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Interaction of a HydraulicTransient with a Leak in a Pipe Flow

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Abstract
A hydraulic transient due to a rapid flow change in a single, pressurized pipeline will interact with a leak and affect the shape of the transient thus making it potentially possible to identify and locate the leak. This is shown through computations and measurements on an experimental 135 m long pipeline set-up. Moreover, a field test on a 3,500 m long underwater pipeline showed promising results for locating an assumed leak.

Introduction
A hydraulic transient (waterhammer) occurs in a pipeline due to a rapid flow change and is characterized by pressure waves propagating back and forth through the pipeline with a wave velocity typically in the range a=300-1200 m/s. Steep and strong pressure waves are most often caused by the stoppage of a low-inertia pump or a rapid valve closure. Besides the nature of the flow change the characteristics of a measured hydraulic transient are mainly related to the design of the pipeline and thus known properties of it such as length, pipe material and pipe diameter. However, the transient will also to a certain extent be affected by other factors (sometimes unexpected) such as a leak or a gas pocket. Thus, generally and theoretically speaking one should be able to explain the shape of a transient provided the effects of different factors are known. This fact emphasizes the viewpoint that a transient contains a certain amount of information about a pipeline, i.e. the transient could be looked upon as a kind of "probe". By measuring and carefully analyzing a transient it should thus be possible to extract hydraulically interesting and important knowledge about a pipeline. Theoretical and some experimental studies on leak detection have been reported by Jönsson [1] and Brunone [2). This paper will further investigate the possibility to detect a leak in a single pipeline by analyzing its effect on a steep pressure wave theoretically and experimentally. In the latter case the effect of a range of leak rates on the measured transient is studied on an experimental pipeline set-up. Different ways of determining an accurate and representative wave propagation velocity are discussed. A comparison between a measured and a computed transient, affected by a leak, is described. Finally results from a field study with a real leak problem are briefly referred to.

Computation of a Transient with a Leak in the Pipeline
The transients are computed according to the standard 1-d, compressible, unsteady St Venant's equations [3] and solved using the method of characteristics. A leak is described as an inner boundary condition:

$$Q_{leak,inst}=\mathrm{const}\cdot H^{0.5}_{pressure,inst} \qquad (1)$$

where $Q_{leak,inst}$ = instantaneous leak flow
$H_{pressure,inst}$ = instantaneous pressure at the leak (>atmospheric pressure)
const = derived in order to reproduce the steady state condition.

The leak inner boundary condition is described using the continuity of flow at each time step, a constant pressure head at each time step at the three nodal points describing the leak and the use of the two characteristic lines from the two neighboring nodal points. Figure 1 shows an example of the computed transient due to a pump stoppage in a 1,000 m long pipeline, diameter 100 mm, wave velocity 1,000 m/s, pipe flow 8 l/s and a steady state leak rate of 6% 300 m downstream of the pumping station. The diagram refers to the computed pressure immediately downstream of the shut-off valve at the pumping station. One could distinguish, figure 1 bottom, the slight pressure rise 0.6 s after pump stop as the initial pressure drop at pump stop has reached the leak and being reflected back towards the pumping station. Another result of the computations is that the leak causes the oscillatory phase of the transient, after valve closure, to attenuate faster than for the case without a leak. Moreover, the computations indicate that the leak gives rise to a distortion of the oscillatory pressures.

The effect of a leak on the transient according to figure 1 indicates the general idea of locating the leak through a careful analysis of a measured transient. Figure 2 illustrates the method in principle. By identifying the return of the reflected wave from the leak to the assumed measurement point at the pump and by measuring the time Δt between the pump stop, i.e. the generation of the steep negative wave at the pump and the return of the reflected wave, the leak location L^1 could be determined according to:

$$L^1 = \frac{\Delta t \cdot a}{2} \qquad (2)$$

where a = wave velocity

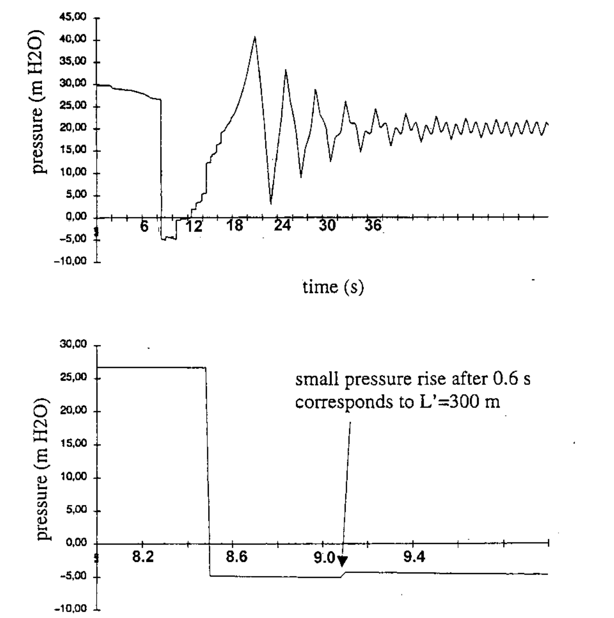

Figure 1. Computed transient due to pump stop in a pipeline with a 6% leak 300 m downstream of the pump

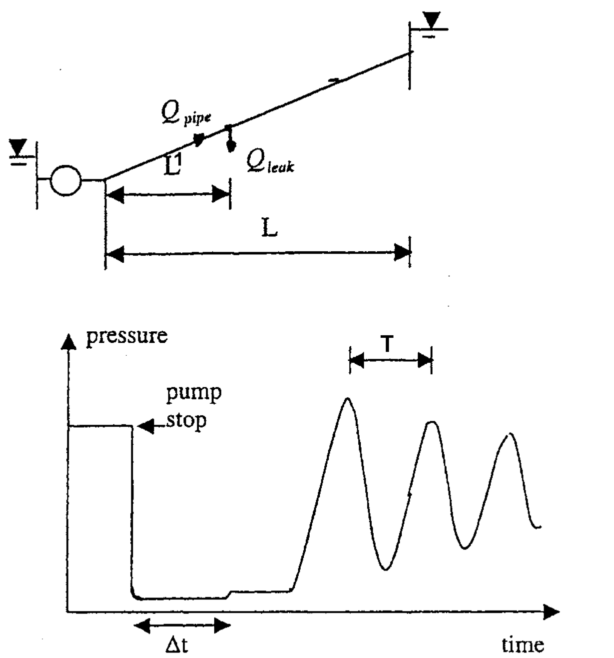

Figure 2. Leak located at a distance L^1 from the pump (top) and the basic feature of the transient at the pump at pump stop (bottom)

If pressure oscillations occur, the wave velocity could be estimated from the measurement according to:

$$T = \frac{4 \cdot L}{a} \tag{3}$$

where L = pipeline length
T = pressure oscillation period.

A steep pressure rise due to a rapid valve closure will interact with a leak in principally the same way. The analysis of the leak location will also be performed as described above.

Transient Measurements on an Experimental Set-up with a Simulated Leak

The interaction between a transient and a leak was studied for an experimental set-up consisting of a 135 m long pipeline of galvanized steel basically made up of an upstream part, 34.9 m long, diameter 40 mm, a 90^0 bend, a flowmeter and a downstream part, 98.35m long, diameter 50 mm (40 mm in some measurements). The upstream part was attached to a large main (pressure 5 bar) acting as a reservoir. The downstream end discharged to the atmosphere via a ball valve, which could be closed very rapidly thus generating a steep hydraulic transient propagating towards the main. A dynamic pressure transducer was located immediately upstream of the ball valve making it possible to determine the transient with a sample frequency of 640 Hz. The pipeline was equipped with simulated leakage points - each consisting of a T-junction, a shut-off valve and a flowmeter – at the distances 42.85 m and 79.65 m respectively from the ball valve.

Transient Measurements on the Experimental Set-up

A number of hydraulic measurements were performed on the set-up for leakage rates Q_{leak}/Q_{pipe} in the range 1-16 % , figure 2, with Q_{pipe} of the order of 1 l/s. Wave velocities were determined in two ways on the basis of the measurements; a_{cycle} according to Eq(2) and a_{refl} according to the time for the initial pressure wave to propagate from the valve to the main and back to the valve (transducer location). The wave velocities could also be compared with the theoretical value according to:

$$a_{theo} = \sqrt{\frac{K_{water} / \rho_{water}}{1 + \frac{K_{water} \cdot D \cdot const}{E_{pipe} \cdot e}}} \tag{4}$$

where K_{water} ,K_{pipe} = bulk modulus of elasticity of water and pipe material respectively
D = pipe diameter
e = pipe wall thickness.
const related to the axial movement of the pipeline. Here const set = 1.0

Figure 3 shows the measured transient for the reference case with no leak, Q_{pipe} =1.43 l/s (water velocity 0.73 m/s). The top figure represents the entire transient including the oscillatory phase after valve closure. The bottom figure shows the initial pressure trace from the start of the valve closure to the return of the reflected wave from the main. The valve closure gives rise to a very steep pressure rise according to the Kutta-Joukowski law. After that the pressure rises slowly due to frictional effects in the pipeline (line-packing) and finally the reflection from the main causes the pressure

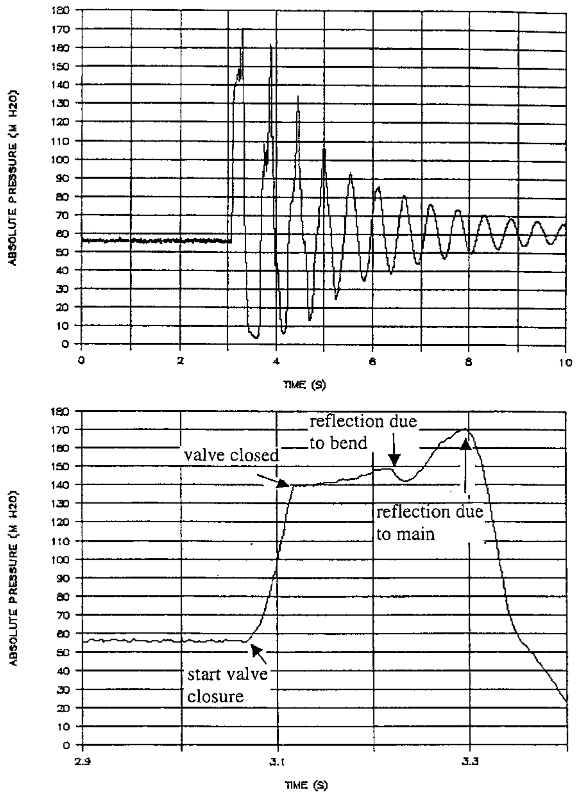

Figure 3. Measured hydraulic transient in the experimental set-up. No leak. Q_{pipe} =1.43 l/s (0.73 m/s). Top: overall transient including pressure oscillations. Bottom: detail of the initial pressure wave including the reflected wave from the main

to drop rapidly (0.2250 s after the initial pressure rise). There is also a distortion of the pressure at about 3.2 s possibly due to a combined effect of a precursor wave and the slightly flexible 90^0 bend. This specific issue has not been investigated.

Figure 4 shows two examples of the initial phase of the measured transient with a leak at 42.85 m; the top figure corresponds to Q_{pipe} =1.05 l/s and a leak ratio of 12% and the middle figure corresponds to Q_{pipe} =0.80 l/s and a leak ratio of 5%. The bottom figure is a computation corresponding to the situation of the top figure. Both the measured situations show a distinct effect of the leak as a more or less abrupt change of the slight pressure rise due to the line-packing effect. Moreover, the bend effect and the reflection from the main are also clearly visible. As for the leak location one could, as an example, make a detailed analysis of the middle figure giving:

$$\Delta t=3.0592-2.9860=0.0732 \text{ s}$$
$$a=1243 \text{ m/s}$$
$$\frac{2 \cdot L^1}{1243} = 0.0732, \text{i.e.} \, L^1 = 45.5 \, \text{m}$$

as compared to the real L^1 =42.85 m.

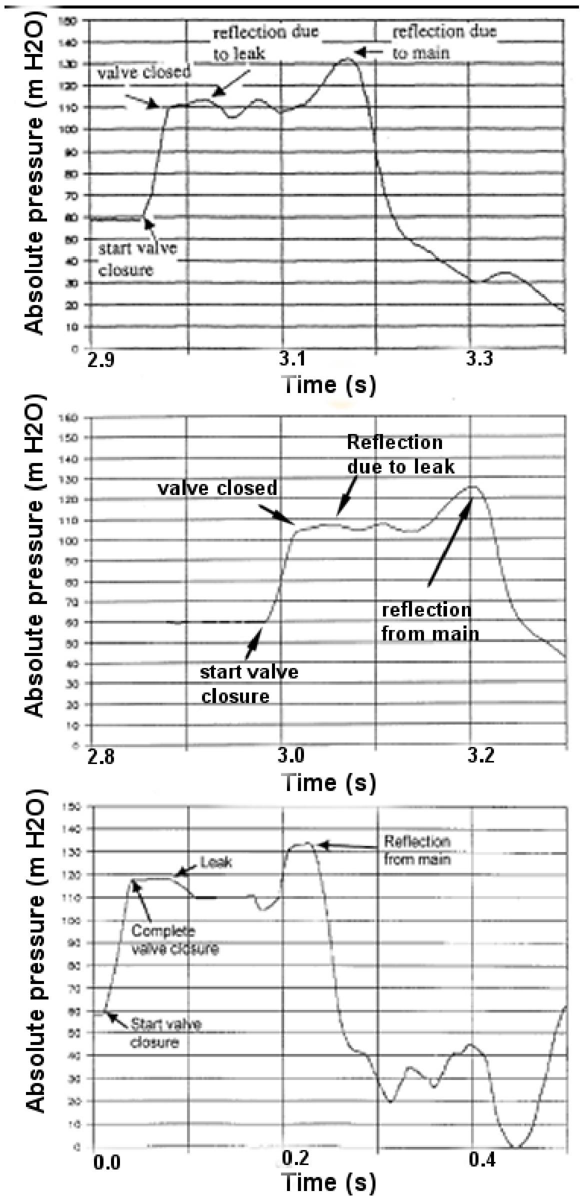

Figure 4. Top: Measured hydraulic transient Q_{pipe} =1.05 l/s, Q_{leak}=0.13 l/s corresponding to a leak ratio of 12%
Middle: Measured hydraulic transient Q_{pipe} =0.80 l/s, Q_{leak} =0.04 l/s corresponding to a leak ratio of 5%
Bottom: Computed transient according to the situation of the measured transient in the top figure.
All three transient traces refer to the initial pressure pulse as obtained at the ball valve

The wave velocity a was determined by means of the reflection time from the main.

Table 1 gives a summary of results of the derived leak location for a number of transients for the case with the simulated leak at 42.85 m. The results from the leak at 79.65 m are not presented as the bend effect seemed to mask the reflection from the leak. One important observation is that the two ways of deriving the wave velocity from the measured transients differ significantly with a_{cycle} significantly lower than a_{refl} . As the latter was in good agreement with the theoretical value, eq(4), and as a_{refl} was representative of the initial part of the transient phase the latter wave velocity was chosen for the evaluation of the leak location.

Q_{pipe} (l/s)	Q_{leak} (l/s)	leak ratio (%)	a_{cycle} (m/s)	a_{refl} (m/s)	computed leak loc (m)
0.83	0.09	10.8	937	1208	42.5
0.80	0.04	5.0	940	1243	45.6
0.80	0.05	6.8	943	1280	48.0
1.05	0.13	12.4	923	1234	41.4
1.18	0.17	14.4	950	1192	41.0
0.24	0.04	16.7	979	1309	41.9
1.67	0.20	12.0	893	1160	39.9
1.67	0.20	12.0	926	1129	44.1
1.67	0.20	12.0	925	1183	43.4

Table 1: Derived wave velocities and leak locations from transients with the simulated leak at location 42.85 m

The measurements described in table 1 are for leak rates from 5% to 16% with derived leak locations in the range 39.9 – 48.8 m and with a mean absolute error (deviation) of 1.92 m, i.e. about 4.5%.

The computed transient, figure 4 bottom, shows the same features because of the leak and the main as observed in the measurement, figure 4 top. The bend was simulated as an elastic cylinder which explains the “dip” at about time t=0.18 s.

Field Study of a Pipeline with a Leak

A sewage water, high-density polyethylene (PEH) main and with the size 200x11.4 mm was located on the bottom of a lake. A pumping station with swing check valves was located on one side of the lake and 3,522 m downstream at the other side of the lake the pipeline discharged to a well. At steady state operation measurements indicated a flow of about 23 l/s in the pumping station and about 15-16 l/s at the downstream end. Thus, there was a leak somewhere along the pipeline. Conventional leak detection methods were not considered suitable or applicable and instead the use of hydraulic transients was tested. These were generated by pump stop and with devices for transient protection disabled whereby a steep pressure drop was obtained. Figure 5 shows an example of the measured transient at the pumping station when stopping one pump. The operational pressure was about 47 m H_2O (absolute pressure) and at pump stop the pressure dropped instantaneously but the check valve closed before atmospheric pressure was reached due to the relatively high water velocity (~ 0.93 m/s) and the low wave velocity . Two unexpected features were detected on the pressure trace, one at about time t=10 s (4.1 s after pump stop) and one at about time t=20 s (15.6 s after pump stop). On the basis of the time period T=53.6 s for the cyclic pressure variations (not shown here) obtained after valve closure the wave velocity a_{cycle} was determined to be a=263 m/s to be compared to the theoretical value for an axially freely moving PEH pipe a_{theor} =278 m/s according to eq(4). Eq(2) gives for the two features for the possible leak location:

	a_{cycle} = 263 m/s	a_{theor} = 278 m/s
4.1 s	539 m	570 m
15.6 s	2,051 m	2,168 m.

Subsequent inspection by a diver revealed a leak at a distance of 2,150 m from the pumping station.

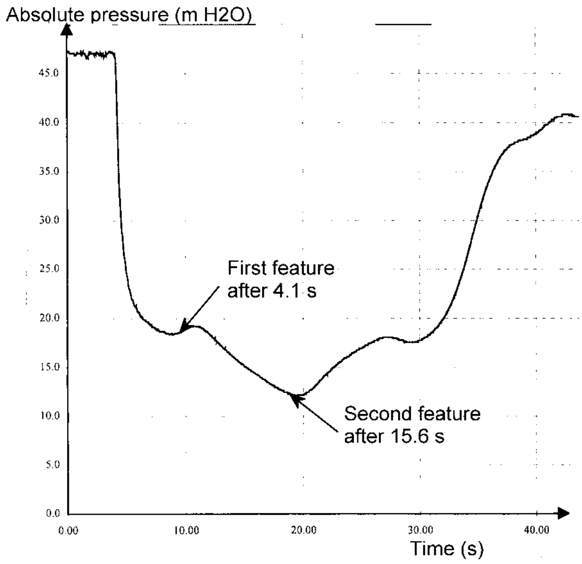

Figure 5. Pipeline on the lake bottom. Measured hydraulic transient at pump stop. Notice the two features on the pressure trace which might indicate a leak

Conclusion

Theoretical and experimental investigations in a single pipeline show that a steep pressure wave will partly be reflected by a leak and thus somewhat change the character of the transient. A careful analysis of the transient using temporal information about the reflection time and the wave velocity makes it possible to assess the location of the leak. The wave velocity was deduced from the initial reflection time of the transient through the whole pipeline. The wave velocity based on the cyclic pressure oscillations was significantly lower and thus not judged to be applicable. According to the experiments the effect of a leak of 5% or more of the pipe flow could be detected and the location of the leak could be determined. A field study of a leak on a 3,500 m long underwater pipeline proved encouraging.

References:

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