Breakdown of air pockets in downwardly inclined sewerage pressure mains

Water Science & Technology **Vol 54 No 11–12 pp 233–240** © IWA Publishing 2006

C.L. Lubbers*, and F.H.L.R. Clemens****

*WL Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands
(E-mail: *Christof.Lubbers@WLDelft.nl*)

**Delft University of Technology, Faculty of Civil Engineering and Geosciences, Section of Sanitary Engineering, P.O. Box 5048, 2600 GA Delft, The Netherlands (E-mail: *f.h.l.r.clemens@citg.tudelft.nl*)

Abstract In the Netherlands, wastewater is collected in municipal areas and transported to centralised WWTPs by an extensive system of pressure mains. Over the last decades these pressure mains did not receive much attention in terms of monitoring of performance or maintenance. A recent inventory showed that half of the pressure mains show an increased pressure loss for no directly obvious reason. One of the many causes that account for the reduction of the flow capacity is the occurrence of free gas in the pipeline. During dry weather periods with low flow velocities, gas may accumulate at high points in the system. Once the velocity increases during storm weather flow, the air pockets may be broken down and transported to the end of the system. A research study is started focussing on the description of the gas-water phenomena in wastewater pressure mains with respect to transportation of gas. An experimental facility is constructed for the study of multi-phase flow. This paper describes the preliminary results of experiments on breakdown rates of gas pockets as a function of inclination angle and water flow rate. The results show an increasing breakdown rate with increasing inclination angle.

Keywords Experimental research; hydraulic jumps; pressure mains; removal of air pockets

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.

Several investigations (Kent, 1952; Wisner, 1975; and Walski, 1994) have been carried out in the past into the minimum required flow velocity to transport gas in downwardly inclined pipes. Lubbers and Clemens (2005) investigated the maximum head loss that may occur if a constant air flow rate is supplied. Hardly any information is given with respect to the period that it takes to remove air pockets once they occur during periods when the flow rate is low. In practice, the flow velocity in wastewater transport lines is not constant. During dry weather periods often a single pump operates and the flow rate is smaller than during storm weather periods when more pumps are in operation and the flow rate is higher. Most of the year, dry weather flow occurs and entrained gas accumulates at high points in the system. Gas may be transported beyond this point if storm weather flow occurs. Experiments have been carried out to study the transport capacity of gas along downwardly inclined pipes as a function of inclination angle and flow rate. In this paper the results of these experiments of gas removal are discussed.

doi: 10.2166/wst.2006.769

Materials and methods

Experimental set-up

The experiments are conducted in a dedicated facility for research on air/gas pockets that are located at the transition from horizontal to inclined pipes. The facility (Figure 1) is specially designed to inject a controlled and monitored airflow into the liquid phase. From a constant head reservoir a pump circulates water through the experimental facility. A flow control valve (FCV) in combination with an electromagnetic flowmeter (EMF) and PC adjust the flow rate to its set value. Air is supplied by the standard 6 bar pressurised air-infrastructure in the building. A combined mass flowmeter and FCV 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 (101,325 Pa and 0°C). The test section consists of a horizontal section, downstream of the air injection point, a downwardly sloping section, having a length of 6 m is followed by a horizontal section. The test section is made of transparent material (Perspex) with an inner diameter of 220 mm. Flexible hoses connect the test section to the reservoir and pump. The water/air mixture returns to the reservoir over a weir in order to strip as much air as possible from the water. 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.

The facility incorporates the instruments given in Table 1. The absolute pressure transmitters are located in the horizontal parts of the test sections. In order to prevent air from disturbing the pressure measurements, the tapping is 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 sampling frequency can be adjusted manually ranging between 0 and 10 kHz. The acquired data are stored on a hard disk. For the air pocket removal measurements, a sample frequency of 1 Hz is applied since no short term changes are expected.

Transport of gas bubbles

The processes involved in air/gas transport in water are well known and not very complex in themselves; buoyancy, drag, equilibrium in surface tensions (water/air/wall). Yet, studying the transport under stationary conditions (constant water and air/gas discharge) reveals that chaotic behaviour occurs. In a downwardly inclined pipe it is seen that gas is only transported if a hydraulic jump is present. If high points are present in a pipeline, gas is accumulated upstream of this point. Gas that has entrained in the system arrives at the high point and if the flow velocity is low enough, the drag is smaller than the buoyancy and the gas is trapped. If sufficient amount of gas is supplied to this point the volume will increase and the water depth will decrease. The water level cannot drop to values below the critical depths that correspond to critical flow. Gas from the air

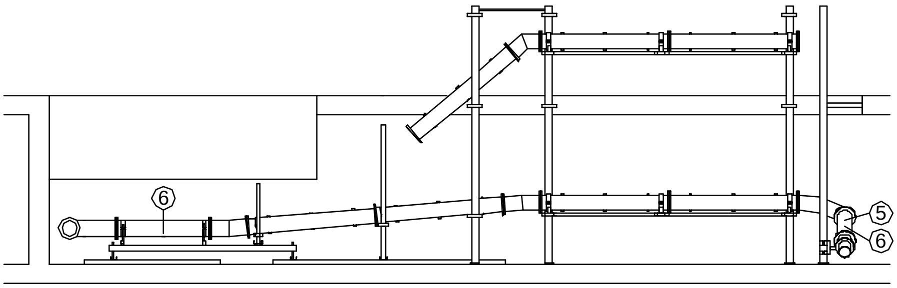

Figure 1 Side view of the experimental set-up with air inlet (5) and pressure transmitters (6)

Table 1 The instruments incorporated in the experimental set-up

	Range	Uncertainty
EMF DN125	0–100 l/s	< 0.25%
Gas flowmeter	1–50 nl/min	< 0.5%
Two absolute pressure transmitters	0–3 bara	< 0.1%
Temperature transmitter	3 to 100 °C	< 0.1 °C

pocket is not transported until the water reaches this critical depth that corresponds to a Froude number of 1. The critical depth can be calculated by taking the depth y that corresponds to the minimum value of the specific energy. Froude number and specific energy are defined as follows:

$$Fr = \frac{v}{\sqrt{gD_h \cos\theta}} \quad \text{and} \tag{1}$$

$$E = y + \frac{Q_w^2}{2gA^2}, \tag{2}$$

where v is the velocity, D_h the hydraulic diameter, y the water depth, Q_w the water flow rate and A the wet area. Similar to free surface weirs, the free surface flow across the bend tends to go to its minimum energy level corresponding to Froude number of 1. The moment that this water depth is reached, the water level cannot decrease further and gas will be forced down into the inclined pipe. Then at the tail of the gas pocket a hydraulic jump occurs (Figure 2).

The characteristics of a hydraulic jump depend on Froude number and inclination angle. The Froude number takes several parameters into account such as flow rate, water depth at the foot of the hydraulic jump, which influences the local velocity and also the width of the water surface at the foot of the hydraulic jump. The entrainment of gas from the gas pocket into the hydraulic jump only occurs along this width. It is assumed that more gas can entrain once this width is larger. At moderate velocities the water depth is small, which has two effects on the efficiency of the transport capacity of the hydraulic jump. Firstly, the width of the water surface is small compared to the diameter and little amounts of air can entrain into the hydraulic jump. Secondly, the air bubble that has entrained into the hydraulic jump has a small drag/buoyancy ratio, which implies

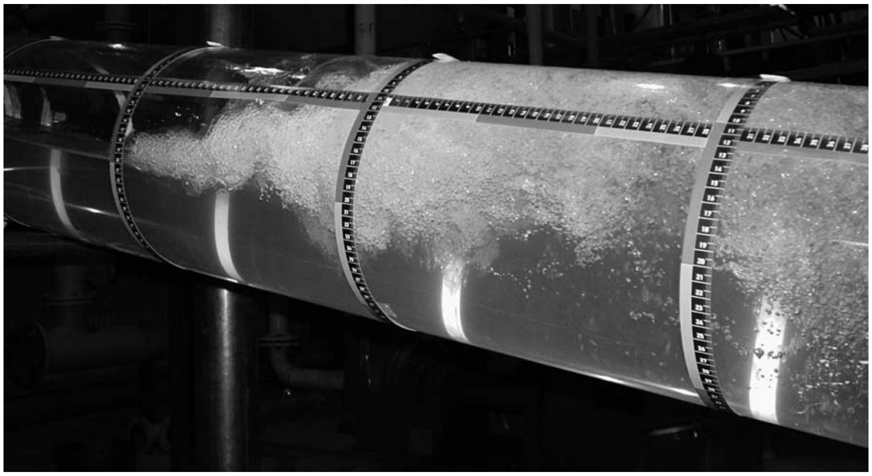

Figure 2 A picture of a hydraulic jump at the tail of the air pocket

difficult gas transport further down the pipe, since the gas bubble will rise to the top of the pipe shortly after it has entrained into the hydraulic jump. As gas bubbles tend to accumulate in this upper region, the bubbles grow larger to the point that the buoyancy force overcomes the drag and the bubble moves against the flow back into the gas pocket.

If the flow rate is larger, the water level will rise, which has beneficial effects on the transport and removal period of gas. Firstly, the gas volume is smaller since the critical water depth is larger. Secondly, the width of the water surface at the foot of the hydraulic jump is larger and therefore more gas can entrain. Thirdly, the average velocity in the hydraulic is larger, which means that the drag/buoyancy ratio is larger.

Test procedure

For three different slopes (30°, 10° and 5°) the transport of gas is determined for different water flow rates. The inherent gas discharge rate of the hydraulic jump is determined by supplying a larger air flow rate towards the high point than the water flow rate would naturally be able to transport. A stationary condition is reached where the gas pocket is larger than normally would occur. If a stationary situation has been established, the air supply is shut off. From that moment, the gas discharge is larger than the supply and the gas pocket volume will consequently decrease. The decrease of the gas pocket is determined using two pressure transmitters. The breakdown rate is quantified by calculating the rise of the location of the hydraulic jump per unit time. The breakdown rate is calculated this way for the different inclination angles in order to be able to compare the efficiency of the hydraulic jump for different inclination angles. As soon as the stationary situation was achieved, the air supply was shut off and the water and air flow rate, the upstream and downstream pressure and the water temperature signals were recorded. All signals have been recorded at a sample rate of 1 Hz until the whole air pocket has vanished or a period of 5 hours has passed. If then the gas pocket has not been removed, the breakdown rate of the gas pocket is regarded as very slow.

The sample rate is sufficiently high to follow the change in the pressure difference signal well. The pressure signal fluctuates in time and a moving average operation is carried out prior to calculating the time derivative of the pressure difference. The breakdown rate is defined as:

$$\text{Breakdown rate} = \frac{(\Delta p_{t_2} - \Delta p_{t_1})}{t_2 - t_1} \cdot \frac{1}{\rho g}[\text{m/h}], \tag{3}$$

where Δp is the pressure difference in Pascal at time t, which is expressed in hours, ρ is the density of water and g is the gravitational acceleration. Measurements are carried out for different combinations of water flow rates and inclination angle. The flow rate varies from 10 l/s to 45 l/s, which correspond to 0.26 m/s to 1.18 m/s. In order to compare the flow rates with those for other pipe diameters a dimensionless velocity is defined as follows:

$$v' = \frac{v}{\sqrt{gD}} \tag{4}$$

where v is the mean velocity for the fully filled pipe and D is the diameter of the pipe.

Results and discussion

A typical time series of the breakdown rate defined according to Equation (3) is given in Figure 3 for the 30° pipe. The dotted line presents the breakdown rate of 30 l/s or a v' of 0.54 is applied. The graph shows that after 2 to 2.5 hours the breakdown rate has dropped to zero which means that the gas pocket has been removed. The dashed line presents the breakdown

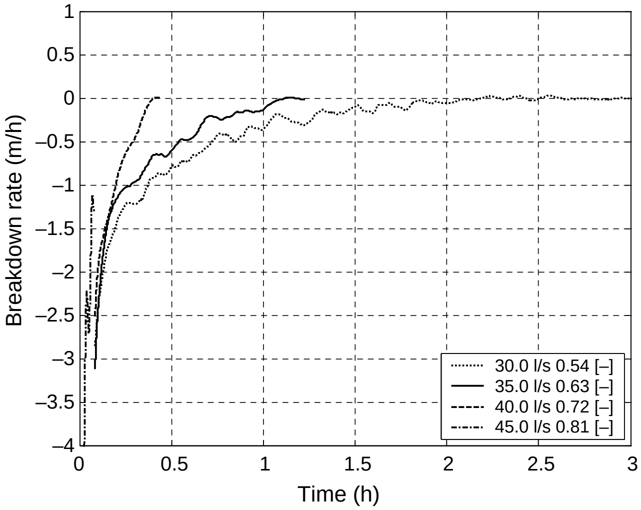

Figure 3 Breakdown rate as a function of time for several flow rates at a pipe inclination angle of 30° bend

rate for 40 l/s or a v' of 0.72. The removal time has decreased to less than half an hour. The outcome itself is not surprising since at higher flow rates the gas discharge capacity is higher and the volume of the gas pocket at stationary conditions is smaller.

Therefore it is better to compare the breakdown rate as function of the location of the hydraulic jump. Figure 4 shows the same breakdown rates as in Figure 3 but as a function of the vertical distance of the hydraulic jump to the top of the upstream horizontal pipe. Figure 4 shows that at stationary conditions prior to the air supply shut off, the location of the hydraulic jump at 30 l/s (dotted line) was 0.95 m under the top of the horizontal pipe. As the gas is discharged from the gas pocket, the hydraulic jump moved up causing the breakdown rate to decrease. For 40 l/s (dashed line) the graph shows that the volume of the air pocket was initially much smaller but the breakdown rate for example at 0.2 m below the top of the horizontal pipe is 3.5 times larger than for 30 l/s.

For smaller flow rates it may happen that the breakdown rate is negligible. The gas pocket and hydraulic jump exist but no gas is effectively removed. Gas is entrained at the

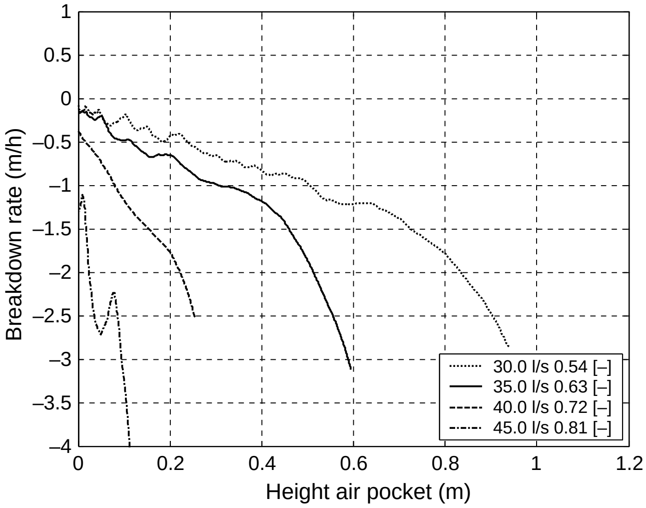

Figure 4 Breakdown rate as a function of the height of the air pocket for several flow rates at a pipe inclination angle of 30°

foot of the hydraulic jump; however, all gas is recirculated back into the gas pocket. Figure 5 shows the time series of the breakdown rate at moderate flow rates of 10, 20 and 25 l/s ($v' = 0.18$, 0.36 and 0.45). For 10 l/s the breakdown rate dropped to 0.2 m/h after 5 hours.

The breakdown rate as a function of the vertical distance to the top of the horizontal pipe is given in Figure 6. It shows that due to the small breakdown rate the location of the hydraulic jump at 10 l/s moved in 5 hours from 2.5 m to 0.75 m below the horizontal pipe. The air pocket therefore still remains present.

In the design phase, a choice has to be made with respect to inclination angle of the pipe in the case that the pipeline needs to pass an obstruction such as a river or a road. Regardless of the selected angle the vertical distance to overcome is the same.

Figure 7 presents an overview of the breakdown rate of four flow rates at different angles. The solid lines present the breakdown rate of 35 l/s, the dotted line of 40 l/s and

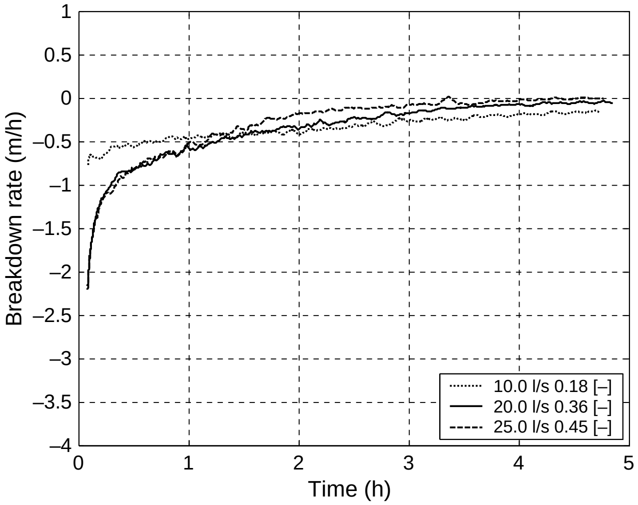

Figure 5 Breakdown rate as a function of time for several flow rates at a pipe inclination angle of 30° bend

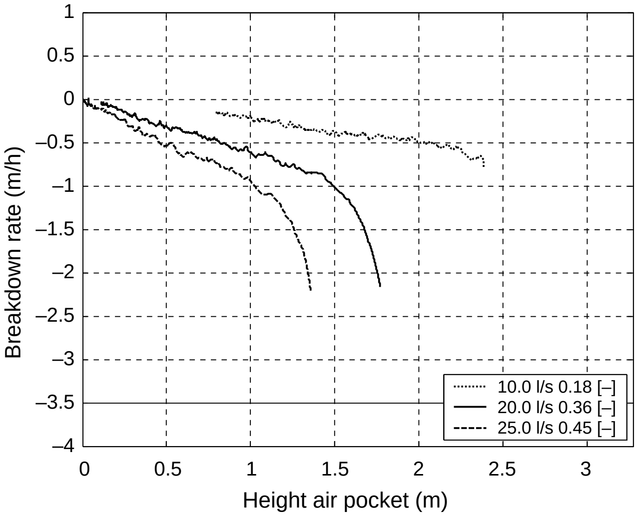

Figure 6 Breakdown rate as a function of the height of the air pocket for several flow rates at a pipe inclination angle of 30°

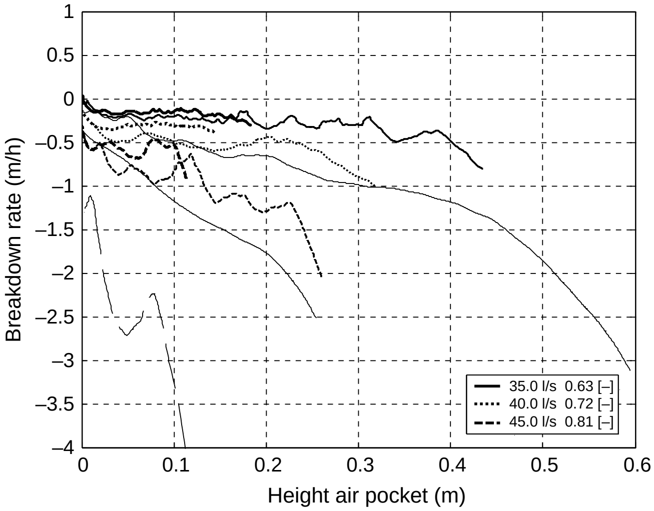

Figure 7 Influence of inclination angle

the dashed line of 45 l/s. The thickest lines present the 5° slope, the medium thick line the values of the 10° slope and the thin line the results of the 30° slope. For 35 l/s or v' of 0.63, the difference in breakdown rate between 5° and 10° is not large compared with the difference in breakdown rate between the 5° and 10° slopes for 45 l/s or v' of 0.81. The difference in breakdown rate between 5° and 10° slopes increases if the flow rates are higher. The larger difference is seen between the 10° and 30° slopes. For all flow rates, the breakdown rate for 30° slopes is significantly larger than for 10° slopes. This result was opposed by the intuition of designers for many years; since buoyancy force plays a larger role for larger inclination angles and was therefore believed to counteract the drag of the flow acting on the gas bubbles. The actual mechanism, though, seems to be the change of the shape of the bubble into an ‘umbrella’ shape. This shape has a much larger surface area perpendicular to the flow, resulting in a large drag to buoyancy ratio.

Conclusion and discussion

This paper presents the first results of the study on air pockets removal in pipelines by the flow itself. The results show that for a certain pipe angle, a larger flow rate transports gas better than a smaller flow rate. Designers of pipelines can choose to decrease the diameter of the pipe locally in order to obtain two effects. Firstly, the maximum volume of the accumulated air is smaller due to a higher critical depth. Secondly, the removal of the air pocket occurs much faster. Since wastewater transport in pressure mains shows a very discontinuous character, obtaining short removal periods is important to guarantee a trouble free operation of the system. The results show that at equal water flow rates, the gas removal capacity in terms of metres per hour vertical length of the gas pocket is much larger for larger inclination angles than smaller ones. If one needs to pass an obstacle at a certain depth a larger inclination angle is to be preferred over a smaller one.

Acknowledgements

The research is funded by: Foundations RIONED and STOWA, the Water boards 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

Kent, J.C. (1952). The entrainment of Air by Water Flowing in Circular Conduits with downgrade Slopes. Thesis presented to the University of California, at Berkeley, Calif.

Lubbers, C.L. and Clemens, F.H.L.R. (2005). Air pockets in sewerage pressure mains. *Water Science and Technology*, **52**(3), 37–44.

Walski, T.M. (1994). Hydraulics of corrosive gas pockets in force mains. *Water Environment Research*, **66**(6).

Wisner, P.E. (1975). Removal of air from water lines by hydraulic means, Proceedings of the American Society of Civil Engineers. *Journal of the Hydraulics Division*, **83**(HY2).