Pipe transients in engineering practice

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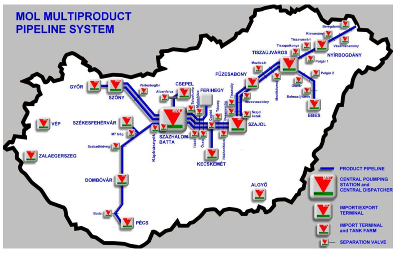
The pipe network and the control system



The control center built by CASON Plc.

1500 km total length
Diameter: 100 - 400 mm
Laid under the ground in 1.5 m depth.
Crossing private farms and forests → Hard to protect.
The recovery of the damage is very expensive.

Project aims

- To develop a monitoring system which is able to
  - detect the fact of leakage or taping ASAP,
  - localize the leakage,
  - estimate the intensity of leakage.
- Not to change the existing sensors.

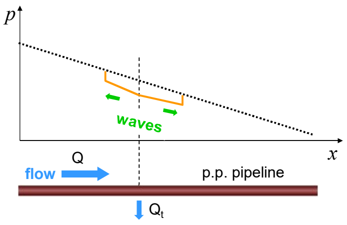
Acoustic method

Based on the detection of pressure waves caused by the tapping.

Hydraulic method

Based on the difference in pipe friction (and hydraulic grad line) upstream and downstream from the taping point.

The acoustic method



$\tilde v$ and $\tilde p$ are the velocity and pressure perturbations caused by the taping.

Two pressure waves are induced: $Q_t = 2A\tilde v$

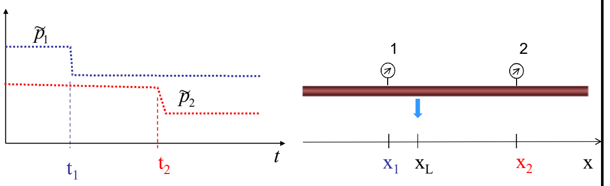
From the Alievi theorem: $Q_t = 2A\dfrac{\tilde p}{\rho a}$

We can estimate the magnitude of the pressure perturbation in a realistic case:

$$\tilde p = Q_t \rho a \frac{4}{2D^2\pi} \cong 0.001\cdot 800\cdot 1000\frac{4}{2(0.2)^2\pi} = 12700\,\text{Pa} = 0.127\,\text{bar}$$

Ok, this is detectable with modern pressure sensors.

The acoustic method

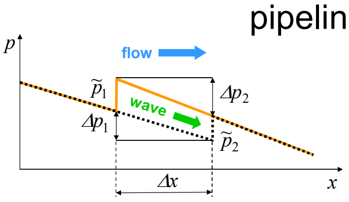


Location of the leakage: $x_L = \dfrac{x_2+x_1}{2} + \dfrac{t_2-t_1}{2a}$

Wave attenuation is so low in closed pipelines, that the reflected waves can be observed as well.

Interestingly, in this case, even one pressure gauge is enough for leakage localization.

Wave attenuation in an operational pipeline



$$\Delta p_1 + \tilde p_1 = \Delta p_2 + \tilde p_2$$

$$\frac{d\tilde p}{dx} = \frac{\tilde p_2 - \tilde p_1}{\Delta x} = \frac{\Delta p_1 - \Delta p_2}{\Delta x}$$

$$\frac{d\tilde p}{dx} = \frac{1}{\Delta x}\left(\frac{\rho}{2}(v-\tilde v)^2\frac{\Delta x}{D}\lambda - \frac{\rho}{2}v^2\frac{\Delta x}{D}\lambda\right)$$

$$\frac{d\tilde p}{dx} = \frac{\rho\lambda}{2D}\left(v^2 - 2v\tilde v + \tilde v^2 - v^2\right)$$

$\tilde v^2 \cong 0$

Wave attenuation in an operational pipeline

$$\frac{d\tilde{p}}{dx} = -\frac{\rho\lambda}{D} v\tilde{v}$$

$$\tilde{p} = \rho a \tilde{v} \longrightarrow \frac{d\tilde{p}}{dx} = -\frac{\lambda}{D}\frac{v}{a}\tilde{p}$$

$$\frac{d\tilde{p}}{\tilde{p}} = -\frac{\lambda}{D}\frac{v}{a}dx$$

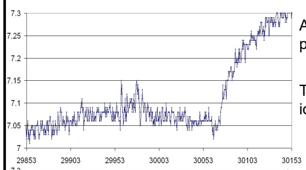
$$ln\frac{\tilde{p}}{\tilde{p}_0} = -\frac{\lambda}{D}\frac{v}{a}L \longrightarrow \tilde{p} = \tilde{p}_0 e^{-\frac{L}{D}\frac{v}{a}\lambda}$$

Let's estimate the attenuation rate in a realistic case:

$$\frac{L}{D}\frac{v}{a}\lambda = \frac{1000}{0.2}\frac{1}{1000}0.02 = 0.1 \longrightarrow \frac{\tilde{p}}{\tilde{p}_0} = e^{-0.1} \cong 0.9$$

Which is 10% per 1 kilometer.

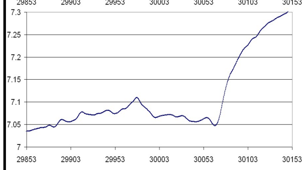
Detecting pressure changes on noisy signals



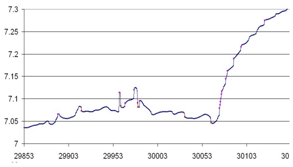
A typical measured pressure signal

The characteristic breakpoints need to be identified.

Live demo



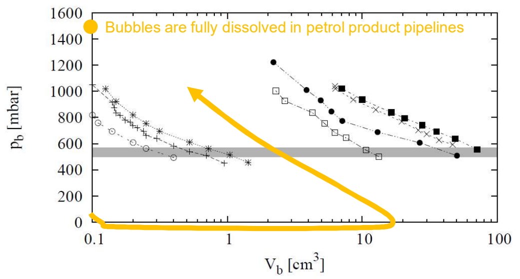
After low-pass filtering



After the application of the purpose developed filter

Bubble content

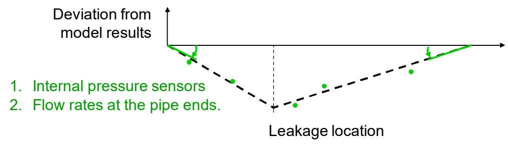
Laboratory experiments on Shell 95 summer benzene:



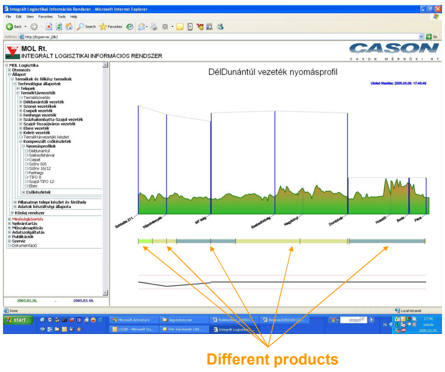
At least 1.5 bar gauge pressure is necessary in the pipeline.

The hydraulic method

- Real time hydraulic simulation of the steady state pressure profile.
- Real time comparison of model results with measured pressure data.
- Estimation of the location of highest deviation.

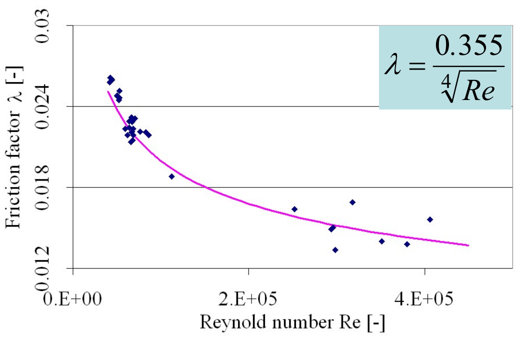


Multi batch operation



Pipe friction

Friction factor was measured on strait sections.



Hydraulic model

Pressure at an arbitrary point of the pipe from the Bernoulli law:

$$p_k = p_0 - Q^2 \sum_{i=1}^{k} \rho_i \lambda_i \frac{x_i - x_{i-1}}{2\, d_i\, A_i^2} - \sum_{i=1}^{k} \rho_i g \cdot \left(z_i - z_{i-1}\right)$$

$$a_k = \sum_{i=1}^{k} \rho_i \lambda_i \frac{x_i - x_{i-1}}{2\, d_i\, A_i^2}$$ Hydraulic coordinate

$$b_k = \sum_{i=1}^{k} \rho_i g \cdot \left(z_i - z_{i-1}\right)$$ Geodetic pressure drop

$$c = Q^2$$ Leakage free flow rate

$$p_k = p_0 - c \cdot a_k - b_k$$ Pressure value from the model

Hydraulic model

The residuum function

$$E_k = p'_k - p_0 + c \cdot a_k + b_k$$

In which p'_k is the measured pressure.

$$E_0 = 0 \text{ and } E_N = 0 \implies c = \frac{p_0 - p_N - b_N}{a_N} = Q^2$$

Leakage increases flow rate on the upstream side

$$E_h^- = p_0 - Q_0^2 \cdot a_h - b_h - p_0 + c \cdot a_h + b_h$$

$$E_h^- = \left(c - Q_0^2\right) \cdot a_h$$

$$\left.\frac{dE}{da}\right|_0 = c - Q_0^2$$

Hydraulic model

Leakage decreases flow rate on the downstream side

$$E_h^+ = p_N + Q_N^2 \cdot \left(a_N - a_h\right) + b_N - b_h - p_0 + c \cdot a_h + b_h$$

$$E_h^+ = \left(Q_N^2 - c\right) \cdot \left(a_N - a_h\right)$$

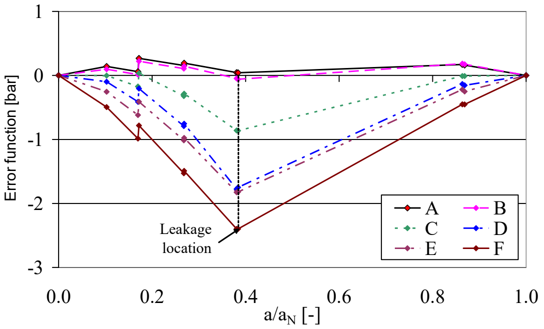
$$\left.\frac{dE}{da}\right|_N = c - Q_N^2$$

Residuum in the taping point

$$E_h^+ = E_h^- \implies a_h = a_N \cdot \frac{c - Q_N^2}{Q_0^2 - Q_N^2} \implies x_h$$

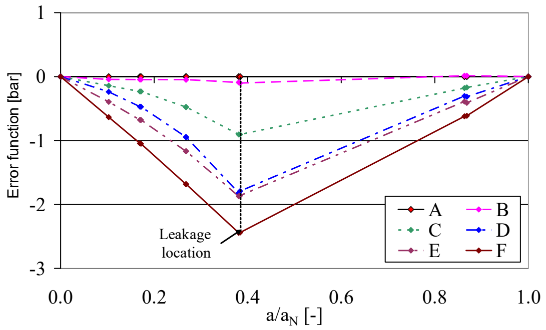
Experimental verification

190 km long pipeline, 3 different diameters, multi-batch operation, Q_t was 5.5% of Q



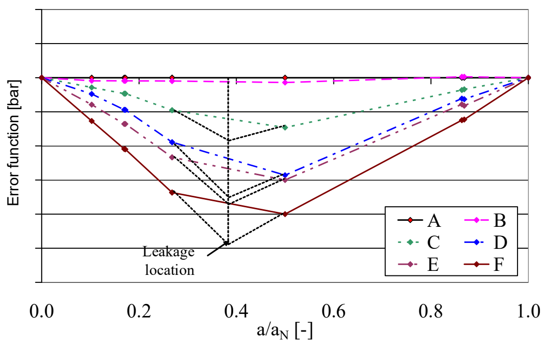
Experimental verification

After compensation with the pre-leakage error function



Experimental verification

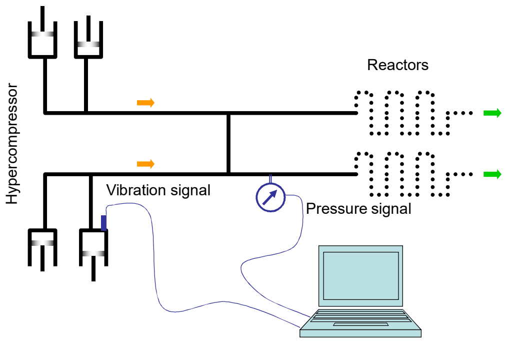
Illustration of the peek estimation problem



Results

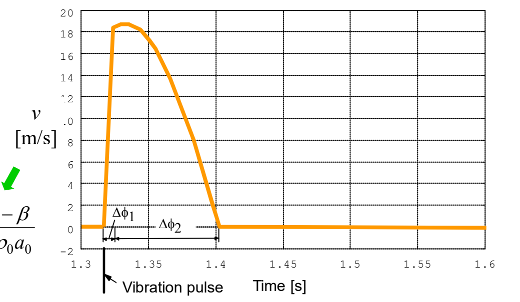
- Both methods have been implemented in the automation system of MOL. The hydraulic model is running in the SQL database of the measured data.
- Real time results are visualized on HTML pages.

Pressure fluctuations in an ethylene polymerization system



Boundary conditions: the compressor

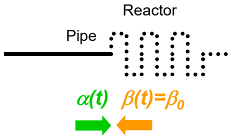
Compressor discharge (Velocity at the pipe inlet)



$$v = \frac{\alpha - \beta}{2\rho_0 a_0}$$

Phase angles of the linear ($\Delta\phi_1$) and the sinusoidal ($\Delta\phi_2$) parts are set on the basis of geometrical assumptions.
The phase angle was obtained from the vibration signal caused by the valve opening.

Boundary conditions: the reactor



Intensive dissipation due to the polymerization process.
Treated as a non-reflective BC:
a constant β value is assumed.

Simulation results vs. on site measurements