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Development of a Mathematical Model for Determining the Leakage Point of the Gas Pipeline at Fuel Supply Energy Complexes and Facilities

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Abstract: This study presents the results of a new approach to detecting the gas leak while accident on the high-pressure gas pipeline at fuel supplying of power facilities. To solve the task developed a mathematical model for solving problems based on the computational mathematics methods with regard to the determination of pressure losses along the gas pipeline. This model is based on the motion equations for the flow of real gas, takes into account the factor of compressibility and temperature unevenness along the pipeline which allows reducing the recovery time of the energy complex during an accident and increasing its reliability. The method for finding the gas leak is developed. Based on this method a PC program was developed to determine the leakage location under real conditions. The results of implementation of the new method are presented and compared with real statistics of gas leak accidents. This method contribute to the mathematical modeling of the processes of gas flow through the pipeline. The conclusions were formulated.

Key words: Energy sector, gas accident, fuel supply, supply pipeline, gas leak, method of computational mathematics

INTRODUCTION

Natural gas supply system is one of the most significant production sectors in economy of the Russian Federation. About 30% of the revenue to the Russian economy are accounted to gas sales. The main purchasers of Russian gas are Germany, France and China (JSC, 2014). Nowadays pipeline is the main type of natural gas transportation. Energy and gas transport system of the Russian Federation is continually evolving. Due to introduction of new gas generating facilities, working pressure and capacity in gas pipelines have increased noticeably. They are laid in difficult and sometimes extreme climatic conditions on the sea-floor and over pikes. As the gas transportation modes change, there always occur pressure ratio and alteration in the temperature of the gas transported.

Taking into consideration the range of entire gas supply system in the RF and its process safety, proper measures for safe operation of the network must be taken. Even when designing loading lines a substantial operational reliability margin is to be planned that will allow continuous supply of natural gas to the consumer for more than a decade.

Today, the main challenge in energy systems and complexes development is associated not only with the solution of the environmental and energy problems but with social and with engineering progress which emerged from fundamentally new technological approaches. The usage of natural gas all over the world offers great opportunities for a number of large and to some extent advanced technological developments in the national economy sectors.

Many modern researchers such as Mischer J., Papay, J. Sigloch H., Novgorodskiy E.E., Chebotarev V.I. and many others have studied the opportunites of improving reliability of gas supply for the development of emergency prevention methods (Dai *et al*., 2007). Central place of the discussions and scientific publications is devoted to the analysis of the current state of energy and gas transport system used for the development of the fuel and energy industry and to environmental problems caused by the extraction, processing and transportation of gas and their solutions. The large-scale events involving various appliances as well as a large human potential result in anthropogenic impact on the surrounding flora and fauna. Results of major accidents are significant damage or even

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may lead to death of the personnel. To sum up, all these effects must be minimized as much as possible and in a long run, anticipated and excluded. Thus, research in this field is essential and require new approaches.

MATERIALS AND METHODS

The great value for cost saving resources of the energy complex in the case of emergency on the incoming gas line is in early identification of the leak and the elimination of the accident (Fig. 1).

Currently, there are several companies in the world that specialize in gathering and analyzing information related to industrial facilities emergencies including the energy and gas sectors. The following organizations are of greater interest:

Concawe: "The oil companies european organisation for environmental and health protection" (Belgium, Brussles). EGIG "European Gas pipeline Incident data Group" (Netherlands, Groningen). Annual report on the activities of Federal service for ecological, technological and nuclear supervision in Russia. UKOPA "UK Onshore Pipeline Operators Association" (United Kingdom Ambergate) Haswell and McConnell, 2014).

PHMSA: "Pipelines and Hazardous Materials Safety Administration" (USA, Columbia) (Anonymous, 2009, 2014, 2016). Based on their reports, one can conclude that accident causes while fuel supply of energy facilities are generally similar with the bulk of them on the linear part of the gas line being caused by: external mechanical impact, corrosion and engineering errors (defects of materials and equipment). Literary review reveals that following methods of searching for leak (Hopkins, 1995; Dai *et al*., 2007):

- Separation of the gas pipeline on small plots and carrying out a re-test
- Adding colorant in the water for a better recognition of leaks
- Adding sulfur hexafluoride SF_6 and carrying out tests with the detector
- Adding of helium and testing with a detector
- Adding methane CH_4 with a concentration below the explosive limit and testing with the detector
- Tests with ultrasound
- Visual inspection
- Use the highly sensitive gas detector
- Probe drilling method
- The method of in-line flaw survey

In order to solve the problem of detecting gas leak in high-pressure gas pipeline, computational mathematics method that considers differential pressure losses along the gas pipeline is used. This model is based on the motion equations for the flow of real gas. It takes into account the factor of compressibility and temperature unevenness along the pipeline which allows reducing the recovery time of the energy facility during an accident and increasing its reliability. To determine the leakage location under real conditions "Leckspot" computer application was developed and registered. Based on the Darcy-Weisbach formula, dependence of inlet and outlet pressure in gas pipeline was obtained:

$$p_1^2 - p_2^2 = \frac{\lambda}{D_i^5} \cdot \frac{16}{\pi^2} \cdot \rho_n \cdot \frac{T_m \cdot z_m}{T_n \cdot z_n} \cdot p_n \cdot V_n^2 \cdot L \quad (1)$$

Where:

p_1 = Gas pressure at the start of gas pipeline, Pa
p_2 = Gas pressure at the end of gas pipeline, Pa
λ = Pipe friction number
D_i = Diameter of the gas pipeline (internal)
ρ_n = Gas density under normal conditions
T_m = Average gas temperature
T_n = Gas temperature under normal conditions
z_m = Average compressibility factor

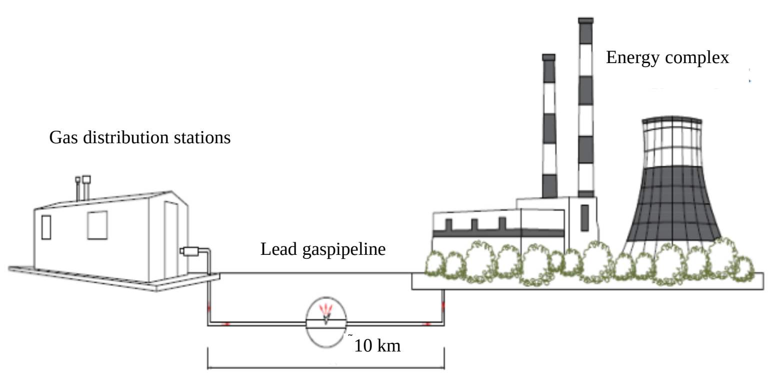

Fig. 1: Fuel supply of energy complex from the gas distribution station

z_n = Compressibility factor under normal conditions
p_n = Pressure under normal conditions
V_n = Volumetric gas flow rate under normal conditions
L = Length of gas pipeline

Having initial parameters, output gas pressure can be determined:

$$p_2 = p_1 \cdot \sqrt{1-\lambda \cdot \frac{L}{D_i^5} \cdot \frac{16}{\pi^2} \cdot \rho_n \cdot \frac{T_m}{T_n} \cdot \frac{p_n}{p_1^2} \cdot V_n^2 \cdot K_m} \quad (2)$$

Where:
K_m = Gas deviation factor
$K_m\, z_m/z_n$ = Introducing C for compact writing gives the following

$$C = \frac{\lambda}{D_i^5} \cdot \frac{16}{\pi^2} \cdot \rho_n \cdot \frac{T_m}{T_n} \cdot p_n \cdot K_m \quad (3)$$

Formula can be written as:

$$p_1^2 - p^2 = C \cdot V_n^2 \cdot x \quad (4)$$

where, x coordinate of the section with pressure p. For the standard mode, the pressure distribution along the gas pipeline can be written Eq. 4 when $0 \leq x \leq L$:

$$p = \sqrt{p_{1*}^2 - C \cdot x \cdot V_*^2} \quad (5)$$

where "*" the corresponding parameters in the nominal mode, i.e. with no any leakage. While deriving the dependences (Eq. 2-5), the following allowance were used: pressure drop in the pipe is determined by the losses along the pipe, i.e., losses on local resistance, level component and pressure changes due to the acceleration of the flow are equal to zero; As average parameters along the pipeline (pressure, temperature) arithmetic mean values at the gas pipeline inlet and outlet are taken.

Taking into account Eq. 4, pressure drop on the section before a pipe break with x_0 and after a breakup can be written as:

$$\begin{aligned} p_1^2 - p_{x0}^2 &= C \cdot x_0 \cdot V_1^2 \\ p_{x0}^2 - p_2^2 &= C \cdot (L - x_0) \cdot V_2^2 \end{aligned} \quad (6)$$

Thence:

$$p_1^2 - p_2^2 = C \cdot V_2^2 \cdot L + C \cdot x_0 \cdot (V_1^2 - V_2^2) \quad (7)$$

According to Eq. 7 volumetric flow rate at inlet and outlet are assumed to be taken under normal conditions. Equation 7 describes the dependence of the pressure change in a pipeline to leakage amount and its location. Distance to the point of leakage x_0 is determined:

$$x_0 = \frac{(p_1^2 - p_2^2) - C \cdot L \cdot V_2^2}{C \cdot (V_1^2 - V_2^2)} \quad (8)$$

Equation 4 for normal mode is:

$$p_{1*}^2 - p_{2*}^2 = C \cdot L \cdot V_*^2 \quad (9)$$

Equation "C" can be derived from Eq. 9:

$$C = \frac{p_{1*}^2 - p_{2*}^2}{L \cdot V_*^2} \quad (10)$$

Thereafter, Eq. 8 taking into account Eq. 10 can be written as:

$$x_0 = \frac{\frac{p_1^2 - p_2^2}{p_{1*}^2 - p_{2*}^2} \cdot V_*^2 - V_2^2}{V_1^2 - V_2^2} \quad (11)$$

Based on the equations obtained, location of leakage caused be damage of the pipeline is possible to calculate.

RESULTS AND DISCUSSION

Example No. 1: In the first case a leakage occurs at a distance x_0 from the start along the high-pressure supply pipeline. Additional amount of gas is flowing in order to compensate gas losses resulting from a leak. However, inlet pressure and flow rate at the outlet of the pipeline in emergency mode are kept equal to the corresponding parameters in the nominal mode. Figure 2 shows the pressure change under normal operation of the network and during a leak.

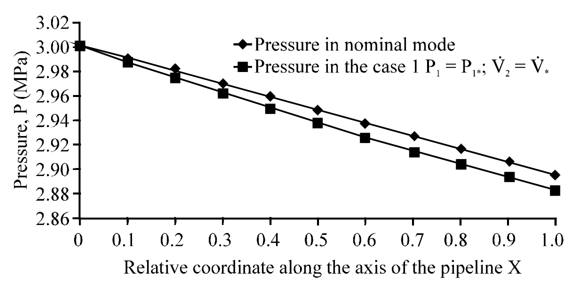

Fig. 2: Changing pressures along the gas pipeline in emergency mode at $x_0 = 0.5L$, $\Delta\dot{V} = 10\%$

Gas pipeline has the following geometric and mode parameters: p_{1*} = 3,0 MPa; p_{1*} = 2,89 MPa; p_n = 0,1 MPa; D_i = 0,33 m; L = 10000 m; λ = 0,01627; ρ_n = 0,747 kg/m^3; k_m = 0,93415; V_* = 40000 m^3/h; ΔV = 0,1V_*; T_m=283,15 k; T_n = 273,15 k. Boundary conditions, for example, No. 1 are denoted:

$$p_1 = p_{1*};\ V_2 = V_* \tag{12}$$

Pressure distribution along the pipeline before and after the leak:

$$p = \sqrt{p_{1*}^2 - C\cdot\left(V_* + \Delta V\right)^2 \cdot x} \quad \text{with } 0 \le x \le x_0 \tag{13}$$

$$p = \sqrt{p_{x0}^2 - C\cdot V^2 \cdot \left(x - x_0\right)} \quad \text{with } x_0 \le x \le L \tag{14}$$

Based on the calculation Eq. 13 and 14 a graph has been made, Fig. 2. Taking into account boundary conditions Eq. 12, 8 is as follows:

$$x_0 = \frac{\left(p_{1*}^2 - p_2^2\right) - C\cdot L\cdot V_*^2}{C\cdot\left(V_1^2 - V_*^2\right)} \tag{15}$$

Taking into account boundary conditions (Eq. 12) , Eq. 11 is as follows:

$$x_0 = \frac{V_*^2\cdot\left(p_{1*}^2 - p_2^2\right)}{\left(p_{1*}^2 - p_2^2\right)\cdot\left(V_1^2 - V_*^2\right)} \tag{16}$$

Two dependencies Eq. 15 and 16 are obtained to determine the fault location in emergency mode No. 1 taking into account the compressibility factor and the temperature unevenness along the pipeline which allow reducing the recovery time of the energy facility during the accident and increasing its reliability.

Example No. 2

Second example: Pressure and flow rate at the outlet of pipeline in emergency mode are kept equal to the corresponding parameters in nominal mode (Fig. 3). Boundary conditions, for example, No. 2 are:

$$p_2 = p_{2*};\ V_2 = V_* \tag{17}$$

Pressure distribution along the pipeline before and after the leak:

$$p = \sqrt{p_{2*}^2 - C\cdot V^2 \cdot \left(L - x_0\right)} \quad \text{with } 0 \le x \le x_0 \tag{18}$$

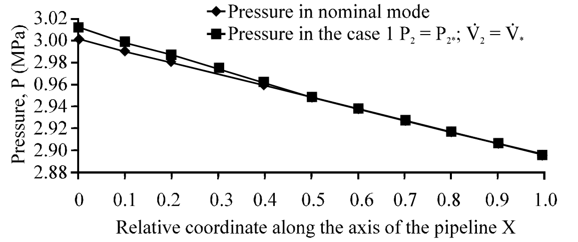

Fig. 3: Changing pressures along the gas pipeline in emergency mode at x_0 = 0.5L, ΔV = 10%

$$p = \sqrt{p_{x_0}^2 - C\cdot\left(V_* + \Delta V\right)^2 \cdot \left(x_0 - x\right)} \quad \text{with } x_0 \le x \le L \tag{19}$$

Based on calculations (Eq. 18 and 19) graphics have been made, Fig. 3. Taking into account boundary conditions 17 (Eq. 8) is as follows:

$$x_0 = \frac{\left(p_{1*}^2 - p_2^2\right) - C\cdot L\cdot V_*^2}{C\cdot\left(V_1^2 - V_*^2\right)} \tag{20}$$

Taking into account boundary conditions (Eq. 17) , Eq. 11 is as follows:

$$x_0 = \frac{V_*^2\cdot\left(p_1^2 - p_{1*}^2\right)}{\left(p_1^2 - p_{2*}^2\right)\cdot\left(V_1^2 - V_*^2\right)}\cdot L \tag{21}$$

Two dependencies Eq. 20 and 21 are obtained to determine the fault location in emergency mode No. 2, taking into account the compressibility factor and the temperature unevenness along the pipeline which allows reducing the recovery time of the energy facility during the accident and increasing its reliability.

The developed mathematical model for determining the leak location can be used for practical calculations of the location of faults in real time which shortens the recovery time for the energy facility after an accident and ultimately reduces financial costs and improves the gas supply of energy complex.

To prove the adequacy of the model developed, comparison with the actual results of gas leaks was made. It was found that, the results of the developed mathematical model have a discrepancy against the actual location of the leak by several meters for gas pipeline length of 11.000 m that explains a high convergence in the results of the numerical experiment (Ksenzov, 2014, 2016) (Fig. 4 and 5).

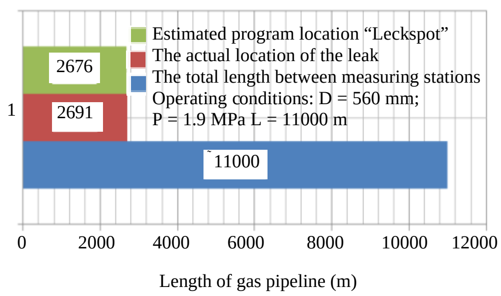

Fig. 4: Comparison of results of calculated and experimental data on determination of leaks in gas pipelines

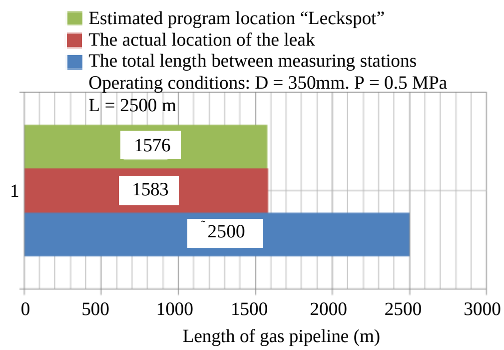

Fig. 5: Comparison of results of calculated and experimental data on determination of leaks in gas pipelines

The prospects for further development of the topic are to create a mathematical model to determine the time of gas outflow and gas emissions through a purge candle on the fuel supply pipeline to power facilities which will improve the quality of repair planning and recovery operations in energy complexes.

CONCLUSION

In case of an emergency during fuel supply to thermal power and heating plants the latter are forced to switch to the reserve fuel supply mode until the accident being detected and eliminated. Early detection and elimination of the accident is urgently necessary.

This study presents the results of a new approach to detecting the gas leak caused by an accident on the fuel supply pipeline at power facilities as well as a new mathematical model based on the computational mathematics methods with regard to the determination of pressure losses along the gas pipeline was developed. This model is based on the motion equations for the real gas flow. It takes into account the factor of compressibility and temperature unevenness along the pipeline which allows reducing the recovery time for energy facility during an accident and increasing its reliability.

LIMITATIONS

The results obtained from the calculations have minor discrepancies with actual data that proves the effectiveness of the new approach.

RECOMMENDATIONS

The results of the work contribute to the mathematical modeling of the processes of gas flow through the pipeline.

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