Detection of gas pockets in pressurised wastewater mains using dynamic system response analysis

ABSTRACT

In the Netherlands, wastewater is mostly collected in combined sewer system and transported to a WWTP through pressure mains. These pressure mains form an element of the system that did not receive much attention lately with respect to monitoring of performance and maintenance. For that reason, their state of functioning is often not known. Failure of operation is only noticed when during storm conditions the capacity of the system drops, resulting in undesirable discharge to the surface water. A recently made inventory showed that about half of the pressure mains show increased pressure loss for no obvious reason. Reduction of the systems nominal capacity can result from many causes, like increased wall roughness, scaling and the occurrence of free gas in the pipeline. The occurrence of gas-pockets may be caused by degassing of dissolved gas, but also by air entrapment at the pump inlet or at air valves. A research project is started that will be carried out from 2003 to 2005. This project focuses on three goals:

- the description of the gas-water transport phenomena in wastewater pressure mains,
- a method to detect and diagnose gas problems, and
- to overcome future problems by either applying remedial measures or by developing improved design methods for wastewater pressure systems.

This paper describes the layout of the experimental set-up to detect and diagnose gas problems and the first results of the experiments are presented and discussed. The results are used to validate a model (Wanda) developed by Delft Hydraulics that describes the phenomena involved in surges in air/water transport.

Keywords: *wastewater transport mains, capacity reduction, gas-liquid mixture experiments, phenomenon description, diagnose problem pipelines.*

INTRODUCTION

The hydraulic capacity of pressure mains does change during its operational life because of scaling, the occurrence of air/gas pockets, wear of pumps etc. In practical cases it is no trivial task to identify the cause of capacity loss in the first place. To find a sound solution for a ‘problematic’ pressure main is in many cases even more difficult since in a significant number of cases a basic design problem seems to be the cause. Free gas in pressurised pipelines/mains can significantly reduce the flow capacity. When the capacity of wastewater pressure mains fails to be in line with the design value, undesirable spills or efficiency loss may be the result.

Delft Hydraulics and Delft University started an extensive research program in 2003 in the processes. One of the objectives of this program is developing a method to quickly diagnose the cause of capacity loss of a pressure main. In this paper the set-up of the experimental facility and the experimental results are discussed. The occurrence of free gas in pressure mains significantly influences system dynamics. The difference in dynamic behaviour is a measure for the amount of free gas present and is therefore used as a tool to diagnose and troubleshoot a problem wastewater main. If the presence of gas alters the wave speed, the presence of gas pockets can be proven, by sending pressure waves through the pipeline. The objective of the study is to diagnose a pipeline that suffers from capacity reduction. Preferably, a method is developed that diagnoses the system with simple measuring devices such as pressure transmitters only, without the need for special instrumentation. In this paper a description is given of the experimental facility in which the influence of air and local air pockets can be investigated.

METHODS AND METHODOLOGY

Theory and methodology

The propagation speed c (celerity) of a pressure wave through a pipeline is determined by the compressibility of the fluid and of the material of the pipe. The equation for the celerity of pressure waves for completely filled pipes with a single fluid reads:

$$c = \left(\frac{\rho}{K} + \frac{\rho D}{eE} \right)^{-0.5} \quad (1)$$

in which

ρ = Density of the fluid
K = Bulk modulus of the fluid
D = Inside diameter of the pipe
e = Thickness of the pipe wall
E = Young's modulus

The propagation speed of pressure waves through a pipeline is significantly influenced by the amount of free gas present in the pipe. Free gas increased the compressibility of the fluid and thus reduces the wave speed. In case free gas is (homogeneously) present ρ and K can be replaced with ρ^* and K^*.

$$\rho^* = (1-f)\rho_v + f\rho_g \quad (2) \qquad \frac{1}{K^*} = \frac{1-f}{K_v} + \frac{f}{K_g} \quad (3)$$

The fraction f of gas in a pipe can be assessed, if the occurring wave speed and material constants are known. In order to assess the presence of free gas one could determine the change in the wave speed. The period T of the wave for a system of length L bounded by reservoirs is:

$$T = \frac{2L}{c} \quad (4)$$

If the period is measured for a system, an increase in T from the reference value (no free gas) indicates that free gas is present. Three different situations can occur:

1. The pipe is completely filled with water.
2. Air is present and is distributed homogeneously over the length of the pipe
3. The pipe is filled with water and only a certain local point a volume of air is present.

In the first situation, the basic equation for wave speed (1) is valid. The resulting period will be T_{ref}. In the second situation, the period T will increase due to a decrease of the wave celerity. The equation for the wave speed for water with homogeneously mixed gas may not be completely valid for situation 2, since air bubbles will be intermittently transported at the upper side of the pipe's diameter. In the third situation, the system can be regarded as two subsystems in between a gas pocket and the systems boundary. The period T will increase due to a local delay of the wave speed at the air pocket:

$$T = \frac{2L}{c_{ref}} + \Delta T \quad (5)$$

The wave celerity in the subsystems will have the reference value, since no air is present. All three situations can be tested in the experimental set-up. By conducting a spectral analysis, the periods T

are reflected in the frequency domain. A Fast Fourier Transform operation is applied to the pressure time series that were recorded at several locations along the pipeline.

In practice, air and gas in pipelines can be divided in two main categories, local accumulation for example at high points and air that is spread over the length of the system. The experimental set-up is designed in a manner that both situations can be investigated. Local air pockets are investigated by injecting an amount of air into a vertical standpipe that is connected to the main line with a T-junction. If air that is equally distributed over the pipeline is investigated, the branch of the T-junction is closed and air is introduced in the system at the beginning of the pipeline.
The pressure wave is introduced to the system by changing the speed of the pump in a controlled manner. The ramp as well as the magnitude of the speed change of the pump can be varied. By lowering the speed of the pump, an under pressure will enter the system that will reflect either at the end of the system and / or at an air pocket.

Experimental set-up
The experiments are conducted in a dedicated facility for research on air/gas pockets. The circuit consists of 625 m long PVC pipe with inner diameter of 235,4 mm and a wall thickness is 7,3 mm. At four locations (see arrows in Figure 1), transparent T-junctions are applied that combine the ability of visual observation and the possibility to contain a certain amount of air at a fixed point along the pipeline. The circuit is located indoors of a large facility building and is situated on the concrete floor. The pipeline is supported by steel supports at each pipe section (10 m length) and wooden blocks to prevent sagging of the pipe. The circuit is sufficiently flat to guarantee an unhindered transport of the air bubbles. Good support is also necessary to minimise negative side effects of fluid structure interactions on the line pressure during pressure transients.
Air can be injected into the system in two different manners. If tests are required with local air pockets, air is locally trapped in vertical standpipes (branch of a T-junction) at several locations. Figure 2 shows a layout of the standpipe used. The diameter of the standpipe is equal to the main pipe and the height is 1.00 m. At the top of the standpipe, two tapping are applied to inject and release air and to install a pressure transmitter. During experiments with local air pocket a fixed amount of air is injected in the standpipes. By reading the water level in the standpipe the exact volume is obtained at the initial line pressure at stationary flow condition. Three locations of the standpipe have been tested. The locations and the corresponding subsystem frequencies are presented in Table 1.

Table 1. Location of the stand pipes and the characteristic frequency of the subsystem

Total length = 625 m (L)	Distance L1 from the pump (characteristic frequency)	Distance L2 to reservoir (characteristic frequency)
Loc 1	99 (1.50 Hz)	527 (0.28 Hz)
Loc 2	229 (0.65 Hz)	397 (0.37 Hz)
Loc 3	394 (0.37 Hz)	231 (0.64 Hz)
Loc 4	525 (0.28 Hz)	101 (1.46 Hz)

The circuit allows investigation of the transport of air that is spread over the entire length of the pipeline. The facility is specially designed to inject a controlled and monitored airflow into the liquid phase. For these tests, air is injected at the beginning of the circuit, just downstream of the pump (upper left side of Figure 1). During these experiments the branch of the T-junction is closed.

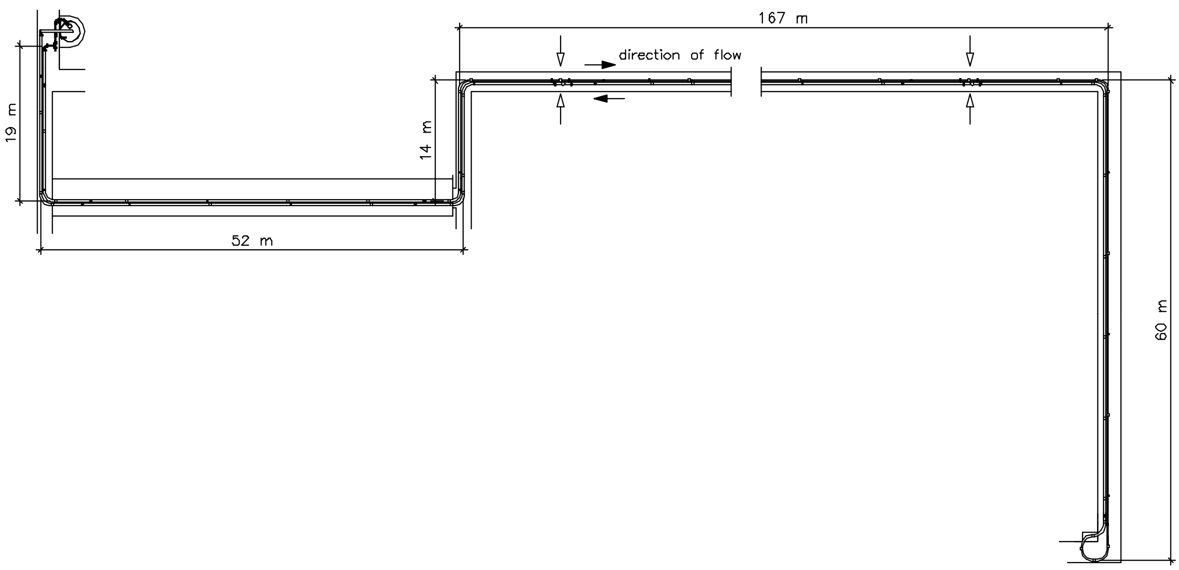

Figure 1. Top view of the experimental set-up.

From a constant head reservoir a pump circulates water through the experimental facility. A flow control valve (FCV) in combination with an EMF flowmeter and PC adjust the flow rate to its set value. The injection of air into the system results in a head increase of the pump, causing the flow rate to drop. The flow control allows a constant flow rate during head changes.

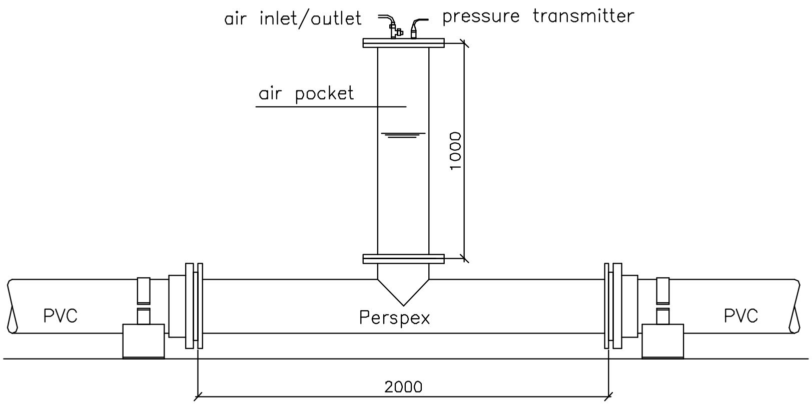

Figure 2. Layout of the stand pipe

Air is supplied by the standard 6 bar pressurised air-infrastructure in the building. A combined mass flowmeter and flow control valve adjusts the airflow to its set value. Since the air flowmeter measures mass, the output gives ‘nl/min’, i.e. a volumetric flow rate at normal conditions (101325 Pa and 0 °C). The facility incorporates the following instrumentation:

	range	Uncertainty
EMF DN125	0 – 100 l/s	< 0.25%
Gas flowmeter	1 – 50 nl/min	< 0.5 %
Four absolute pressure transmitters	0 – 3 bar	< 0.1 %
Four pressure differential transmitters	1.20 mbar – 2.5 bar	< 0.1 %
Temperature transmitter	3 to 100 °C	< 0.1 °C

The facility comprises tappings at 14 locations, where 4 absolute pressure transmitters and/or 2 differential pressure transmitters can be applied. In order to prevent air from disturbing the pressure measurements, the tappings are located at the bottom of the pipe. The temperature transmitter is located at the reservoir in order to monitor possible temperature increase caused by the pump. All signals are recorded using an automated data-acquisition system in which the applied sampling frequency is 100 Hz. The acquired data are stored on a hard disk.

RESULTS AND DISCUSSION

This paper presents the experimental results of local air accumulation using the standpipes. A large number of experiments have been conducted with different combinations of air column height and ramp and magnitude of the speed change. The steepness of the pressure drop and the minimum value depends on the ramp and amplitude of the speed change of the pump. The pressure waves travels into the system and reflects while it attenuates. After approximately 40s the amplitude of the wave has dropped below the natural fluctuations of the line pressure. A typical time series of the pressure with and without an air pocket is given in Figure 3.

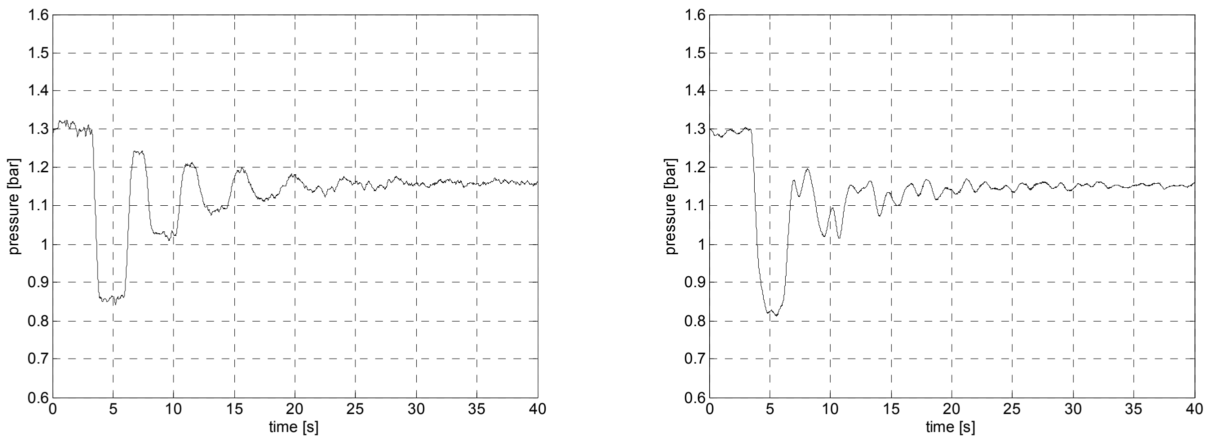

Figure 3. Example of a pressure time series without air pocket (left) and with air pocket (right).

The effect of the air pocket on the period is seen in Figure 4. The period of the wave has increased which is presented by a shift of the first frequency peak to the left from 0.232 Hz to 0.208 Hz.
The increase of the reflection period depends on the size of the air pocket and its location along the system. Figure 5 clearly shows the increase ΔT of the reflection period compared to T_{ref}. Also the location has an influence on the value of ΔT. Although the initial volume of the air pocket is equal, the resulting period increase is smaller if the air pocket is located further downstream of the pump. The maximum/minimum pressure ratio during the event is at a location downstream smaller than upstream and the period of low pressure is shorter than at a location upstream. This results in a smaller air volume increase at the end of the pipe and therefore smaller increase in reflection time T.

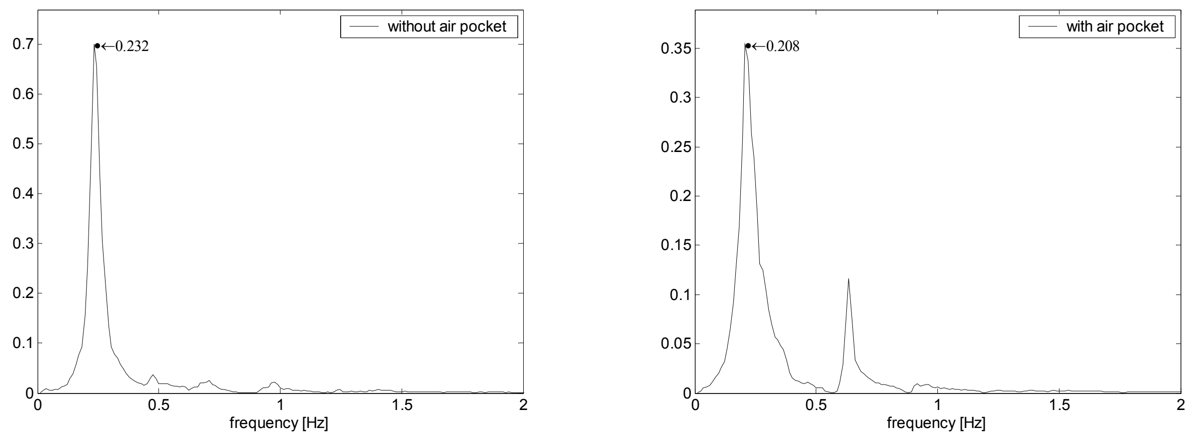

Figure 4. Frequency content of the pressure time series without air (left) and with air pockets (right).

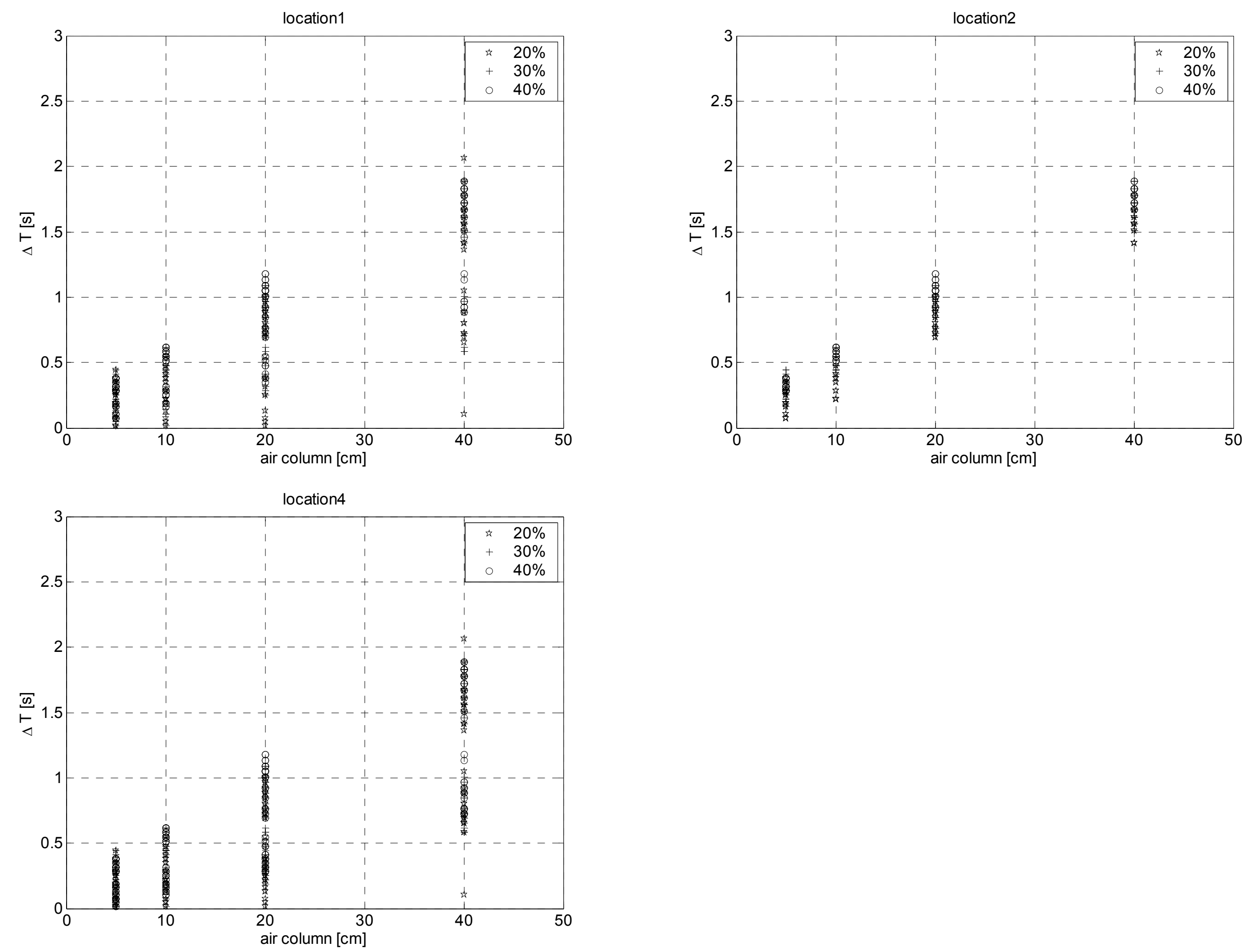

Figure 5. ΔT as a function of the air column height for different speed changes and ramp

Figure 6 shows the values of the measured reference wave speed without standpipes. The value does not vary significantly with ramp speed. The average value is approximately 295 m/s which is close to the theoretical values calculated with Eq. (1), which is 300 m/s.

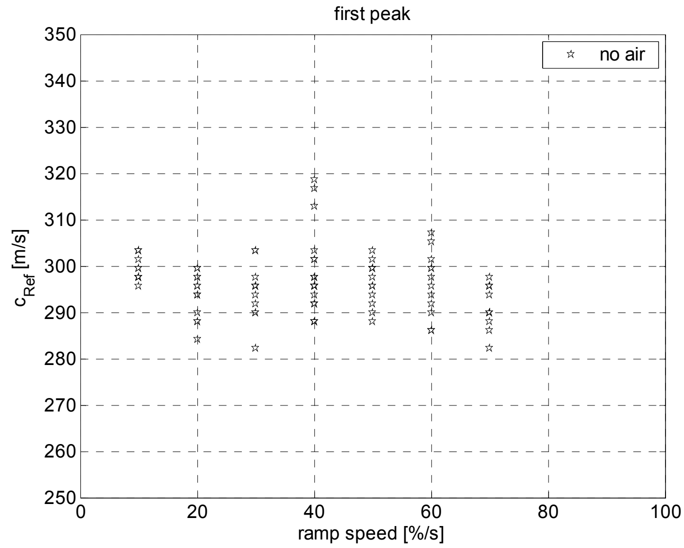

Figure 6. Measurements of the reference value of the wave speed without standpipes.

Assuming that an air pocket will divide the system into two subsystems, a frequency peak should appear around the characteristic frequency of the length of the subsystem shown in Table 1.
The prediction of the location of the standpipe is best given by pressure transmitters located upstream of the standpipe.

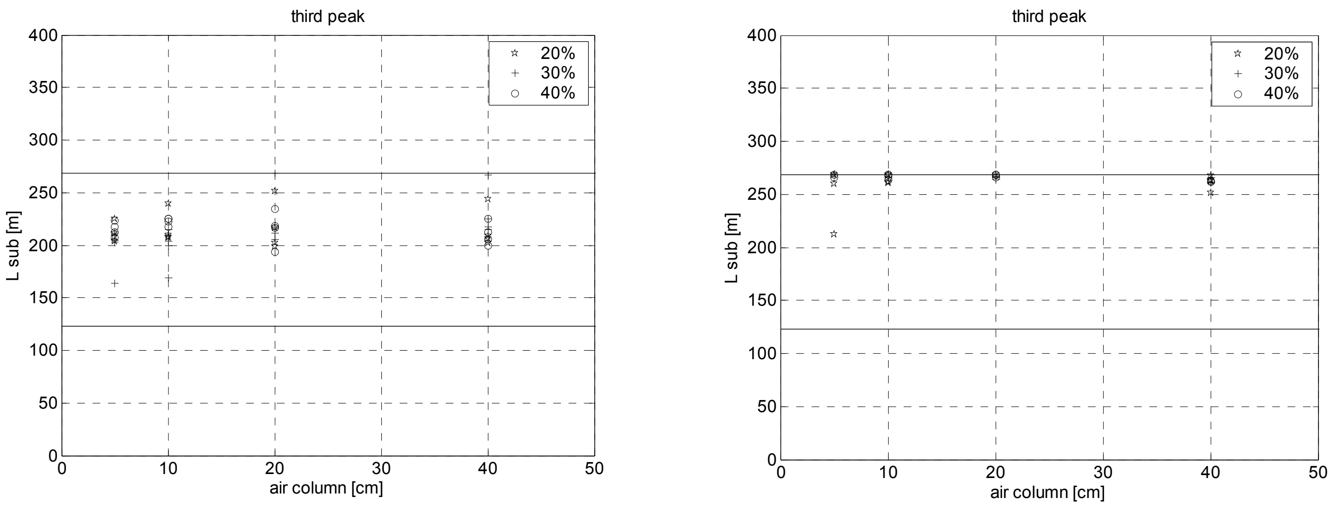

Figure 7. Frequencies of peaks between 125 and 270 m for standpipe at location 1 (right) and 2 (left)

The distance of standpipe 2 is 229m from the pump. Figure 7 (left) shows the peaks found within a search window ranging between125 and 270m form an upstream pressure transmitter. For the situation of the standpipe at location 1 (right) all peaks (maximum value within the window) are found at the edge of the search window meaning that only lower values were in the centre of the search window. The distance of standpipe 1 is 99m from the pump. Figure 8 (left) shows the peaks found within a search window that ranges from 79 and 122m at upstream pressure transmitter. For the situation of the standpipe at location 1 (right) almost all peaks are found at the edge of the search window meaning that only lower values were in the centre of the search window.

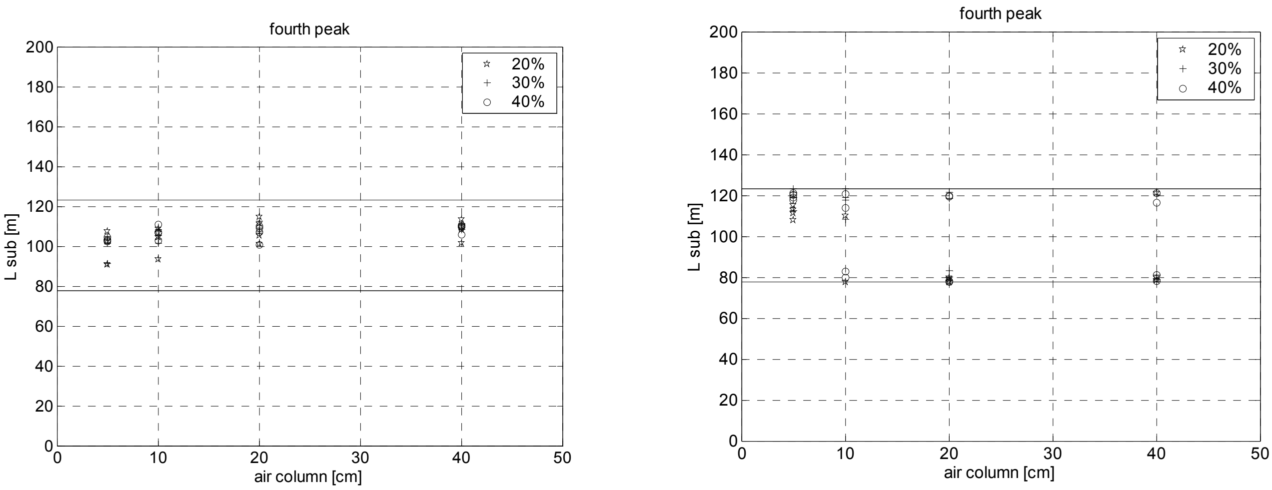

Figure 8. Frequencies of peaks between 79 and 122m for standpipe at location 2 (right) and 1 (left)

In real wastewater pipeline, a priori knowledge of verticale pipe profile is available and therefore information about the location of high points should be assessed first. At these high points air pockets with different sizes can be modelled numerically (using the Wanda 3.50 software for simulating transients in pipeline system), and varied until both the measured and simulated results agree well. Lubbers et al. (2005) show results of the numerical simulation using this software.

CONCLUSIONS

It is fairly easy to assess whether air pockets are present or not. The experiments show that the first peak in the frequency domain of the pressure time series changes if air is present. However, to determine the location and size from the frequency domain of a pressure time series is not unambiguously be determined. The frequency content not only changes with air volume and location but also due to location of the pressure transmitters with respect to the air pocket. Also prior knowledge of the air pocket location is necessary. In real systems this means that from the pipe profile, high points should be identified first. At these high points air pockets with different sizes can be modelled numerically (using the Wanda software for simulating transients in pipeline system), and varied until both the measured and simulated results agree.

Further analysis of the test data will be performed in order interpret and analyse the difference in location and volume of the air pocket. The aim of the investigation is to be able to diagnose a pipeline system in a way that the location and the amount of air can be determined.

ACKNOWLEDGEMENT

The research is funded by: Foundations RIONED and STOWA, the Waterboards of Aquafin, Brabantse Delta, Delfland, DWR, Fryslân, Municipality of The Hague, Hollandse Eilanden en Waarden, Hollands Noorderkwartier, Reest en Wieden, Rivierenland, Veluwe, Zuiderzeeland and the Engineering/consultancy companies DHV and Grontmij.

REFERENCES

Lubbers C.L., Clemens F.H.L.R., (2005) On detecting gas pockets in pressurised wastewater mains. *Proc. 10th International Conference on Urban Drainage Copenhagen*.

Wylie, E.B. and Streeter, V.L., 1993: *Fluid transients*, McGraw-Hill, New York.