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Possibilities of Estimating the Amounts of Gas Dissipated in Transport Pipelines

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Abstract

The fluid losses from the hydrocarbon pipelines – that occur as a consequence of the fissures or corrosion perforations of the pipe wall – can be detected by a rigorous balance of the inflows and outflows. This paper deals mainly with an algorithm relative to the calculation of the gas flow rate lost by a fissure situated at a known distance from the pipeline's initial section. For this purpose, the equation governing the gas flow from a tank through an orifice is solved. The case study included here proves that our calculation method is a reasonable procedure for solving this problem.

Key words: *hydrocarbon pipelines, fluid losses, flow rate, pipeline inspection.*

Fundamental Aspects

Virtually, to detect fluid leaks from hydrocarbon pipelines, we can rely on keeping a very good evidence of fluid quantities that go in and out these pipelines, while using meters of adequate accuracy.

In this paper, we will mainly stipulate an algorithm [4] relative to the calculation of gas flow rate leaked by a fissure accidentally appeared on a gas transport pipeline, using the solution of gas outflow from a tank by an orifice, as in figure 1.

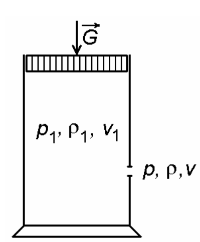

Fig. 1. Gas outflow through an orifice

Denoting by ρ_1, p_1, v_1 gas density, pressure and velocity in the tank, and by ρ, p, v the same movement parameters in the cross section of the mentioned orifice, the microscopic energy equation, written as

$$\frac{\mathrm{d}p}{\rho} + v\,\mathrm{d}v + g\,\mathrm{d}h_l = 0 \tag{1}$$

and associated with the state equation expressed, for an adiabatic process, thus

$$\rho = \rho_1 \left(\frac{p}{p_1} \right)^{1/k}, \tag{2}$$

where k is the adiabatic coefficient, can be brought to the formulation

$$\frac{p_1^{1/k}}{\rho_1}\frac{\mathrm{d}p}{p^{1/k}}+v\,\mathrm{d}v+g\,\mathrm{d}h_l=0\ , \tag{3}$$

in which the local energy losses have the expression

$$h_l=c_l\frac{v^2}{2g}\ , \tag{4}$$

c_l being the orifice local losses coefficient.

By integrating equation (2) we get the relationship [1, 2, 4]

$$\frac{k}{k-1}\frac{p_1^{1/k}}{\rho_1}\left[p^{(k-1)/k}-p_1^{(k-1)/k}\right]+\frac{1}{2}\frac{v^2}{v_1^2}+g\,h_l=0\ , \tag{5}$$

which, by neglecting the term $v_1^2/2$, leads, for the velocity v, to the formula

$$v=c_v\sqrt{\frac{2k}{k-1}\frac{p_1}{\rho_1}\left[1-\left(\frac{p}{p_1}\right)^{(k-1)/k}\right]}\ , \tag{6}$$

where the velocity coefficient c_v is given by the expression

$$c_v=\frac{1}{\sqrt{1+c_l}}\ . \tag{7}$$

Taking into account that the mass flow rate M can be formulated as

$$M=c_c\,A\rho\,v\ , \tag{8}$$

where c_c is the gas vein contraction coefficient at the orifice outlet, then using the relationships (2) and (6) we will obtain the equation

$$M=c_d\,A\sqrt{\frac{2k}{k-1}p_1\rho_1\left[\left(\frac{p}{p_1}\right)^{2/k}-\left(\frac{p}{p_1}\right)^{(k+1)/k}\right]}\ , \tag{9}$$

in which the flow rate coefficient c_d is defined as

$$c_d=c_c\,c_v\ . \tag{10}$$

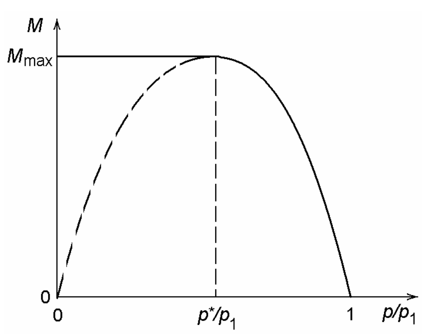

Fig. 2. Mass flow rate versus pressure ratio plot

By plotting the mass flow rate M defined by equation (9), the graph in figure 2 is obtained, where the intermittent portion of the curve has no physical meaning and, consequently, it is replaced by the horizontal straight line corresponding to $M = M_{\max}$. This line indicates the fact that, as soon as the gas pressure in the orifice reaches the critical (sonic regime) value p^*, the mass flow rate M can no longer increase with decreasing pipeline's cross-section.

Imposing to the function $M(p/p_1)$ defined by the relationship (9) the maximum condition expressed as

$$\frac{\mathrm{d}M}{\mathrm{d}(p/p_1)}=0\ , \tag{11}$$

the critical pressure p^* is obtained under the form

$$\frac{p^*}{p_1}=\left(\frac{2}{k+1}\right)^{k/(k-1)}\ , \tag{12}$$

which, put into the relationship (6), leads to the formula

$$v^* = c_v \sqrt{k \frac{p^*}{\rho^*}} = c \,, \tag{13}$$

which shows that the increase of mass flow rate over the $M_{\max}$ value is impossible, because the gas vein is unable to exceed the sound velocity c into the orifice. This inability of gas movement to evolve in the supersonic range can be undone by replacing the orifice by a convergent – divergent nozzle, whose usefulness is certain in the domain of supersonic jet planes, as well as in that of gas turbines used to produce electric energy.

In the case of air flow through an orifice in the sonic velocity range, $k = 1.4$ and, according to equation (12), the dimensionless critical pressure has the value

$$\frac{p^*}{p_1} = \left(\frac{2}{2.4}\right)^{1.4/0.4} = 0.528 \,,$$

which indicates that the plot in figure 2 is not symmetrical around the p^*/p_1 abscissa.

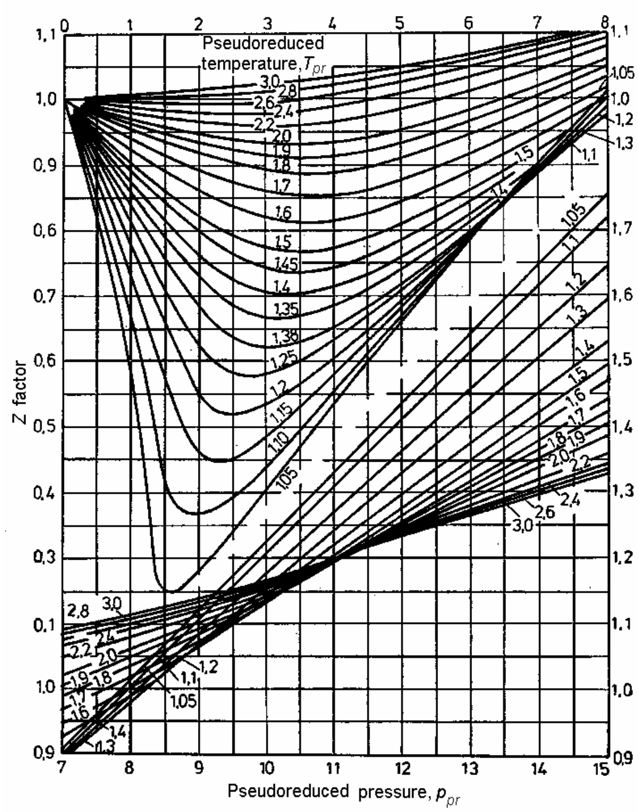

Fig. 3. Standing – Katz diagram

Case Study [4]

Let us consider a pipeline having the inner diameter d_i = 148.2 mm, which transports natural gas upon the distance l = 90 km, at the flow rate Q_0 = $2{\cdot}10^5$ $\mathrm{m_N^3/day}$. Supposing that the gas pressure in the pipeline's initial section is p_1 = 4.5 MPa, and that, at the distance l_f = 70 km, a fissure, having the area A_f = 5 mm^2, appeared in the pipe wall, we intend to estimate the gas flow rate lost by this fissure, accepting the following values: gas relative density ρ_r = 0.554, gas adiabatic exponent k = 1.32, air constant R_a = 286.79 J/(kmol·K), and gas constant temperature T = 285 K.

In absence of the fissure in the pipe's wall, the gas pressure in the pipeline's final section has the expression [2, 3, 4]

$$p_2 = \sqrt{p_1^2 - \left(\frac{4 p_0 Q_0}{\pi d^2 T_0}\right)^2 \frac{1}{R_a} \frac{\lambda Z \rho_r T l}{d}} \,, \tag{14}$$

where the hydraulic resistance coefficient λ is given by Weymouth's relationship written as

$$\lambda = \frac{0.009407}{\sqrt[3]{d}} \tag{15}$$

and having the value $\lambda = 0.01777$.

Accepting, for a first attempt, the value $Z = 0.95$, the relationship (14) leads to $p_2 = 2.5$ MPa.

The check-up of the Z value can be done using the Standing – Katz diagram in figure 3 [1, 5].

Taking into account that the natural gas considered here has the critical parameters $p_c = 4.58$ MPa and $T_c = 190.7$ K, the reduced parameters, defined as

$$p_r = p_m / p_c \ , \tag{16}$$

$$T_r = T/T_c \ , \tag{17}$$

where the average gas pressure in the pipeline has the expression

$$p_m = \frac{2}{3}\left(p_1 + \frac{p_2^2}{p_1 + p_2} \right) , \tag{18}$$

yielding $p_m = 3.59$ MPa, will have the values

$$p_{r1} = \frac{3.59}{4.58} = 0.78 \ ,$$

$$T_r = \frac{285}{190.7} = 1.49 \ ,$$

which lead, in figure 3, to $Z = 0.93$, close enough to the value $Z = 0.95$ considered in the previous calculations.

On the other hand, the equation [1, 3]

$$p^2 = p_1^2 - \frac{p_1^2 - p_2^2}{l} x \ , \tag{19}$$

expressed in the fissured region as

$$p_f = \left(p_1^2 - \frac{p_1^2 - p_2^2}{l} l_f \right)^{1/2} , \tag{20}$$

gives $p_f = 3.53$ MPa.

Consequently, the pressure ratio in the gas leaking region is formally equal to

$$\frac{p_0}{p_f} = \frac{1.01325}{35.3} = 28.703 \cdot 10^{-3} \ .$$

Actually, relationship (12) gives for the pressure critical ratio the value

$$\frac{p^*}{p_f} = \left(\frac{2}{1.32 + 1} \right)^{1.32/(1.32-1)} = 0.542 \ ,$$

which, being greater that p_0/p_f, shows that the gas flow rate lost by the fissure will be defined by equation (9) written for $p/p_1 = p^*/p_f = 0.542$.

In these conditions, admitting that $c_d = 0.90$, the maximum flow rate lost from the pipeline is obtained, according to relationship (9), as having the value

$$M_f = M_{\max} = 32.078 \cdot 10^{-3} \ \text{kg/s} = 2{,}771.539 \ \text{kg/day}$$

which is equivalent to a volume flow rate in normal pressure and temperature conditions equal to

$$Q_{0f} = \frac{M_f}{\rho_0} = \frac{2{,}771.539}{0.554 \cdot 1.2} = 4{,}168.98 \ \text{m}_\text{N}^3/\text{day} \ ,$$

representing $2 \cdot 10^{-4}$ % of the flow rate transported through the pipeline in a steady-state regime.

Assimilating the fissured pipe wall with a diaphragm belonging to a flow meter, and taking into account that the flow rate formula for the flow meter [6, 7, 8, 9] can be written as follows

$$Q = C\sqrt{\Delta h \, p_s} \ , \tag{21}$$

where Δh is the differential pressure expressed as height of fluid column, p_s is the static pressure in the diaphragm region, and the flow rate coefficient C has the relationship

$$C = C_b \, C_{pb} \, C_{tb} \, C_{tc} \, C_g \, C_r \, C_e \, C_{sc} \, C_m \, C_l \, C_{et} \ , \tag{22}$$

in which C_b is the basic orifice flow coefficient, C_{pb} – reference pressure coefficient, C_{tb} – reference temperature coefficient, C_{tc} – fluid temperature coefficient, C_g – gravity effect coefficient, C_r –Reynolds number coefficient, C_e – gas expansion coefficient, C_{sc} – super-conductibility coefficient, C_m – manometer coefficient, C_l – manometer positioning coefficient, C_{et} – diaphragm orifice thermal expansion coefficient, the effects described by this global coefficient are found in equation (9), in which the flow rate coefficient c_d can play an important role.

Conclusions

- The pipeline systems used to collect hydrocarbons or to transport them at long distances are virtually made of steel, and the pipe pieces are usually assembled by welding, in conditions of dependency of pipeline diameter mainly on mass flow rate which has to be transported.
- Normally, the hydrocarbon flow lines in petroleum fields have inner diameters ranging from 50.8 mm (2 in) to 1,524 mm (60 in), the collecting flow lines consist of pipes whose diameter is from 101.6 mm (4 in) up to 304 mm (12 in), while the main flow lines, for long distance transportation of oil and gas, can attain an outer diameter of 1,422.2 mm (56 in). Many of the steel flow lines are protected on the outside by an anticorrosive layer.
- The relatively low cost price, the easier and less expensive installation, as well as the elimination of cathode anticorrosive protection associated to the plastic made pipes constitute the main arguments for their preferential use in the natural gas distribution domain.
- An essential parameter of a steel or plastic gas pipeline design is represented by the maximum work pressure, for a diameter and a material quality imposed; that maximum pressure determines the pipeline mass flow rate, when the other system parameters are set, in correlation to the physical and chemical properties of the pipeline material.
- Each hydrocarbon transportation pipeline system has unique characteristics, which imposes the choice of the most adequate type for its supervisory control system.
- An efficient supervisory control system can and has to ensure: a) pipelines and related equipment protection, by monitoring and adjusting pressure and other operating variables, and launching warning signals when the limit values specific to the operation conditions are exceeded; b) monitoring the performance of the engines and equipments in the network; c) fluid losses detection, and d) performing a predictive and preventive maintenance in order to keep the operation expenses at a low level.
- The use of SCADA (Supervisory Control And Data Acquisition) systems, defined as computer hard and soft systems which perform a specific set of monitoring and control functions, permits the detection of fluid leaks out the pipelines and also deliver data on gas movement parameters through the supervised pipeline system.
- To maintain the integrity of a steel-made flow line, a cathode protection system can be used, the electrical power needed to actuate this system being supplied, if possible, by solar energy converters.
- Controlling hydrate formation in pipelines, removing water from gas, eliminating traces of hydrogen sulphide possibly present in gas, as well as mercaptane addition has to be

primordial concerns for fully safe gas delivery, either for pipeline gas transporters or for house and industrial gas consumers.

- Detection of fluid losses from hydrocarbon transportation pipelines can be done by keeping an accurate balance of gas quantities that go in and out each pipeline, while using meters with indisputable certitude degree.
- Traditionally, hydrocarbon transportation pipelines are visually inspected, by going through its route on land or by patrolling the route with a cruise airplane. Nowadays, the aerial inspection is associated with the use of monitoring and instrumental equipment, which is able to show rapidly and precisely the position of the fluid loss from the pipeline, as well as the leakage potential.
- The inner inspection of the pipelines can be performed using intelligent pigs equipped with sophisticated device packages, which moves ahead through the pipeline, driven by fluid pressure, and detects the fissures, corrosion degrades or out-of-roundness distortions.
- The case study presented in this work, relative to the estimation of the gas flow rate dissipated through a fissure formed in pipe's wall, offers a reasonable procedure for solving this problem.

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Posibilități de estimare a cantităților de gaze disipate din conductele de transport

Rezumat

Detectarea pierderilor de fluide din conductele de hidrocarburi este posibilă prin ţinerea unei evidenţe stricte a cantităţilor de fluide intrate respectiv ieşite din acestea, utilizând contoare de mare precizie. În lucrarea de faţă este preconizat, în principal, un algoritm relativ la calculul debitului de gaze scurse printr-o fisură a unei conducte de transport, situată la o anumită distanţă faţă de secţiunea iniţială a conductei. În acest scop, se apelează la soluţionarea ecuaţiilor scurgerii gazelor dintr-un recipient printr-un orificiu. Studiul de caz inclus în lucrare atestă faptul că metoda de calcul propusă reprezintă o procedură rezonabilă pentru rezolvarea acestei probleme.