RZ_{kr}T_i}}\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}} \tag{6}$$

where:

p_i – the gas pressure in the pipeline to rupture, Pa;

A_r – the cross-sectional area of the rupture, m^2;

R – the gas constant, J/(kg K);

T_i – the gas temperature in the pipeline to rupture, K;

Z_{kr} – the coefficient of compression of gas for parameters p_{kr}, T_{kr} on an exit.

The mass conservation factor is calculated by the dependence:

$$\eta=\frac{M_g}{\varepsilon\cdot\Gamma\cdot G_i} \tag{7}$$

where:

M_g – the total mass of gas that can flow out of the insulated section of the pipeline, kg;

ε – the constant of time, s.

The expression for a constant time is based on the assumption of the isothermal nature of the flow of gas at most of the length, the cut off section of the pipeline

$$\varepsilon = \frac{2L^*}{3a_0}\sqrt{\frac{k \cdot f_f \cdot L^*}{d_0}} \qquad a_0 = \sqrt{kRZ_i T_i} \tag{8}$$

where:

L^* – the length of the disconnected section of the pipeline, m;

a_0 – the sound speed in gas to rupture, m/s;

f_f – the coefficient of friction of gas on the pipe wall;

d_0 – the internal diameter of the pipeline, m.

The total mass of gas that can flow off during a rupture is determined from the expression:

$$M_g = \frac{L^* \cdot A^* \cdot p_0}{R \cdot Z_i \cdot T_0} \tag{9}$$

where:

Z_i – the coefficient of compression of gas to rupture of pipe for p_i, T_i;

L^* – the length of the disconnected section of the pipeline, m;

A^* – the cross-sectional area of the pipeline, m²;

p_0 – the absolute pressure, Pa.

To analyze the possible consequences of an accident on an industrial pipeline, we will determine the nature of the change in mass flow rate of gas at pipeline rupture, depending on the diameter of the pipeline, the initial pressure, time and distance from the location of the pipe damage, using the Bell equation (5).

The results of calculations are shown in figures 1-3.

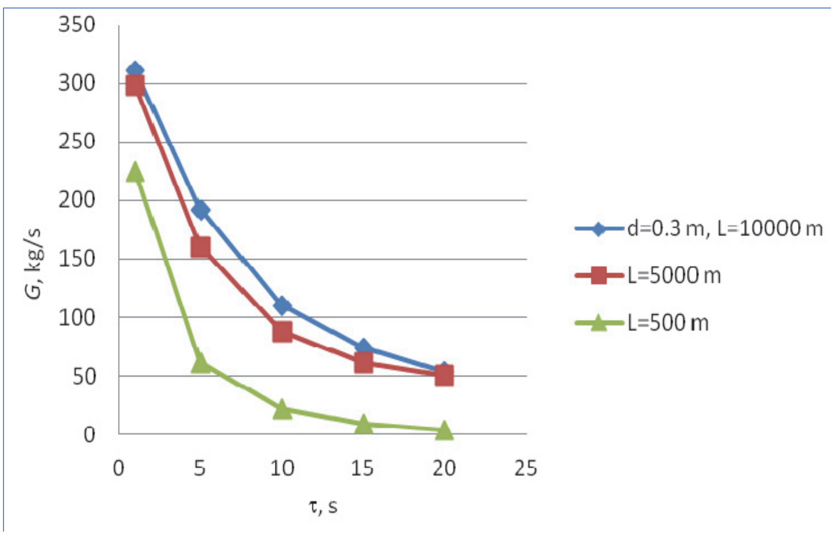

***FIGURE 1.** Changing the gas mass flow rate at the rupture of a pipeline with the diameter of 0.3 m, depending on the time*

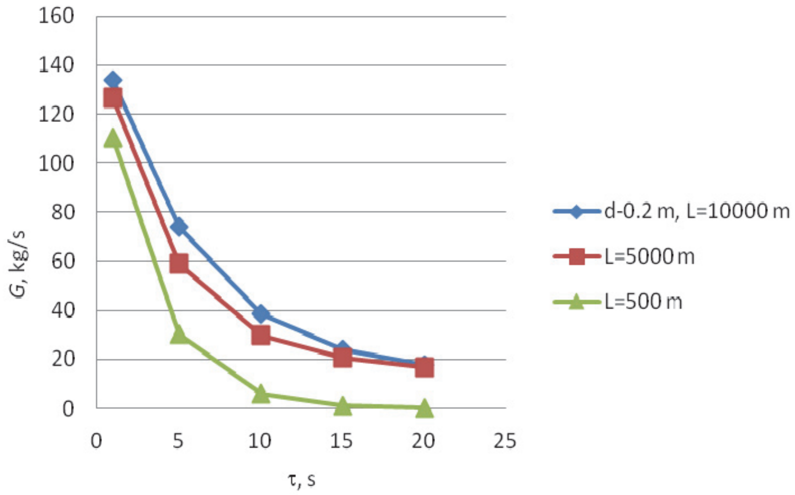

FIGURE 2. *Changing the gas mass flow rate at the rupture of a pipeline with the diameter of 0.2 m, depending on the time*

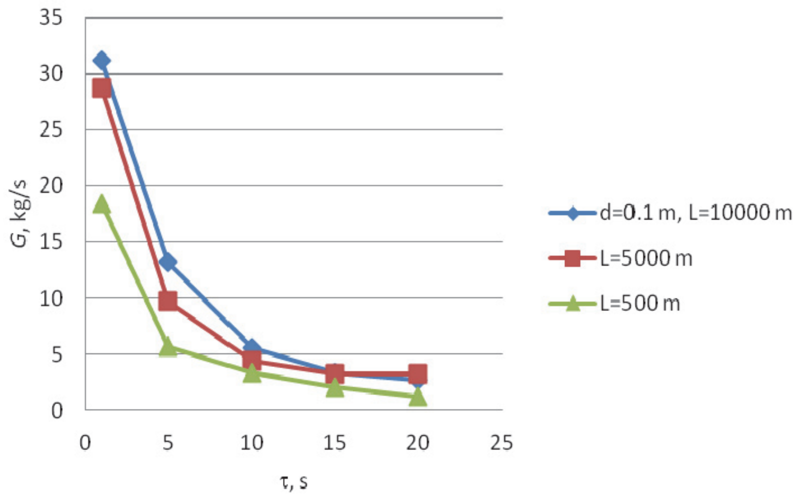

FIGURE 3. *Changing the gas mass flow rate at the rupture of a pipeline with the diameter of 0.1 m, depending on the time*

From the analysis of the graphs it follows that at the "guillotine" rupture of the industrial pipeline with a diameter of 0.3 m and a length of the disconnected section of 10,000 m, the initial leakage of the gas mass is 320 kg/s.

If the length of the disconnected section is 500 m, then the initial gas leakage is 220 kg/s.

It should be noted that after 5 seconds at the maximum length of the cut off area, the gas mass flow rate is 190 kg/s, and for the minimum length of the cut off area, the mass flow rate of gas will be 60 kg/s (fig. 1).

If the pipeline 0.2 m in diameter ruptures and the length of the cut off area is 10,000 m, then the initial leakage of gas is 130 kg/s. If the pipeline 0.2 m in diameter ruptures and the length of the cut off area is 500 m, then the initial leakage of gas is 115 kg/s. After 5 seconds at the maximum length of the cut off area, leakage of gas is 78 kg/s and, at the minimum length of the cut off area, the mass flow rate of gas will be 30 kg/s (fig. 2).

Similarly, if a pipeline with a diameter of 0.1 m and a length of the cut off area of 10,000 m are ruptured, then initial flow off is 32 kg/s. If the length of the of the cut off area is 500 m, then the initial leakage of gas is 19 kg/s. After 5 seconds, at the maximum length of the cut off area, the leakage of gas is 13 kg/s and at the minimum length of the cut off area is 5 kg/s (fig. 3).

Conclusions

Consequently, the larger the pipelines diameter and the length of the cut off area, the greater the gas losses at the pipeline ruptures, causing significant damage to the environment.

Emergency emissions of gas in the presence of intermittent sources of ignition can ignite. This is especially dangerous for staff working at risk area.

Having diagnostic data on the surface of the pipeline with intelligent pigs, it is necessary to predict in advance the probability of damage to the pipeline in the most dangerous areas and take a number of measures to improve the industrial safety of pipelines transporting hydrocarbon energy carriers.

The further direction of research is to develop a multifunctional system for ensuring the environmental safety of industrial pipelines.

References

[1] Mazur I.I.: *Safety of the pipeline systems* / I.I. Mazur, O.M. Ivantsov. M.: ITS "ElIMA", 2004.-1104 p (in Russian).

[2] Govdiak R.M., Semchuk Ya.M., Chabanovych L.B., Shelkovsij B.I., Kryvenko G.M.: *Energyecological safety of oil and gas objects*. Ivano-Frankivsk: Lileya - HV, 2007, 556 p. (in Ukrainian).

[3] *Methodical guidance as evaluated by consequences of emergency explosions of Fuel – air mixtures* (ratifie by the order of Federal service on the ecological, technological and atomic supervision from March, 31, 2016, No 137) (in Russian).

[4] *Guadance on safety "Metodology as evaluated by risk of accidents on linear objects, there are a fire and an explosion dangers.* (ratifie by the order of Federal service on the ecological, technological and atomic supervision from" October, 23, 2014) (in Russian).

[5] Lurye M.V.: *Mathematical modeling of pipeline transportation processes for oil, oil products and gas* / M.V. Lurye M.: Oil and Gas, 2003, 335 p. (in Russian).

[6] Kryvenko G.M.: *Research of influence of diameter of pipeline on distribution of shock wave in emergency situation* / G.M. Kryvenko, M.P. Vozniak, L.V. Vozniak, S.O. Kryvenko // Scientific Bulletin of IFNTUNG. Ivano-Frankivsk: No 1 (36), 2014, pp. 110-117 (in Ukrainian).

[7] Voronin A.N.: *An analysis of complex risk in the main pipeline systems* / A.N. Voronin, V.K. Lipskij, Materials of X1 of the International educational-scientifically-practical conference. Ufa: UGNTY, 2016, pp. 33-34 (in Russian).

[8] Serenkov P.S.: *Methods of management of quality. Methodology of stimation of risk of standardization*: monograph / P.S. Serenkov, V.L. Gurevich, V.M. Romanchak, A.V. Yanuskevich. Mn BNTY, 2014, 244 p (in Russian).

[9] Kryvenko G.M.: *Forecasting of emergency oil losses through the defective orifices in industrial pipelines* / G.M. Kryvenko, L.V. Vozniak, World Science, Multidisciplinary Scientific Edition. Warsaw: No 3 (31), vol. 1, March 2018., pp. 17-25 (in English).

[10] Askarov G.R.: *Maintenance of the safe operation of the linear part of the gas pipelines by means of intra- tube diagnosuics* / G.R. Askarov, Materials of XIII of the International educational-scientifically-practical conference. Ufa: UGNTY, 2018, pp. 10-11 (in Russian).