Gas transport in pressurized sewerage mains: Results of industrial scale test rig experiments.

Tonny Schuit[1], Ivo Pothof[1,2] and François Clemens[1]

[1]Delft University of Technology, Faculty of Civil Engineering and Geosciences, Section of Sanitary Engineering, P.O. Box 5048, 2600 GA Delft, The Netherlands; PH +31(0)15 27 84946; FAX +31(0)15 27 84918; email: a.d.schuit@tudelft.nl
[2]Deltares, Industrial Hydrodynamics, P.O. Box 177, 2600 MH Delft, The Netherlands; PH +31(0)883358448; email: ivo.pothof@deltares.nl

ABSTRACT

Gas pockets in declining sections of sewerage pressure mains cause additional head loss and associated capacity reduction. A discrepancy between results of laboratory tests and field tests has been observed in a previous study by Lubbers (Lubbers 2007). Lubbers concluded that fluid properties and/or pipeline conditions between the lab and the field must have caused the differences. To bridge this gap, an industrial scale field test rig (ø192 mm, L = 40 m, angle = 10°) was built and validated with clean water. The effect of surface tension was studied with the addition of surfactant to the clean water. The next step towards reality was running the test rig with wastewater during dry weather flow conditions. The effect of increased absolute pressure on the gas transport was investigated by throttling a downstream valve. The lower surface tension of wastewater does not enhance the gas transport due to the dynamic character of the surface tension. Increase of absolute pressure (+0.5 bar) however shows significant increase in the dissolved gas transport.

Keywords: *wastewater pressure mains, two-phase flow, experimental work, surface tension, pressurized flow, Henry's law, industrial scale test rig, gas transport.*

INTRODUCTION

Gas pockets are an important cause of capacity reduction in existing sewerage pressure mains with a negligible static head, which is typical for drainage systems in highly urbanized delta's. The traditional design approach for wastewater mains allowed admitting gas (mainly air) in the system via the pumps and via air valves in the pumping stations. The pipeline was designed to transport the gas pockets through the line in order to prevent the installation of air valves along the pipeline. The following design equation was used to determine the required water velocity v_w to transport gas pockets to the bottom of a downward slope α (Kent 1952).

$$F = \frac{v_w}{\sqrt{g \cdot D}} = 1.23 \cdot \sin\alpha \tag{1}$$

33rd IAHR Congress: Water Engineering for a Sustainable Environment

ISBN: 978-94-90365-01-1

F	[-]	flow number
v_w	[m/s]	cross section averaged water velocity
D	[m]	pipe diameter of downward slope

Lubbers (2007) has studied the behavior of a gas pocket at different configurations (diameter, inclination, length, liquid and gas velocities) of a downward sloped pipe in a laboratory environment using clean water. Lubbers (Lubbers and Clemens 2006) has shown experimentally that Kent's equation is too optimistic at $\alpha < 25°$.

Field tests indicated that the lab results were conservative in the removal of gas pockets. This deviation was attributed to differences in fluid properties and/or pipe configurations. A second research project was started to investigate the differences between lab and field data.

In the industrial scale test rig, the effects of reduced surface tension (0.072 to 0.045 N/m) of water and increased absolute pressure (increase of 0.5 and 1.0 bar) are studied. Also the behavior of the gas pocket using clean water and wastewater (at dry weather flow) is compared.

After the introduction of the capacity reduction in existing sewerage pressure mains, a summary of the applicable theoretical concepts is presented. Next the actual layout of the validated test rig is explained. Finally the results of the variation in surface tension and the experiences with the use of wastewater including those with increased absolute pressure are discussed and conclusions are drawn.

THEORY

Gas can be transported in a liquid flow as smaller bubbles in a two phase system or by dissolving of the gas in the liquid phase.

Bubble transport. When a gas pocket is present in an inclined pipe, the water is flowing with increased velocity underneath this gas pocket. A hydraulic jump occurs at the end of the gas pocket. In this hydraulic jump gas bubbles are entrained in the turbulent water and the flow of water is decelerated. For a bubble to be transported out of the inclined pipe, the ratio of the drag force to the buoyancy force must be larger than 1. The drag force depends on the relative velocity of the water to the bubble and the cross sectional area of the bubble perpendicular to the flow direction. The buoyancy force is related to the density difference of the media and the volume of the bubble. For spherical bubbles this ratio is depending on 1/diameter. For turbulent liquid flow fields, Hinze (Hinze 1955) derived an equation (equation (2)) for the maximal diameter of a bubble (d). This diameter is depending on the surface tension (σ), the density of the liquid (ρ), the pipe diameter (D) and the mixture velocity (v). f is the Darcy friction factor.

$$d = 0.725\left(\frac{\sigma}{\rho}\right)^{0.6}\left(2f\frac{v^3}{D}\right)^{-0.4} \tag{2}$$

Dissolve gas transport. At the gas-liquid interface, mass transport between the two phases takes place. In the boundary layer a concentration gradient is present between the maximal solubility of the gas into the liquid (defined by Henry's law) and the concentration in the bulk of the liquid (C_{bulk}). The added mass theory is used to make an order of magnitude assessment of the dissolved gas transport. The added mass theory states that the volume of the boundary layer is 50% of the volume of the bubble, resulting in a thickness of the boundary layer of 0.145 times the diameter of the bubble (d). Mass transfer for a transient diffusion in a stationary medium is analogous to heat transfer and for one spherical bubble, defined by equation (3), one finds:

$$N_r = \left(k_H m_g p_l - C_{bulk}\right)\pi D_{dif} d 15.8 \tag{3}$$

in which

N_r	[mol/s]	Molar rate
k_H	[mol/(m^3.atm)]	Constant of Henry for air (0.78)
p_l	[atm]	pressure in liquid phase
D_{dif}	[m^2/s]	Diffusivity of air in water (2.4E-09)

EXPERIMENTAL SETUP

An industrial scale test rig was built at the wastewater treatment plant in Hoek van Holland. The first configuration (figure 1) includes a reservoir for recirculation of water. This configuration is used for the validation experiments with clean water and the experiments involving water with reduced surface tension. In the second configuration (figure 2), the test rig is connected to the influent flow of the primary clarifier of the treatment plant.

The test rig is constructed of PVC pipes (D= 200 mm). Transparent PVC with a wall thickness of 4 mm is used for the sloped section to visually monitor the flow pattern.

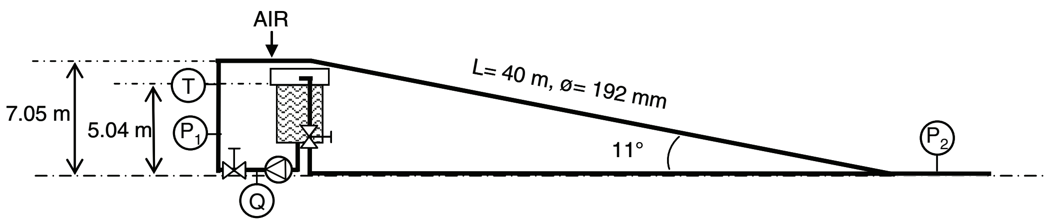

Figure 1. Schematic setup for experiments with clean water and reduced surface tension.

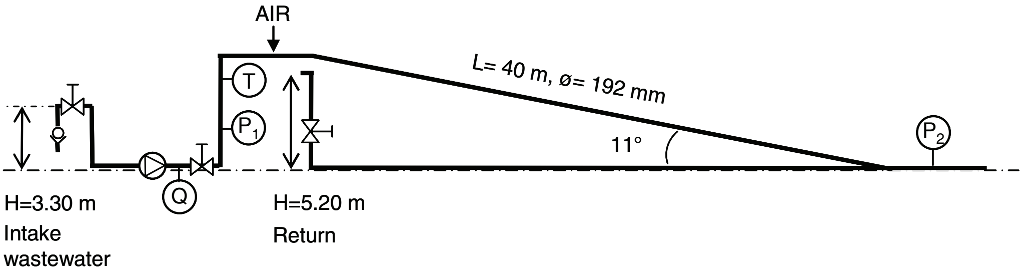

Figure 2. Schematic setup for experiments with wastewater.

The liquid flow is controlled using a frequency controlled centrifugal pump, an electro magnetic flow meter (Q) and a pneumatically controlled regulating valve next to the flow meter. A feedback control (PI type) is used to operate the control valve. The air injection is controlled with a mass flow controller (not shown in figures). For conversion into volumetric flow units, the actual pressure (P_1) and temperature (T) are used. A second pressure transducer is located at the downstream end of the downward slope. Samples for surface tension measurements are taken at a sampling port between the pump and the flow meter. An overview of the used instrumentation is given in table 1. The instrument accuracy as the percentage of the full scale is indicated in the third column. The uncertainty mentioned in the last column is the typical measured uncertainty in the 100 Hz series. The values correspond to the interval of 2 times the standard deviation on the measurements.

Table 1. Characteristics of used instrumentation (FS= full scale)

Instrument	Range	Accuracy (%FS)	Uncertainty (2 times standard deviation)
EMF liquid flow meter	0-100 l/s	< 0.25	0.2 l/s
MFC-1 air	0-50 nl/min	< 1	4% of recorded value
MFC-2 air	0-3 nl/min	< 0.25	2% of recorded value
Absolute pressure sensor	0-3 bar	< 0.1	P_1 60 mbar (pump influence) P_2 30 mbar
Temperature sensor	0-50 °C	< 1	0.3°C
Surface tension	10-100 mN/m	0.1	2 mN/m

Test procedure. The total head loss is the sum of the vertical level difference of the pressure sensors, the dynamic head loss due to local losses and wall friction at different water velocities and the head loss induced by the presence of the gas pocket (*Hgas*). The static and dynamic head loss is determined in a system without gas pockets.

$$\Delta H_{gas} = \Delta H_{tot} - \Delta H_{ll} - \Delta H_{fric} - \Delta H_{lev} \tag{4}$$

At a given gas and liquid velocity flow rate, the system is gradually moving towards a new equilibrium state. This process is monitored by measuring the pressure at a frequency of 1 Hz. To confirm stationarity, measurements of 30 seconds at a frequency of 100 Hz are performed at 5 minute intervals. When the averages of 7 consecutive measurements are within a bandwidth of 5 mbar (5 cm approximately), the system is defined as stationary. Typical gas pocket head losses vary from 1 m to 7 m; i.e. the elevation difference of the downward slope. Since the residuals in the 100 Hz measurements are uncorrelated, the uncertainties of the 30 s average values (last column of table 1) drop with a factor 55 to negligible values.

The surface tension was measured during the experiments with reduced surface tension and wastewater as static surface tension according to the Langmuir principle. The samples for the surface tension measurements were extracted at 15 minute intervals and analyzed immediately.

A complete test matrix of liquid and gas flow rates has been performed for the clean water measurements. The liquid flow step was 7.12 l/s, starting from 3.6 l/s up to 46 l/s, the gas flow rate step was 0.71 l/min up to 7.1 l/min. A selected number of measurements has been performed with clean water with reduced surface tension. Table 2 shows the test matrix for the wastewater measurements:

Table 2. Test matrix with wastewater. Values in table are number of experiments performed at given flow setting.

	Q_l [l/s]	3.56	10.67	17.79	24.90	28.46	32.02	35.58	42.69	46.25
Q_g [l/min]	F_l [-] / F_g [-]	0.09	0.27	0.45	0.63	0.72	0.81	0.90	1.07	1.16
7.12	3.E-04	1	1	1	2		1	1	1	1
1.42	6.E-04	1	1	1	2		1			
0.71	3.E-03		1	2	3	1	1	1	1	

RESULTS AND DISCUSSION

For comparison to previous research the results are scaled to a dimensionless expression. The expression is derived using the definition sketch in figure 3.

The relative head loss is defined as the ratio of the head loss due to the presence of a gas pocket and the total vertical height of the downward slope: $\Delta H_{gas} / L \cdot \sin\alpha = \Delta H_{gas} / H_{stat}$

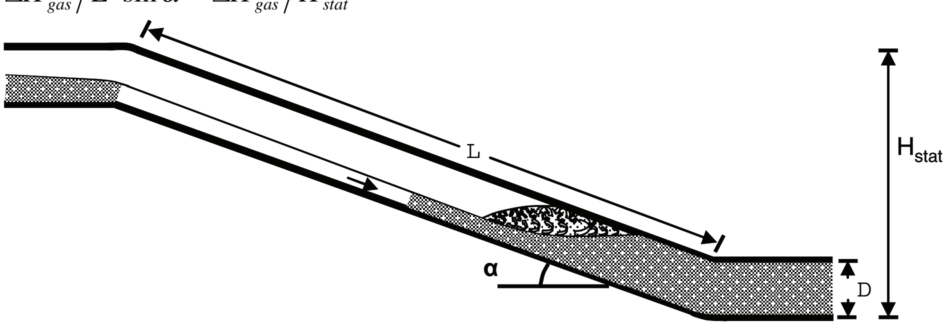

Figure 3. Definition sketch of experimental setup.

Surface tension. As described in equation (2), a reduction in surface tension from 0.072 to 0.045 N/m will result in a smaller bubble diameter (d2=0.75*d1). Equation (3) predicts a decrease in mass transfer per bubble with the same ratio. Assuming that the gas entrainment rate at the toe of the hydraulic jump is not affected by the surface tension, the number of entrained bubbles increases with a factor 2.3, which implies that the total mass transfer increases with a factor 1.8. To investigate this effect, a detergent is added to the water to reduce the surface tension to a level comparable to the surface tension of wastewater (0.072 – 0.035 N/m). The results are presented in Figure 5 showing the effect on the relative head loss. The reduction of the surface tension results in a linear decrease of the relative head loss. This reduction is caused by a combination of smaller gas bubbles and larger mass transfer into the dissolved state.

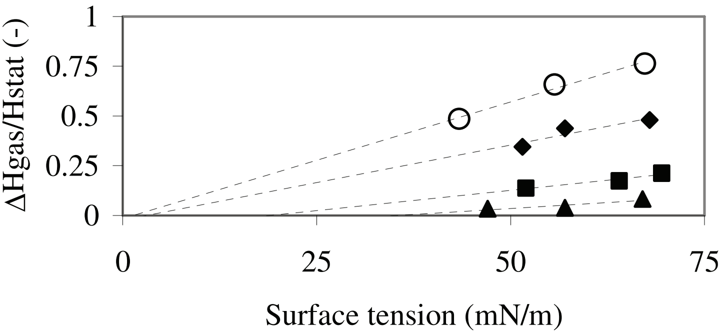

Figure 5. Effect of surface tension on relative head loss (○: F = 0.62, Qg=7.1 l/min; ♦: F = 0.45, Qg=0.71 l/min; ■:F = 0.63, Qg=0.71 l/min; ▲: F = 0.72, Qg=0.71 l/min).

Absolute pressure. The declined sections in a sewerage pressure main can be located close to the pumping station or near the wastewater treatment plant. These locations have different levels of absolute pressure due to resistances and friction losses in the system. Also the intermittent operation of the pumping station will cause a variation of the absolute pressure. This variation in absolute pressure will influence the dissolved gas transport.

In the industrial scale field test rig, the absolute pressure is increased by throttling the manually operated valve in the return line.

Measurements were performed at three pressure levels and at three liquid flow numbers. The results are presented in figure 6 for a volumetric gas flow of 0.71 and 7.1 l/min. At the low gas flow of 0.71 l/min, the influence of the absolute pressure on the relative head loss is significant. An increase of 0.5 bar reduces the extra resistance of the gas pocket by 50%. At a gas flow of 7.1 l/min, the effect is limited. The extra contribution of mass transfer into the dissolved state must be of the order of magnitude of the gas flow of 0.71 l/min at a pressure increase of 1 bar.

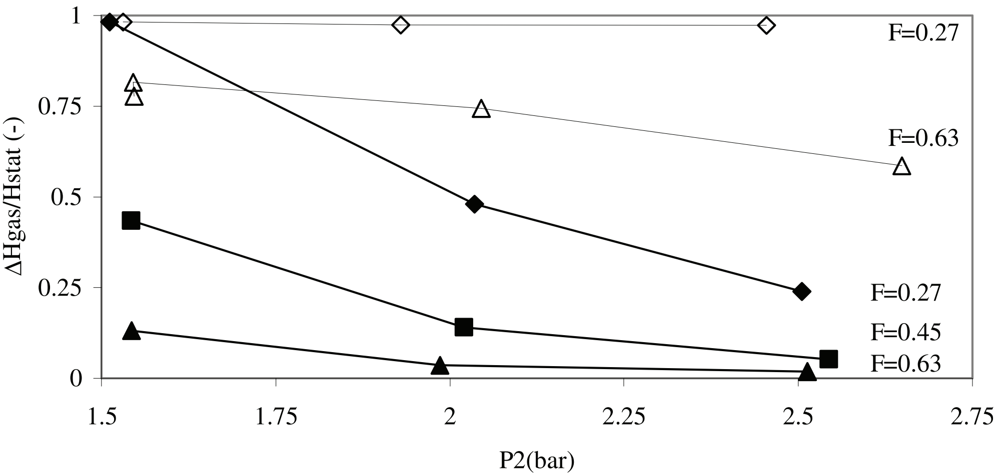

Figure 6. Effect of absolute pressure on the relative head loss at volumetric gas flow of 0.71 l/min (closed symbols) and 7.1 l/min (open symbols).

Wastewater. It is expected that the different constituents in wastewater will influence the gas transport processes. To quantify this effect, the treatment plant inflow, extracted after the sand trap, is used as the feed flow in the test rig. Initial tests with the wastewater showed that the surface tension of dry-weather-flow hardly varied during the day. Therefore, measurements could be performed at constant liquid and gas flow rates. Figure 7 shows that the gas pocket head loss in wastewater is comparable with the head loss in clean water, despite the smaller surface tension of wastewater. Similar results are obtained at the other liquid and gas flow rates. The insensitivity of the gas transport for the surface tension of wastewater is probably caused by the lower molecular diffusion of the σ-reducing constituents in wastewater compared to the detergent used to reduce the surface tension of the clean water. The measurement of the dynamic surface tension of a few wastewater samples supports this conclusion.

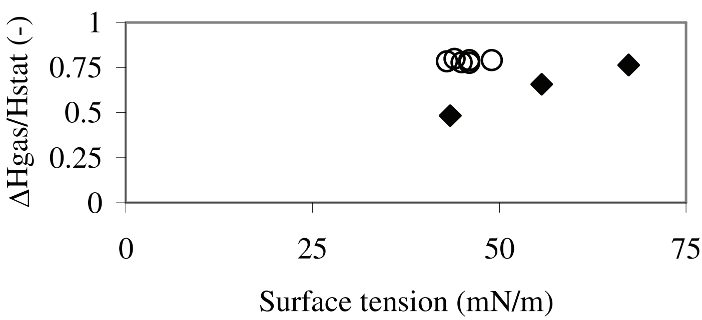

Figure 7. Comparison of measurements of wastewater at DWF (o) with clean water and surfactant (♦) at F=0.63 and Qg=7.1 l/min.

CONCLUSION AND DISCUSSION

Reduction of the surface tension of clean water by means of surfactants shows a linear reduction of the gas pocket head loss. The reduced surface tension reduces the bubble size of entrained bubbles in the hydraulic jump, which enhances gas transport. Furthermore, more gas will dissolve in the liquid phase, because of the larger contact surface.

Despite the fact that the static surface tension of the wastewater is significantly smaller than that of clean water, the experiments show that the gas pocket head loss is similar to the gas pocket head loss of clean water. This discrepancy in test results is caused by the dynamic character of the surface tension. The effective surface tension of wastewater on the time scale of the bubble creation in the hydraulic jump is similar to the surface tension of clean water. The surfactants in wastewater (mainly proteins, fat molecules) are too slow to migrate to the bubble interface and affect the bubble creation. Hence the lower surface tension of wastewater does not enhance the gas transport.

The experiments with clean water and wastewater at three different absolute pressures show that a significant fraction of the gas flow dissolves in the hydraulic jump, even at a moderate absolute pressures of 1.5 bara.

When gas pockets are present in a pressurized sewerage main, they can be removed more quickly by temporarily increasing the system pressure by throttling a downstream valve.

ACKNOWLEDGEMENT

This research is funded by: Dutch ministry of Economic affairs, Foundation STOWA, the waterboards of Aquafin, Brabantse Delta, Delfland, Fryslân, Hollands Noorderkwartier, Hollandse Delta, Reest en Wieden, Rivierenland, Waternet, Zuiderzeeland, ITT Water and Wastewater and the engineering consultants Grontmij and Royal Haskoning.

REFERENCES

Hinze, J. O. (1955). "Fundamentals of the hydrodynamic mechanism of splitting in dispersion processes." AIChE.J(1): 289-295.

Kent, J. S. (1952). The entrainment of air by water flowing in circular conduits with downgrade slopes, University of Berkley, California.

Lubbers, C. L. (2007). On gas pockets in wastewater pressure mains and their effect on hydraulic performance. Civil and Geotechnical Engineering. Delft, Delft University of Technology. PhD: 290.

Lubbers, C. L. and F. H. L. R. Clemens (2006). "Breakdown of air pockets in downwardly inclined sewerage pressure mains." Water Science & Technology 54(11-12): 233-240.