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Spotting the Failure Position and Estimating the Rate of Wear of a Pipe

Doru Stoianovici, Maria Stoicescu, Tudora Cristescu

Universitatea Petrol-Gaze din Ploieşti, Bd. Bucureşti 39, Ploieşti
e-mail: doru.stoianovici@yahoo.com

Abstract

Failures (leaks or breakages) could appear during a pipe exploitation due to corrosion, breakages, accidental loadings or overstressing.
These failures have various sizes and it is difficult to find them because the transportation system is mostly buried, the period of time when a great deal of transported products is leaking-off resulting in the pollution of pipe adjacent areas.

Key words: *failure spot, pipe wear.*

Detecting a Potential Failure Spot

Finding a failure has a special importance in the pipe exploitation regardless if the failure has a slow evolution in time or if it appears as a result of a local accident. The first situation is more difficult to observe since the modification of nominal parameters has a temporally slow evolution. The size of the failure directly influences the period of time it could be found; a small failure is harder to find than a big one.

Theoretically, a careful following of the products balance-sheet pumped from a place and received in another place could result in a failure appearance place finding, regardless of its size.

The occurrence of a gap through which the flow rate, Q_e, results in hydraulic regime modification, both upstream as well as downstream.

It is stated that at a certain distance, l_1, measured from the start point of the pipe, the pipe pressure was p_{d1} before the failure appearance and p_{d2} after that.

It is also stated that the transported flow rate between the start point and failure was Q_1 before the failure appearance, then, after the failure, the flow rate in the start point decreases at Q_2 and at the end of the pipe the flow rate is Q_3.

In the case of the liquid phases transportation, the relation between the flow rates mentioned above is the following

$$Q_2 = Q_3 + Q_\mathrm{e} \tag{1}$$

Before and after the failure appearance, Bernoulli's equations rectified with losses of pressure between the start point and the failure of the pipe result in the following equations:

$$p_{i1} + \rho g z_1 = p_{d1} + \rho g z_d + \frac{8\rho Q_1^2 l_1 \lambda_1}{\pi^2 d^5}, \tag{2}$$

$$p_{i2} + \rho g z_i = p_{d2} + \rho g z_d + \frac{8\rho Q_2^2 l_1 \lambda_2}{\pi^2 d^5} \tag{3}$$

Here p_{i1} and p_{i2} are pumping pressures in the start point of pipe before and after the failure appearance. z_i is altitude of the start point and z_d is altitude of the place on the pipe where the failure appeared. Alsou ρ is density of transported fluid through the pipe having inside diameter d, λ_1 and λ_2 are hydraulic strength factors according to debits Q_1 and Q_2, respectively (figure 1).

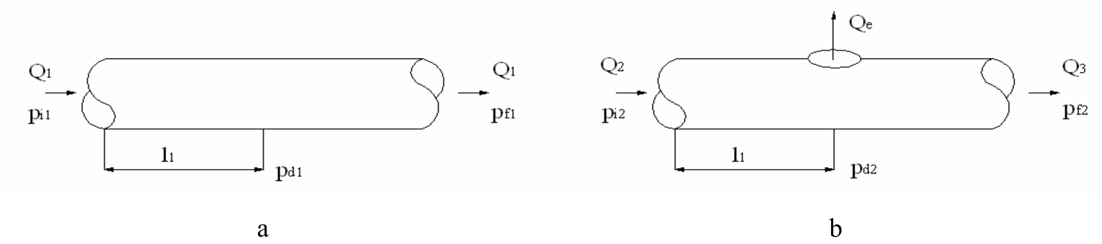

Fig. 1. Study schemes: a-before failure; b-after failure

If the following notations are introduced: $\Delta p_i = p_{i1} - p_{i2}$ and $\Delta p = pd_1 - pd_2$, from (2) and (3) results the equation

$$\Delta p_i = \Delta p + \frac{8\rho l_1}{\pi^2 d^5}\left(Q_1^2 \lambda_1 - Q_2^2 \lambda_2\right). \tag{4}$$

Between the failure and the end point of the pipe characterized by altitude z_f, p_{f1} and p_{f2} - pressures before and after the failure appearance, similar to equations (2) and (3) we can write another two equations where losses of pressure due to friction are generated by debits Q_1 and Q_3, respectively:

$$p_{d1} + \rho g z_d = p_{f1} + \rho g z_f + \frac{8\rho Q_1^2 (l - l_1)\lambda_1}{\pi^2 d^5} \tag{5}$$

$$p_{d2} + \rho g z_d = p_{f2} + \rho g z_f + \frac{8\rho Q_3^2 (l - l_1)\lambda_3}{\pi^2 d^5} \tag{6}$$

Subtracting them, the result is

$$\Delta p = \Delta p_f + \frac{8\rho (l - l_1)}{\pi^2 d^5}\left(Q_1^2 \lambda_1 - Q_3^2 \lambda_3\right) \tag{7}$$

where $\Delta p_f = p_{f1} - p_{f2}$, λ_3 is strength factor according to debit Q_3, and l is length of pipe.

Eliminating differential pressure, Δp in the equation (4) şi (7) we can determine the length, l_1 between the start point of the pipe and the failure

$$l_1 = \frac{\left(\Delta p_i - \Delta p_f\right) - \frac{8\rho \cdot l}{\pi^2 d^5}\left(Q_1^2 \lambda_1 - Q_3^2 \lambda_3\right)}{\frac{8\rho}{\pi^2 d^5}\left(Q_3^2 \lambda_3 - Q_2^2 \lambda_2\right)}. \tag{8}$$

It can be noticed that a careful registering of debits and pressures at the start and at the end point of pipe leads to the calculation of the length, l_1.

Numerical Example

Pipe Diameter	**F**	**[m] =**	0.324
Fluid Density	**r**	**[kg/mc] =**	830
Length of the Pipe	**L**	**[m] =**	46,000
Kinetic Viscosity	**n**	**[m2/s] =**	0.00000295
Normal pumping regime			
Pumping Flow	$\mathbf{Q_1}$	**[mc/h] =**	220
Pumping Pressure	$\mathbf{pi_1}$	**[bar] =**	45
Pressure at the end of the Pipe	$\mathbf{pf_1}$	**[bar] =**	4
Modified pumping regime			
Pumping Flow	$\mathbf{Q_2}$	**[mc/h] =**	203
Flow at the end of the Pipe	$\mathbf{Q_3}$	**[mc/h] =**	201
Pumping Pressure	$\mathbf{pi_2}$	**[bar] =**	44
Pressure at the end of the Pipe	$\mathbf{pf_2}$	**[bar] =**	3.85
Leak Position (as resulted from computing it)	$\mathbf{L_d}$	**[m] =**	16,379.2

Leakage of Fluid through a Clogged Failure

The leaked fluid is filtered through a porous material adjacent to the failure having the role to adjust the leaked debit through the failure.

The leakage of fluid through the porous material is complicated both by the fact that the streamlines have complex geometrics and by continuous modification of the filtration regime from the exit of the hole up to the ground surface.

The debit through a hole with a cross-section, S and a discharge coefficient, α has the following formula

$$Q_e = \alpha S \sqrt{\frac{2}{\rho}\left(p_{d_2} - p_e\right)} = \alpha S V_0 . \tag{9}$$

As it was stated before, p_{d2} is pressure inside the pipe and p_e is pressure out of the failure.

Here α has different values depending both of the geometry of hole and of the flow regime through the failure. Usually, in practice, we only consider the first variable, so α is in the range of 0,6 şi 0,7, and V_0 is average leaked fluid velocity through the hole.

After the fluid leaked through the hole, it is filtered by the porous material adjacent to the failure up to the ground surface.

The filtration velocity can be calculated using Darcy's formula:

$$V = -\frac{k}{\mu}\frac{\mathrm{d}p}{\mathrm{d}l} \tag{10}$$

where k is porous material permeability, μ - fluid dynamic viscosity, dp/dl - gradient of pressure due to the filtration process, and x is the distance measured from the hole level.

Debit crossing a section, *S(x)* of the porous material is the following

$$Q_e = -S(x)\frac{k}{\mu}\frac{\mathrm{d}p}{\mathrm{d}l} . \tag{11}$$

Section *S(x)* derives noticing that velocity in a point at the ground surface placed at a distance r against the vertical line through the pipe' failure is

$$\mathrm{v}=\frac{k}{\mu}\frac{p_e-p_a}{\sqrt{H^2+r^2}} \tag{12}$$

and velocity, v_n surface normal in the same point is

$$\mathrm{v}_n=\frac{k}{\mu}\frac{p_e-p_a}{\sqrt{H^2+r^2}}cos\,\theta=\frac{k}{\mu}\frac{p_e-p_a}{\sqrt{H^2+r^2}}\frac{H}{\sqrt{H^2+r^2}}\,. \tag{13}$$

Here Θ is the angle between the normal plane on the failure and the line joining the failure and the point of velocity v (figure 2).

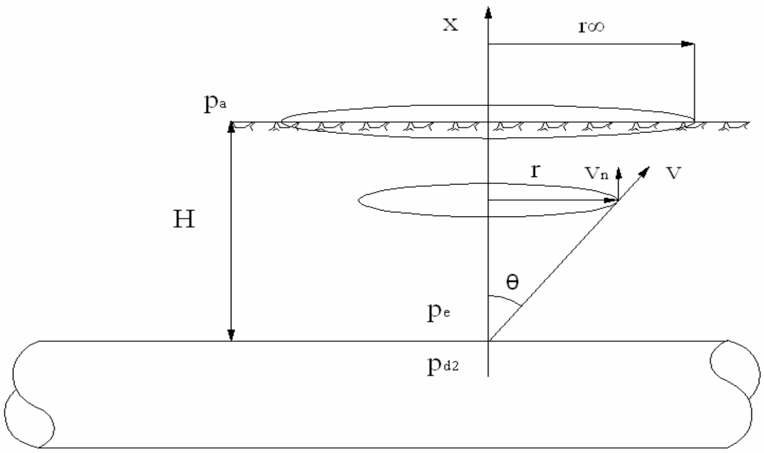

Fig. 2. A failure on an underground pipe. Diagram of the fluid filtration velocity

We can be notice that the velocity, v_n decreases on the ground surface proportional to r^2. If we introduce base velocity, v_s as the highest normal velocity (when $r = 0$) results

$$\mathrm{v}_n=\mathrm{v}_s\frac{H^2}{H^2+r^2}\,. \tag{14}$$

The radius, r_∞ is introduced so that the velocity, v_n becomes small enough, practically considered zero, in this case the filtrated fluid debit at the ground surface through the circle with radius r_∞ is

$$Q_e=2\pi\int_o^{r_\infty}\mathrm{v}_n r\mathrm{d}r=\pi H^2\mathrm{v}_s\int_0^{r_\infty}\frac{2r}{H^2+r_\infty^2}\mathrm{d}r=\pi H^2\mathrm{v}_s\ln\frac{H^2+r_\infty^2}{H^2}\,. \tag{15}$$

It can be admitted that at the ground surface, through the circle with radius r_∞, the same debit is filtrated as through the circle with radius $H\sqrt{\ln\frac{H^2+r_\infty^2}{H^2}}$, in the last case the filtration velocity being constantly and equal to v_s.

If a linear variation of filtration area *S(x)* in regard of x in the porous background is allowed

$$S(x)=S+\frac{x}{H}\left(\pi H^2\ln\frac{H^2+r_\infty^2}{H^2}-S\right) \tag{16}$$

taking into account the relation (11), the following differential equation in p and x results

$$\mathrm{d}p = -\frac{\mu Q_e}{k}\frac{H}{SH + x\left(\pi H^2 \ln\dfrac{H^2 + r_\infty^2}{H^2} - S\right)}\mathrm{d}x\,. \quad (17)$$

So, the fluid filtration through the porous material is assimilated with a filtration through a conoid having bases areas S and $\pi H^2 \ln\dfrac{H^2 + r_\infty^2}{H^2}$, respectively, and high, H.

The resulted differential equation is being integrated in the following boundary condition:

$$\text{at } x = 0, p = p_e\text{ ; at } x = H, p = p_a\,. \quad (18)$$

The equation (17) thereby goes to

$$Q_e = \frac{k(p_e - p_a)\left(\pi H^2 \ln\dfrac{H^2 + r_\infty^2}{H^2} - S\right)}{\mu H \ln \pi \dfrac{H^2}{S} \ln\dfrac{H^2 + r_\infty^2}{H^2}}\,. \quad (19)$$

The obtained debit is equal to the one resulted by formula (9), so the following equality becomes feasible

$$\frac{k(p_e - p_a)\left(\pi H^2 \ln\dfrac{H^2 + r_\infty^2}{H^2} - S\right)}{\mu H \ln \pi \dfrac{H^2}{S} \ln\dfrac{H^2 + r_\infty^2}{H^2}} = \alpha S \sqrt{2\frac{p_{d2} - p_e}{\rho}}\,. \quad (20)$$

The obtained relation allows to determine whichever of the variables it consists of. Practically, the greatest interest is to determine the failure size of the pipe, i.e. section S, which determines the rate of the pipe wear.

It is possible to simplify equation (20),and so it is known that for a small argument x, the following approximation exists: $\ln(1+x)\approx x$, and because of that we can get the following result

$$\ln\left(1 + \frac{r_\infty^2}{H^2}\right) \cong \frac{r_\infty^2}{H^2}\,. \quad (21)$$

The term $\pi H^2 \ln\dfrac{H^2 + r_\infty^2}{H^2} - S$ can be successively written

$$\pi H^2 \ln\frac{H^2 + r_\infty^2}{H^2} - S = \pi H^2 \frac{r_\infty^2}{H^2} - S \cong \pi r_\infty^2\,, \quad (22)$$

where section S is stated much smaller than πr_∞^2.

Similarly we can proceed with denominator of the left term of equation (20) which becomes

$$\frac{k(p_e - p_a)\pi \cdot r_\infty^2}{H\, ln\, \pi \dfrac{r_\infty^2}{S}} = \alpha S \sqrt{2\frac{p_{d2} - p_e}{\rho}}\,. \quad (23)$$

The resulted equality can be written in terms of medium velocities v_0 and v_s, assuming discharge coefficient $\alpha = 1$ as

$$\frac{v_0}{v_s} = \frac{\frac{\pi \cdot r_\infty^2}{S}}{\ln \frac{\pi \cdot r_\infty^2}{S}} . \tag{24}$$

Introducing $y = \pi \frac{r_\infty^2}{S}$, the function f(*y*) has the following expression

$$f(y) = \frac{v_0}{v_s} = \frac{y}{\ln y} \tag{25}$$

and it is represented in regard to y only for its positive values, as in figure 3

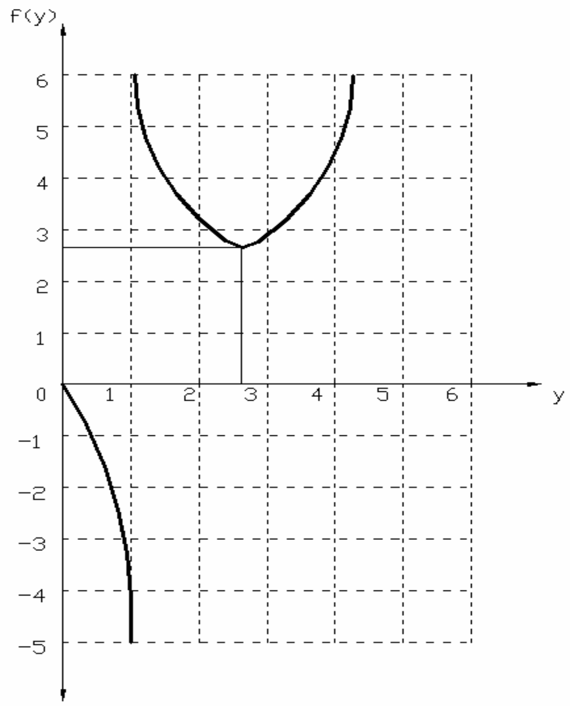

Fig. 3. Graphic representation of the function f(y)

It is noticed that ratio v_0/v_s is negative for $0 \leq y \leq 1$; that means v_0 şi v_s are not compatible in this range. Ratio v_0/v_s is positive for any $y \geq 1$ and its smallest value is when y= e

$$\left(\frac{v_0}{v_s}\right)_{min} = \frac{e}{\ln e} = e \tag{26}$$

Theoretically, that means that variation limits of v_0 / v_s are in the range (e, ∞).

Criteria to Determine the Rate of a Pipe Wear off

Analyzing the chart in figure 3 we can see that parameter $\pi r_\infty^2 / S$ could have two distinct variation ranges, namely from 1 to e and from e to ∞.

In the first domain it can be simply proved that a variation of parameter $\pi r_\infty^2 / S$ is impossible. Thus, starting from the definition of radius r_∞, this can satisfy the following relation

$$\varepsilon \leq \frac{H^2}{H^2 + r_\infty^2}. \tag{27}$$

From formula 27, we can obtain

$$r_\infty^2 \leq \frac{H^2(1-\varepsilon)}{\varepsilon} \cong \frac{H^2}{\varepsilon}. \tag{28}$$

This approximation was due to the fact that $1/\varepsilon \geq 1$. If the non-dimensional parameter would be in the range (1, e) the following situation would exist

$$1 \leq \frac{\pi \cdot r_\infty^2}{S} \leq \mathrm{e}, \tag{29}$$

this leading to the equivalent expressions

$$1 \leq \frac{\pi \cdot H^2}{\varepsilon \cdot S} \leq \mathrm{e}. \tag{30}$$

Thereby, a contradiction appears regarding *ε,* because the following expressions would be simultaneous:

$$\varepsilon \leq \frac{\pi \cdot H^2}{S} \qquad \textit{and} \qquad \varepsilon \geq \frac{\pi \cdot H^2}{\mathrm{e}S}. \tag{31}$$

When parameter $\pi r_\infty^2 / S$ varies in the range (e, ∞), the result is

$$\mathrm{e} \leq \frac{\pi \cdot H^2}{\mathrm{e}S} < \infty \tag{32}$$

and for a certain value of *S*,

$$\varepsilon \leq \frac{\pi \cdot H^2}{\mathrm{e}S}. \tag{33}$$

The following expression is also in the range (e,∞):

$$\pi \cdot H^2 \leq \infty(\varepsilon \cdot S) \tag{34}$$

Besides, the variation range of v_0/v_S from 1 to e shall be excluded being practically impossible to be achieved because parameter $\pi r_\infty^2 / S$ is close to unit; according to the continuity equation, that goes to a value for v_0 closed to v_S, and in no way it leads to a high value for v_0/v_S, as we can see in figure 3.

These reasons also allow to state that $\pi r_\infty^2 / S$ is in the range (e, ∞), which leads to the simultaneous writing of the expressions

$$0 \leq \frac{S}{\pi \cdot r_\infty^2} \leq \frac{1}{\mathrm{e}}. \tag{35}$$

That means the section area of a pipe failure is in the range

$$S = (0.....0{,}3678) \cdot \pi \cdot r_\infty^2 \tag{36}$$

and it represents an important parameter in pipe rate of wear appreciation. For an allowable value of *ε* and a pipe burying depth, H, radius r_∞ can be easily determined according to (28) when, practically, H is more often known than r_∞. Evidently, in case of a non-failure pipe *S*=0, so we can appraise a zero rate of wear. The higher rate of wear, the bigger S. Maximum value of S will be $0.3678 \cdot \pi \cdot r_\infty^2$ and it will correspond to a maximum rate of wear (unit).

The rate of wear *u* is determined using the following expression:

$$u = \frac{S}{\pi \cdot (0.6065 \cdot r_\infty)^2} \tag{37}$$

allowing values of *u* in the range (0,1) and so it becomes a pipe wear evaluation standard.

Conclusions

The occurrence of a failure during a pipe exploitation results in the hydraulic regime modification, both upstream as well as downstream.

A careful following of the products balance-sheet pumped from a place and received in another place couls result in a failure appearance place finding regardless of its size.

In this paper, an important parameter in the pipe rate of wear appreciation was determined based on an analytical criterion.

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Determinarea poziţiei unui defect şi estimarea gradului de uzură al unei conducte

Rezumat

Sunt analizate posibilitaţiile depistării prin calcul a unui defect format pe o conductă prin urmarirea continua a parametrilor tehnologici de pompare, precum şi relaţiile de calcul a debitului de lichid scurs printr-un orificiu astupat. Se stabilesc criterii pentru aprecierea gradului de uzură al unei conducte de transport produse lichide.