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ENSURING THE ENVIRONMENTAL SAFETY OF THE OIL PIPELINES OPERATION*

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Abstract

Ensuring the environmental safety of pipeline transport of hydrocarbons is one of the priorities of the oil and gas industry. The long lifetime of pipelines leads to the appearance of a significant number of defects in the body of the pipe. In case of increasing pressure during the operation of industrial pipelines, an emergency situation may occur, that may lead to oil leakage and environmental pollution. Analysis of the real operating modes has shown that during the operation of industrial pipelines there is an unsteady-state flow. It is caused by a change in the density of the oil or the frequency of the current, which leads to hydraulic shock. The purpose of the work is to reduce the impact of industrial oil pipelines on the environment by predicting the technical risk. The object of research is the industrial oil pipelines. The subject of research are factors that influence the technical risk when oil density changes. A simplified analytical realization of the problem of pressure distribution at the hydraulic shock for prediction of industrial pipelines safe operation is developed. Dependence for the determination of relative technical risk, taking into account the possibility of the hydraulic shock, is proposed. The character of distribution of pressure along the pipeline with taking into consideration of hydraulic shock for industrial pipelines of different diameters with the use of the simplified model is investigated. The proposed dependence enables to predict maximum possible pressures at the beginning of the pipeline and to analyze the safety of the pipeline's operation.

Keywords: defect, hydraulic shock, oil pipeline, pressure, risk

1. Introduction

Ensuring the environmental safety of pipeline transport of hydrocarbons is one of the priorities of the oil and gas industry. Oil and gas pipelines are an integral part of

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technological schemes of oil and gas extraction facilities. Since the total length of the industrial pipelines coincides with the length of the main pipelines, special attention is paid to improve the safety of their operation. Nowadays, the main sources of man-made hazard are enterprises for the extraction, transportation, and processing of hydrocarbon energy carriers, which are accompanied by the emission of extremely harmful substances. This is due to the extreme situations that arise during the operation.

Ukraine's oil pipelines have been operating for several decades. The long lifetime of the pipelines leads to the appearance of a significant number of defects in the body of the pipe with different length and depth. Deep defects of a small length are more dangerous than long defects of the negligible depth. The key to the reliable and safe industrial pipelines operation is the operational analysis of the most dangerous hazardous states and their timely elimination. It follows that the directions of scientific research and a list of tasks, that need to be solved, should be guided by the issues of technogenic safety of pipelines used for pumping hydrocarbon energy carriers.

The causes of pipelines failures are highlighted in the scientific papers (Andrusyak, 2008; Elaoud et al., 2011; Mandryk, 2013; Voronin et al., 2016), in which it is accentuated that most of the accidents on oil pipelines are caused by worn out of pipes, due to both internal and external corrosion. According to Babadzhanova et al., (2010) and Kryvenko et al., (2018a), one of the main factors influencing the trouble-free operation of the pipeline is maintaining pressure at the beginning of the pipeline within safe limits. Therefore, it is necessary to define which factors affect the values of initial pressure and how to minimize this effect.

In order to prevent emergencies, it is necessary to adjust pressure losses in industrial pipelines with a significant lifetime. Consequently, for the safe operation of the pipelines, it is necessary to know the nature of the distribution of pressure at any operating conditions. It is possible to adjust the working pressure and reduce the risk of emergencies, after obtaining results of the pipeline`s surface diagnosis and pressure distribution for different volumetric flow rates.

Known hydrodynamic dependencies for determining the pressure drop for a stationary pumping process do not always correspond to real conditions. There is an unsteady-state flow regime in the process of exploitation of industrial pipelines under certain conditions. For example, this mode causes a change in the density of the oil or the frequency of the current, which leads to a hydraulic shock. This factor must be taken into account when forecasting the safe operation of industrial pipelines. When replacing the light crude oil by the heavy oil with a significant difference in the density, for example, ρ = 800 – 920 kg/m^3, the hydraulic shock occurs. It causes emergency situations at the beginning of the pipeline.

Starting and stopping of pumping units, opening and closing of shut-off devices, unpredictable stopping of pumps that may occur as a result of a violation of the power supply or the activation of pipeline protection systems during the operation of oil pipelines – all this lead to a hydraulic shock and the possibility of an emergency. This problem is highlighted in a number of scientific papers (Grigorsky et al., 2014; Zhifeng et al., 2013).

Nevertheless the numerical methods proposed by (Mazur et al., 2004) are time-consuming in calculations related to the preparation of input data. Therefore, these methods are unsuitable for forecasting of emergency modes, as they do not allow to find an immediate solution for preventing damage to the pipeline. Thus, there was a need to develop a simplified analytical realization of the problem, which is related to a hydraulic shock in the pipeline during operation.

The purpose of the work is to reduce the impact of industrial oil pipelines on the environment by predicting technical risk. In the process of research, the following tasks were solved:

1) development of a simplified analytical realization of the problem of determining the distribution of pressure at hydraulic shock to predict the safe operation of industrial pipelines;

2) determination of relative technical risk, taking into account the possibility of the hydraulic shock.

The object of research is industrial oil pipelines. The subject of research are factors that influence the technical risk when changing the density of oil. Method of research is the analytical simulation of the regularities of hydrodynamic processes in industrial pipelines.

2. Materials and methods

The authors of the article assessed the degree of danger of defects, classified of damage to the pipeline. It is pointed out that it is necessary to take into account reduced pressure due to the loss of metal in the pipes during long-term operation.

Fig. 1 shows the dependence of the depth of the defect of the pipe on its length. In this case, three groups of defects are distinguished in terms of the safety of exploitation of this site, namely: extremely dangerous, dangerous, and relatively dangerous. Proceeding from the fact that it is impossible to repair all defects for economic and technical reasons, oil companies have developed methods for assessing the hazards of defects. Since there is no information on the possible interaction of defects, the speed of corrosion (if defects are caused by it) and, as a result, further destruction of the metal, therefore it is necessary to attribute the second group (Fig. 1) to the extremely dangerous defects also now, and not after some time (Kryvenko et al., 2018b).

The probability of the fact that, out of 20 defects in the body of the pipe, six, which belong to the first and second groups, can lead to an emergency was defined. It is known that the number of failures on industrial pipelines ranges from 0.15 to 1.15 per kilometer per year (Mazur et al., 2004). The local Maura-Laplace formula (Kulinich and Lybid, 2003) was used for calculations of the probability of failure. The probability of failure is $P_6(20) \approx 0.503$. Given the long lifetime of industrial pipelines, the presence of defects in the body of the pipe, which increases the risk of emergencies and environmental pollution, it is necessary to predict safe modes of their operation.

To predict the distribution of pressure along the length of the pipeline, taking into account hydraulic shock and its impact on the operation of industrial pipelines, we use the laws of conservation of mass and momentum (Eqs, 1, 2) (Lurye, 2003):

$$-\frac{\partial \rho}{\partial t} = \frac{\partial(\rho v)}{\partial x} \tag{1}$$

$$-\frac{\partial p}{\partial x} = \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\alpha \rho v^2)}{\partial x} + \rho g \sin\varphi + \frac{\lambda}{2d}\rho v^2 \tag{2}$$

where ρ is the density of oil;

t – time;

v –the mean velocity of oil;

x – linear coordinate;

p – pressure;

α – dimensionless velocity distribution;

g – the gravitational acceleration;

φ – the angle of inclination of the pipeline to the horizon;

λ – the friction factor;

d – internal diameter of the pipeline.

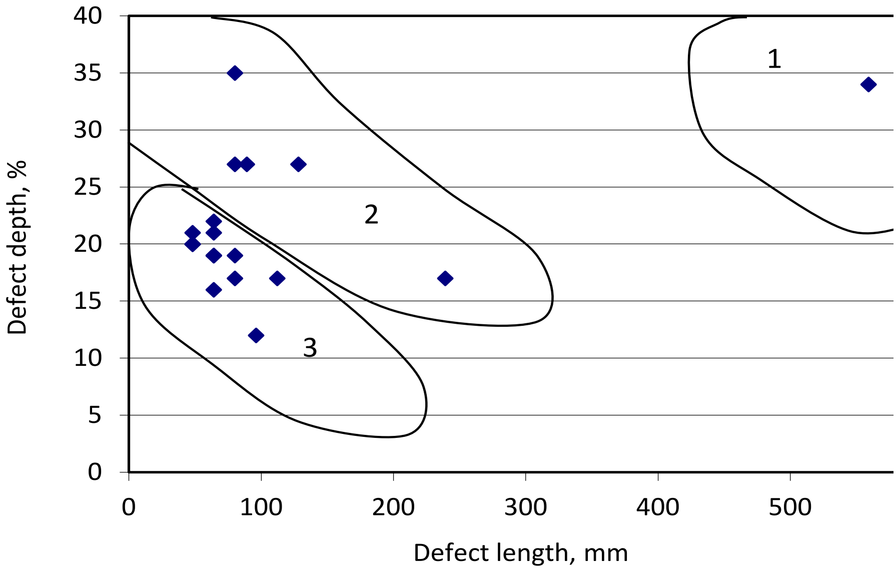

Fig. 1. Dependence of the depth of the defect on its length: 1 – extremely dangerous defects; 2 – dangerous defects; 3 – relatively dangerous defects

The use of well-known numerical methods for the implementation of the considered system of equations is time-consuming. Therefore, the proposed method is simplified analytical realization of the problem. After completing a series of mathematical transformations, we get Eq. (3).

$$b^2 \frac{\partial^2 p}{\partial x^2} = \frac{\partial p}{\partial t}, \qquad (3)$$

where $b^2 = \frac{A_0}{A}$, $A_0 = \frac{c^2}{S}$, $A = \frac{2a}{S}$, $\frac{\lambda v}{2d} = 2a = const$;

S – cross-sectional area of a stream normal to the velocity;

c – the sound speed.

Let's consider how the hydraulic shock will change over time, using the Eq. (3).

To solve the Eq. (3) we accept the following assumptions:

1) the pressure at the end of the pipeline is constant and does not depend on the hydraulic shock;

2) Eq. (3) takes into account only a hydraulic shock.

We use the method of integral transformations for solving equations of mathematical physics. This method consists in replacing the unknown function with its integral transformation (“image”), which allows transforming differential equations with partial derivatives to the usual differential equation with respect to the corresponding images. We obtain a simplified analytical dependence for the determination of pressure, taking into account hydraulic shock (Eq. 4) (Kurpa and Linyk, 2011):

$$p_p = p_x \left(1 - \frac{4}{\pi}\sum_{k=1}^{\infty}\frac{(-1)^k}{2k+1}\cdot e^{-\left(\frac{2k+1}{2}\right)^2 \cdot \frac{\pi^2 t}{b^2 l^2}} \cdot \cos\frac{(2k+1)\pi(l-x)}{2l}\right) \tag{4}$$

where x is a linear coordinate;

p_x– the pressure on the length x from the beginning of the pipeline;

l – the length of the pipeline;

t – the time.

The expression $\left(1 - \frac{4}{\pi}\sum_{k=1}^{\infty}\frac{(-1)^k}{2k+1}\cdot e^{-\left(\frac{2k+1}{2}\right)^2 \cdot \frac{\pi^2 t}{b^2 l^2}} \cdot \cos\frac{(2k+1)\pi(l-x)}{2l}\right)$ takes into account the hydraulic shock depending on the time.

Denote with B the coefficient that takes into account the hydraulic shock will be determined by Eq. (5):

$$B = \left(1 - \frac{4}{\pi}\sum_{k=1}^{\infty}\frac{(-1)^k}{2k+1}\cdot e^{-\left(\frac{2k+1}{2}\right)^2 \cdot \frac{\pi^2 t}{b^2 l^2}} \cdot \cos\frac{(2k+1)\pi(l-x)}{2l}\right) \tag{5}$$

3. Results and discussion

The distribution of pressure along the pipeline is determined by Eq. (6).

$$p_x = p_o - \Delta p_x \tag{6}$$

where p_o – pressure at the beginning of the pipeline;

Δp_x – pressure drop on the length x.

To determine the loss of pressure, we use a simplified mathematical model.

Since in the industrial pipelines the oil moves mainly the turbulent flow, "smooth pipe" flow, then the pressure drop will be determined by the dependence (7) (White, 1994):

$$\Delta p = 0.241 l \rho^{3/4} \mu^{1/4} d^{-4.75} Q^{1.75} \tag{7}$$

where ρ – density; kg/m^3;

μ– dynamic coefficient of viscosity, kg/(m·s);

d – internal diameter, m;

Q – volumetric flow rate, m^3/s.

If hydraulic shock is taken into account, then the nature of the pressure distribution will look like given by Eq. (8):

$$p_p = p_x \cdot B \tag{8}$$

We calculate the distribution of pressure in the pipeline by Eq. (8). The results of calculations for industrial pipelines with diameters of 0.1m, 0.2m and 0.3m are shown in Fig.2-4, with an oil flow rate ranging from 0.008 m^3/s to 0.106 m^3/s, the oil density varied within 790 kg/m^3 to 900 kg/m^3. A change in pressure during time t = 0.1 s from the moment of oil injection into the pipeline higher density was shown on the Fig. 2-4.

There is a sharp increase pressure in the process of injection oil into the pipeline with a higher density. This growth is similar to a hydraulic shock.

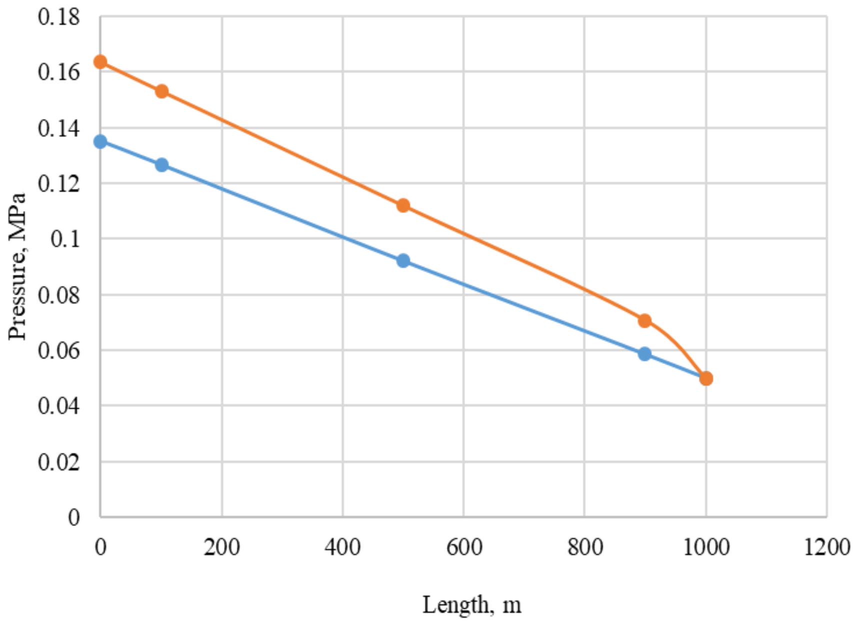

Fig. 2. Pressure distribution along a pipeline with a diameter of 0.1 m
without the hydraulic shock
with the hydraulic shock

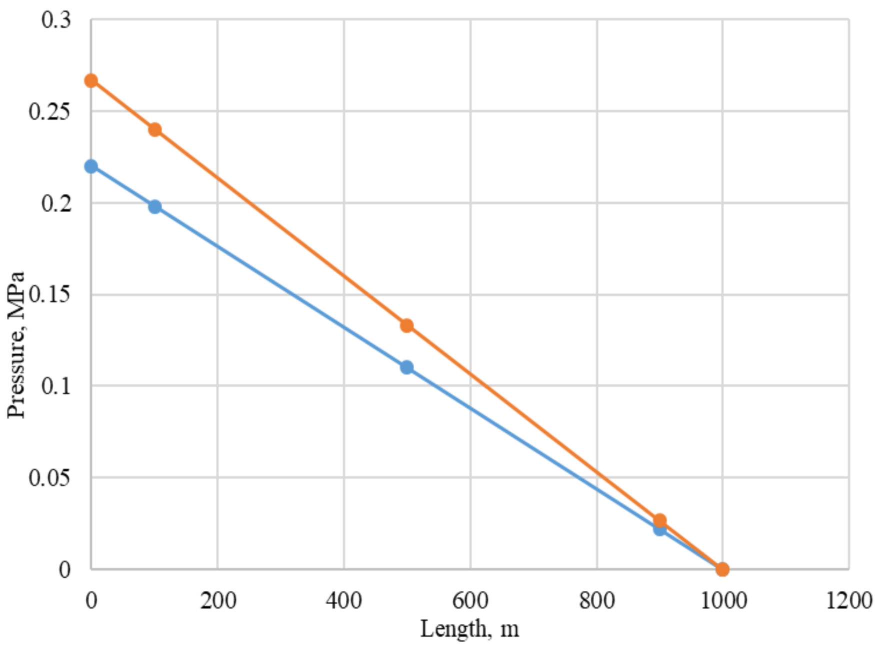

Fig. 3. Pressure distribution along a pipeline with a diameter of 0.2 m
without the hydraulic shock
with the hydraulic shock

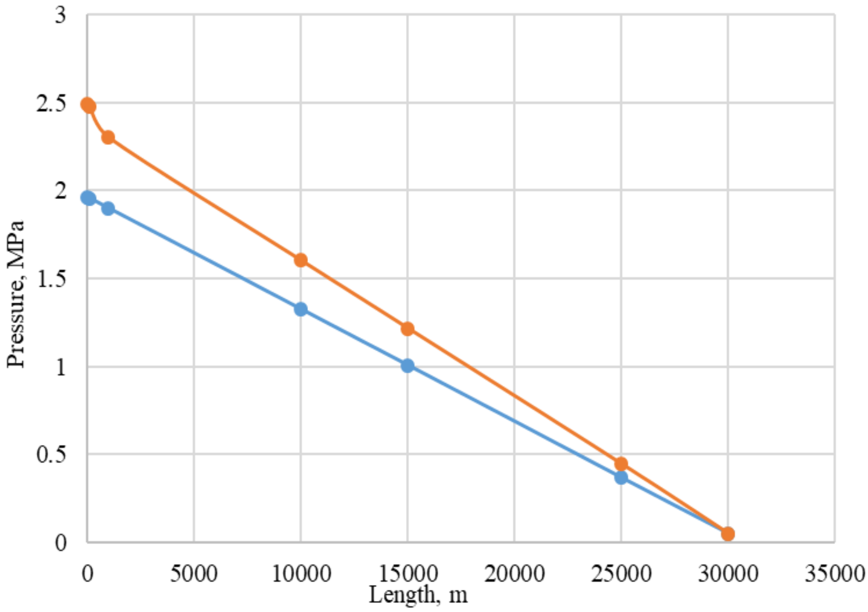

Fig. 4. Pressure distribution along a pipeline with a diameter of 0.3 m
without the hydraulic shock
with the hydraulic shock

From the analysis of the pressure distribution graphs along the pipeline, it follows that for a pipeline of 0.1 m in diameter, a fast pressure increase at the beginning of the pipeline is 0.0229 MPa, at a distance of 500 m – 0.019 MPa, and at a distance of 900 m – 0.012 MPa. For an industrial pipeline with a diameter of 0.2 m, a fast pressure increase at the beginning of the pipeline is 0.047 MPa, at a distance of 500 m – 0.023 MPa, and at a distance of 900 m – 0.0046 MPa. For an industrial pipeline with a diameter of 0.3 m, the fast pressure increase at the beginning of the pipeline is 0.526 MPa, at a distance of 10,000 m – 0.278 MPa, and at a distance of 25,000 m – 0.077 MPa.

Analysis of Fig. 5 allows us to set a change in factor B, which takes into account the hydraulic shock. In the process of replacing light oil by heavy oil, there is a fast pressure increase at the beginning of the pipeline. Impact pressure increase extends over the whole pipe. But the system is not in equilibrium. Pressure rises (and also decreases), but not instantaneously. In addition, oscillation damping is observed, that is, the decrease of its amplitude values. The analysis of Fig. 5 indicates that when determining the fast pressure increase depending on the time, the maximum value of k can be lower than five since the amplitude value of damped waves at k = 5 is reduced relative to the initial by 75%.

The proposed Eq. (8) reproduces real processes of damping of a fast pressure change over time and along the length of the pipeline.

One of the main factors influencing the risk of accidents is the pressure at the defect location. It is necessary to take into account the possibility of the hydraulic shock for the safe operation of industrial pipelines. Therefore, such a dependence (Eq. 9) is proposed for the assessment of relative technical risk in the long-term operation of industrial oil pipelines.

$$R = \sum_{i=1}^{n} \frac{p_{p.i}}{p_{r.i}} \cdot \frac{\varepsilon}{\varepsilon_a}, \qquad (9)$$

where $p_{p.i}$ – the pressure distribution, taking into account the hydraulic shock, MPa;

$p_{r.i}$ – the value of the reduced pressure, taking into account the losses of metal, MPa;

n – the number of defects in the body of the tube as a result of the diagnosis;

ε – frequency of accidents 1/(year km);

ε_a – average frequency of occurrence of accidents 1/(year km).

For example, the predicted technical risk for a pipeline with a diameter of 0.2 m is 0.274.

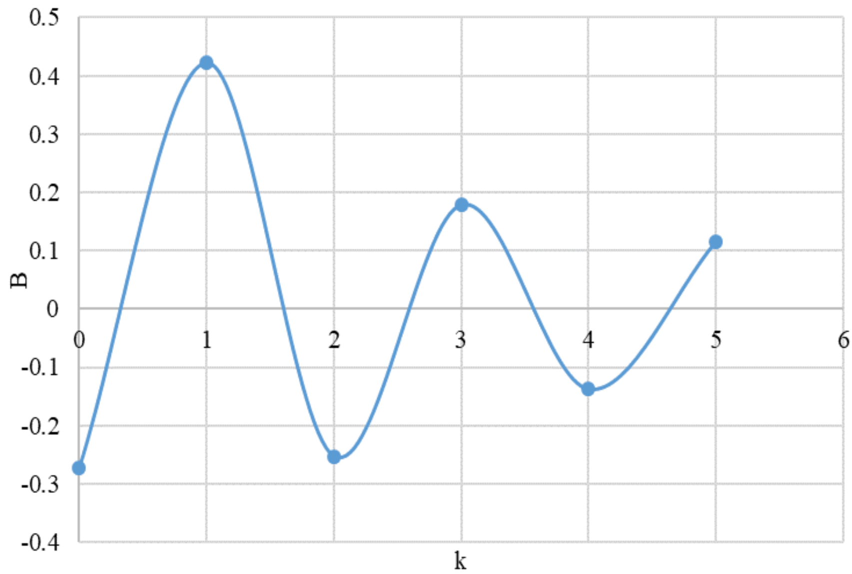

Fig. 5. The nature of the change of coefficient B that takes into account the hydraulic shock

It is obvious that reducing the value of maximum operating pressure at the beginning of the pipeline leads to a decrease in the throughput capacity of the industrial pipeline and an increase in energy costs for oil pumping. Since during the process of replacing light oil by heavy oil, which essentially differs in density, for example, the difference is ρ = 790 ... 900 kg/m^3, the pressure at the beginning of the pipeline increases from 3.7 MPa to 4.2 MPa, which may lead to an emergency situation, therefore this factor should be taken into account when exploiting oil pipelines. In Fig. 6 intersection of the trend line with the value of the critical initial pressure gives the conditional value of the maximum mass flow rate (Govdyak et al., 2007).

4. Conclusions

The analysis of the real operating modes of industrial oil pipelines shows that in the process of their operation there is an unsteady-state flow, therefore the dependence for the determination of pressure is considered, taking into account hydraulic shock, in order to predict the safe transportation of hydrocarbons.

Since there is no information on the possible interference of defects, it is necessary to include a group of dangerous defects in a extremely dangerous group immediately, and not after a while, and to carry out repairs on the pipelines in a timely manner, where dangerous defects were discovered during the diagnostics of the pipeline surface with intelligent pigs.

Proposed dependence for the determination of relative technical risk taking into account the possibility of hydraulic shock, which will minimize the impact of the industrial oil pipeline on the environment.

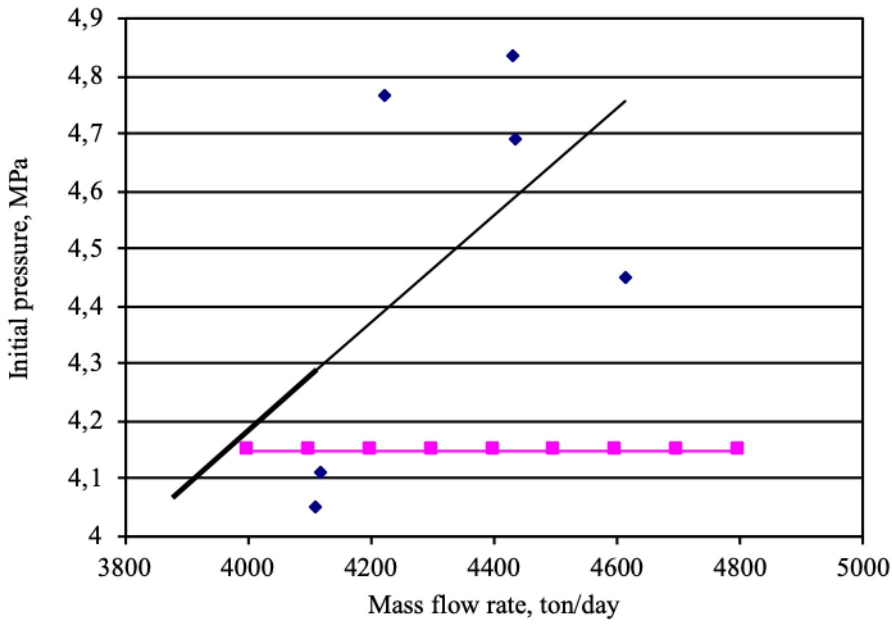

Fig. 6. Determine the maximum mass flow rate

♦ – data of industrial measurements;

-■-– the value of the critical initial pressure;

—— – trend line

The recommended dependence (8) allows one to predict possible maximum pressures at the beginning of the oil pipeline and to analyze whether they will be safe during the operation of the pipelines, whether do not exceed the value of reduced pressure, which is calculated taking into account defects in the body of the pipe, whether they will be able to ensure safe operation of oil pipelines.

The task of the following studies is to predict the appearance of emergencies in industrial oil pipelines and recommend measures to reduce the negative impact on the environment.

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