Technical Note

Subject: **AIR IN WATER AND WASTEWATER PIPES**

A review of air pocket movement dynamics in water and wastewater pipes, including an outline of design measures to facilitate air release, thereby eliminating the risk of capacity reduction due to trapped air.

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AIR POCKETS IN WATER AND WASTEWATER PIPES

INTRODUCTION

Trapped air in water and wastewater pipes, that are intended to flow full bore, effectively reduces the liquid flow cross-section at air pocket locations, thereby resulting in an increase in head loss and potentially reduced carrying capacity. Hence, elimination of the risk of trapped air pocket formation is an important element in the hydraulic design of such systems and key to the reliable prediction of performance. Air may be retained in pipes during initial priming or may be entrained during on-off pumping cycles, typical of rising main operation in urban wastewater conveyance systems. As the following discussion refers equally to water and wastewater conduits, the designation water may be taken to include wastewater.
The problem facing the designer may be considered in two parts (a) identification of potential locations for air pocket formation, and (b) deployment of appropriate remedial measures.

AIR POCKET FORMATION

During the process of priming a new main the contained air is expelled as the main is filled with water. However, where the main includes downward sloping segments trapped air pockets may be formed, particularly where the downward slope exceeds that of the prevailing hydraulic gradient for full-bore pipe flow. This circumstance is depicted in Fig 1, which also shows the head loss due to the air pocket.

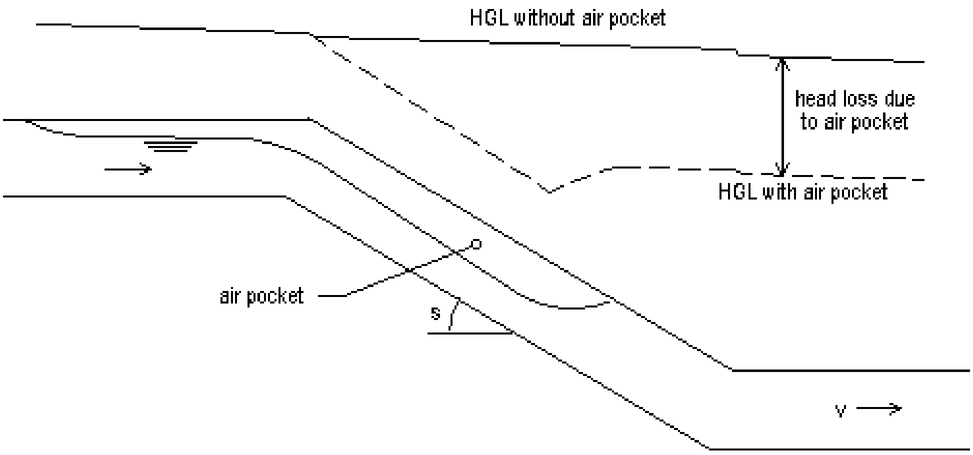

Fig 1 Pipeline trapped air pocket schematic

AIR POCKET MOVEMENT

Under the action of buoyancy, air trapped in pipes conveying water, that would flow full bore in the absence of air, typically forms a stratified layer or a series of large segregated bubbles at the soffit of the pipe. Where the pipe has an ascending gradient in the direction of flow it is clear that the buoyancy effect would push the air pocket upward and that this forward movement would be enhanced by the interface drag force generated by the water flow. Where the pipe has a descending gradient in the flow direction the movement of a trapped air mass is influenced by the water flow velocity, the diameter of the pipe and the pipe gradient. It has been shown that air movement in pipes having a downward slope in the flow direction can be characterised using the non-dimensional flow parameter F_w, defined as follows:

$$F_w = \frac{v}{\sqrt{gD}}$$

where v (m/s) is the pipe velocity flowing full, D (m) is the pipe diameter and g is the gravity constant. A critical operating condition is the F_w value required to clear air pockets downward in the flow direction, thereby eliminating the risk of trapped air pocket formation. Based on the writer's interpretation of published studies, it is proposed that the following F_w value ranges may be used to predict air pocket movement direction in downward sloping pipes:

$$F_w \geq 0.6 + 0.6(\sin s)^{0.5} \quad \text{Air pocket is cleared downward}$$
$$F_w \leq 0.5(\cos s)^{0.5} \quad \text{Air pocket moves upward}$$

where s is the downward pipe slope (deg).

The implication of the foregoing correlations over the typical working ranges of pipe diameter and operational velocity encountered in water and wastewater pipeline hydraulic design is illustrated in Fig 2.

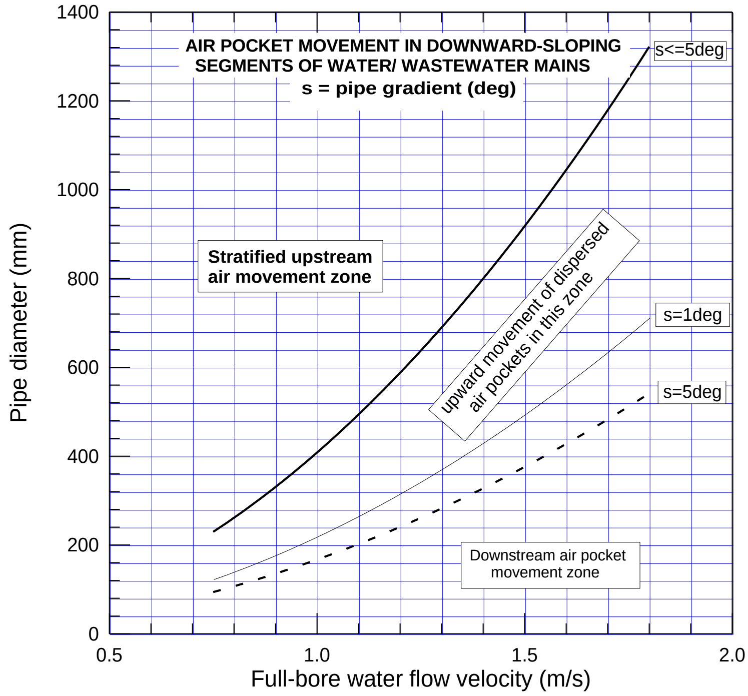

Fig 2 **Air pocket movement prediction**

The lower curves in Fig 2 define the critical lower limit pipe velocity above which air pockets are predicted to move downward in the direction of flow for a given pipe diameter, thereby eliminating the risk of trapped air pocket formation and the associated head loss. The lower graphs, which relate respectively to downward pipe slopes of 1deg (1:57 gradient) and 5deg (1:11.5 gradient), reflect the influence of the downward pipe slope on the velocity required to prevent trapped air pocket formation.

The upper curve in Fig 2 defines the critical upper limit pipe velocity below which **stratified** upstream air movement is predicted for a given pipe diameter. The graph indicates that the limit value is not sensitive to pipe slope for slopes $\leq 5deg$.

Where the full-bore pipe velocity is insufficient to cause transportation of air in the flow direction remedial measures are required to reduce the risk of formation of trapped air pockets and the associated head losses. Deployment of automatic air valves is the most commonly applied design solution as discussed in the following section.

AIR VALVES

Automatic air valves are used to regulate the admission and release of air in water and wastewater pipe systems. Single-acting air valves (SAV) allow air release only, while double-acting air valves (DAV) allow both air release and air admission. While the particular focus of this note is air release from mains, air admission is used to prevent pipe collapse resulting from negative pressure generated by events such as pump trip-out and pipe bursts.
The following is a rough guide to the ratio of air valve diameter to pipe diameter typically deployed in municipal water and wastewater pipe systems:

SAV	1:12
DAV	1:8

The larger size used in DAV selection reflects the requirement to limit the differential pressure drop across the DAV in air inflow, to prevent pipe collapse, following an event such as a pipe burst. The differential pressure limit is typically set in the range 0.1-0.3 bar.

To facilitate air-release an air valve should preferably located a short distance downstream of the upper end of the associated down-sloping pipe, as illustrated Fig 3, which depicts a typical double-acting air valve installation in a wastewater rising main with intermittent flow. In the illustrated example air is drawn into the main during pump-off periods, creating the zero-flow air volume defined by the dotted horizontal lines. On resumption of pumping, air is forced out through the air valve by the combined influences of displacement by the incoming water flow and the increasing back pressure associated with downstream flow development.

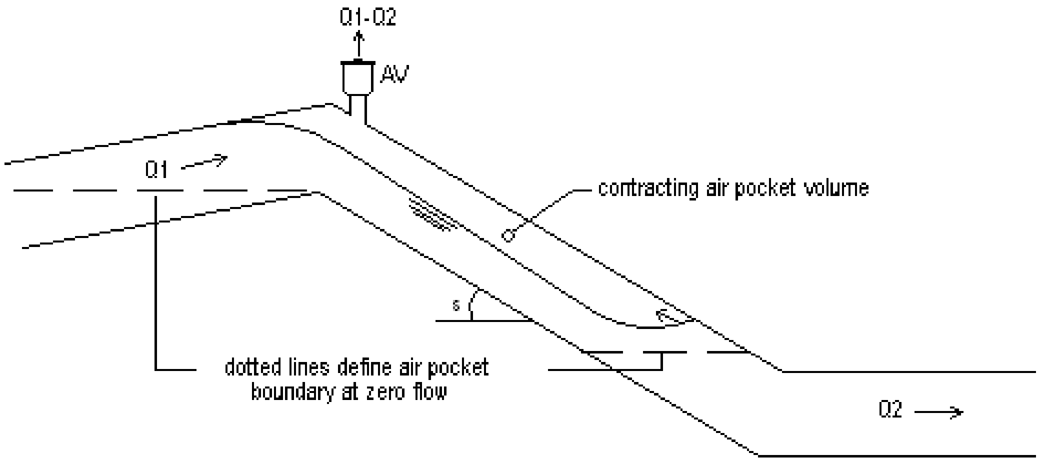

Fig 3 Air-release valve schematic

It is conventional design practice that rising mains are laid to specified gradients, determined by the prevailing ground surface profile and subject to the twin constraints of minimum pipe cover and avoidance of excessive excavation depth. Where the slope of the down leg pipe exceeds that of the flowing-full hydraulic gradient (HGL), free surface flow would develop, as depicted in Fig 3, creating space to facilitate the upward movement of air towards the air valve exit. However, where the down-slope s is less than that of the flowing-full HGL, the water flow rate would exceed the gravity flow capacity of the down leg segment, resulting in the obstruction of upward air movement to the air valve exit point. If this situation were coincident with an operational steady flow full-bore velocity less than the clearing velocity required to move air downward in the flow direction, the capacity for air removal would be somewhat compromised due to the restricted upward movement to air valve exit points. Referring to Fig 2 this circumstance is represented by operation in the zone designated for predicted upward movement of dispersed air pockets. It is clear that increasing the local pipe diameter would reduce the full-bore pipe velocity resulting in movement towards the zone designated as facilitating stratified upstream air movement, while reducing the diameter would increase the full-bore pipe velocity resulting in movement towards the downstream air clearance operating zone.

Over-sizing of air-release valves should be avoided as the associated accelerated air release and linked rapid water velocity change rate could have the potential to generate significant transient pressure fluctuation. The residual steady flow pressure in the main, following completion of air pocket expulsion, should be sufficient to satisfy the seal recommendation for the selected air valve.

AIR INTAKE PREVENTION

In wastewater pumping installations, where the outflow elevation exceeds the highest point on the upstream pipeline, positive pressure is maintained in the rising main during pump-off periods, thereby ensuring air-free pipe conditions on pump start-up in rising mains where an appropriate air valve deployment has been installed.

However, in those wastewater pumping installations where part of the rising main is at a higher elevation than the main outlet there is an inevitable intake of air during pump-off periods, resulting in the formation of air pockets on the downstream side of DAVs, as illustrated in Fig 4 in the following section. Such an intake of air could be prevented by an automated main outlet valve that would prevent main drain-down on pump stopping and would re-open following pump start -up, operating to an automated timing control regime designed to maintain positive gauge pressure during the pump-off period of the pumping cycle.

The use of this type of air intake prevention measure merits consideration in circumstances where (a) the rising main profile is such that large volumes of air would be drawn into the main in each pumping cycle, (b) release of large air volumes would be undesirable for environmental reasons such as odour nuisance, or (c) air release capacity through air valves proves to be problematic, resulting in the risk additional head loss and reduced carrying capacity.

The transient pressure fluctuation generated by a necessarily rapid outlet valve closure rate is a significant operational characteristic of this air intake prevention option, that requires careful analysis, particularly since it would be repeated every pumping cycle.

ILLUSTRATIVE EXAMPLES

Example 1

Example 1 is a 6.12 km long wastewater rising main transferring wastewater from a rural village to a nearby suburban wastewater treatment plant. The rising main profile is plotted in Fig 4. In this case the term “rising main” is a misnomer as there is an actual drop in elevation of some 13m between the inflow and discharge ends of the main. It is noted that the presentation in Fig 4 exaggerates the undulating profile of the main due to the unequal plotting scales of the axes in Fig 4, thereby greatly distorting the visual representation of actual pipe gradients.

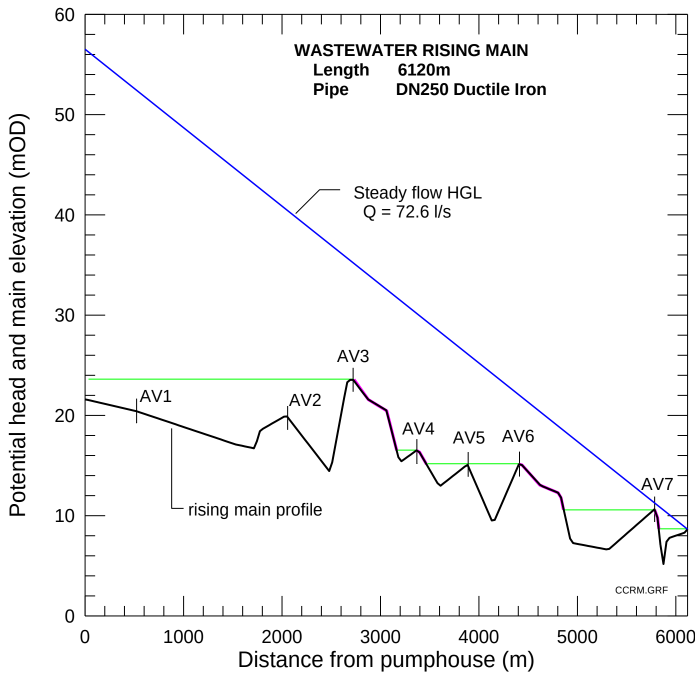

Fig 4 Wastewater rising main example 1

As shown in Fig 4 there are seven air valves installed on the rising main. Because of the undulating profile of the main it is evident that air would be admitted to the main through air valves AV3, AV4, AV6 and AV7 during periods when pumps were not running. The horizontal lines define the resultant air pocket volumes created downstream of these air valves under zero flow conditions.

The pipe downslopes downstream of the foregoing air valves vary within the range 0.34-5.13 deg. The mean full-bore flow velocity at the duty discharge rate of 72.6 l/s is 1.456 m/s (pipe ID=252mm). This regime places the pipe system safely within the operating zone where air pockets are forced downward in the flow direction, as illustrated in Fig 5.

The calculated slope of the HGL at the discharge rate of 72.6 l/s is 0.448 deg. While two pipe segments have downslopes less than this value, this is not problematic because the pipe velocity exceeds the critical value required to move pockets downward in the flow direction.

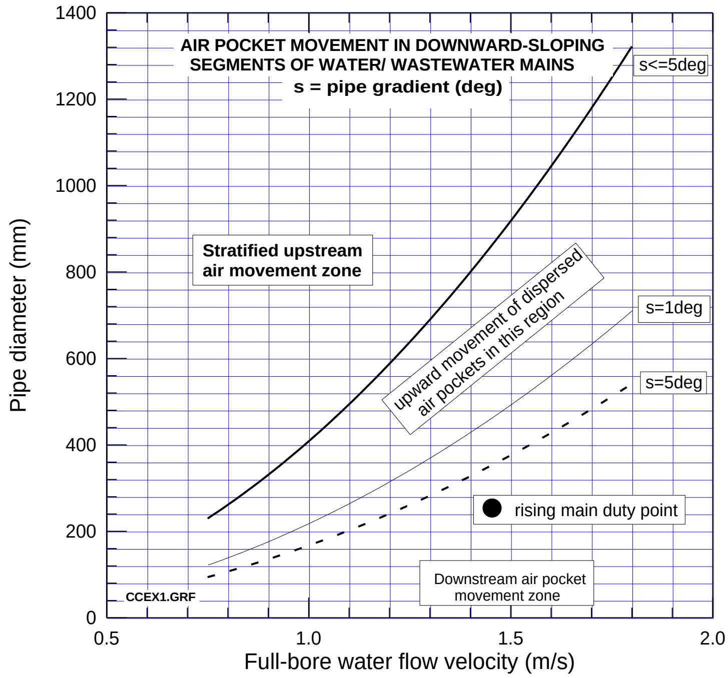

Fig 5 **Example 1 rising main air pocket movement prediction**

One further aspect of this illustrative example merits attention insofar as it could potentially impact the pump sump volume required to ensure the full expulsion of air following pump re-start. As illustrated in Fig 4, four air pockets with an estimated combined volume of 64.5 m^3 would develop in each pumping cycle, following pump shut-down. This corresponds to a 14.8 minutes duration pumping output. However, as illustrated in Fig 3, the simultaneous water outflow from each air pocket pipe section reduces the rate of air expulsion, thereby significantly extending the pumping duration required for complete air expulsion. Where complete air expulsion is necessary to ensure the development of a self-cleansing velocity in the rising main in each pump cycle, the pump-on duration should be checked to determine if it meets this objective.

Example 2

Example 2 is a 4.35 km long wastewater rising main, the salient features of which are set out in in Fig 6. The plotted profile of the main shows that it rises to a high point around mid-length while the end-points are at almost the same elevation. As in Example 1, it is noted that the presentation exaggerates the undulating profile of the main due to the unequal plotting scales of the axes, thereby greatly distorting the visual representation of actual pipe gradients.

The steady flow HGL, based on full-bore flow, shows that AV3 is the effective terminal point of the rising main. The elevation of the main at the AV3 location relative to the discharge point elevation comfortably exceeds that required to support gravity flow downstream of AV3.

As shown in Fig 6 there are five air valves installed on the rising main. Because of the undulating profile of the main it is evident that air would be admitted to the main through air valves AV1, AV3 and AV4 during periods when pumps were not running, resulting in the formation of the three air pockets the limits of which are defined by the horizontal lines in the diagram. The outlet segment of the main downstream of AV5 would also fully drain down.

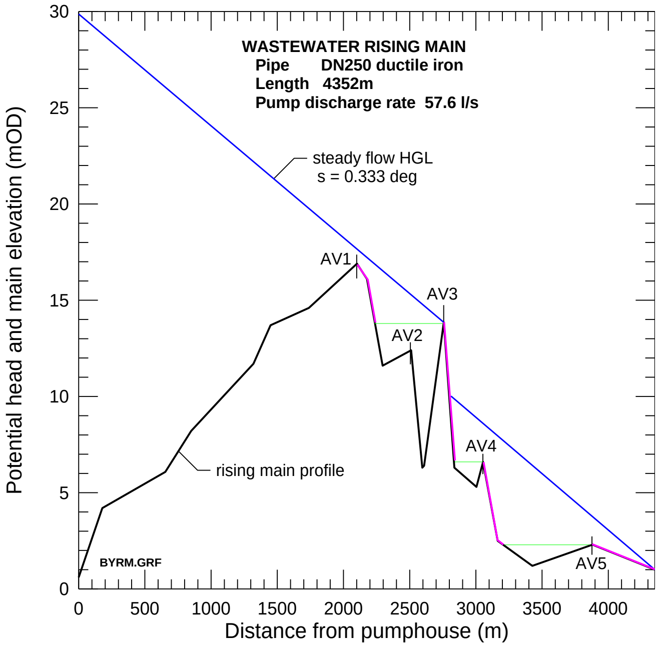

Fig 6 **Wastewater rising main example 2**

It is clear from the plotted profile of the rising main that the gradients of the pipe segments in which air pockets would form, following pump shut-down, significantly exceed the steady flow full-bore HGL, thereby facilitating free air flow to the respective air valve outlets, following pump start-up.

The gradient of the outlet-end pipe segment downstream of AV5 (s = 0.158 deg) is less than the full-bore HGL, but, as shown in Fig 7, the full-bore velocity at the design discharge of 57.6 l/s marginally exceeds the critical velocity for forward air movement and thus facilitates expulsion of air from this pipe segment.

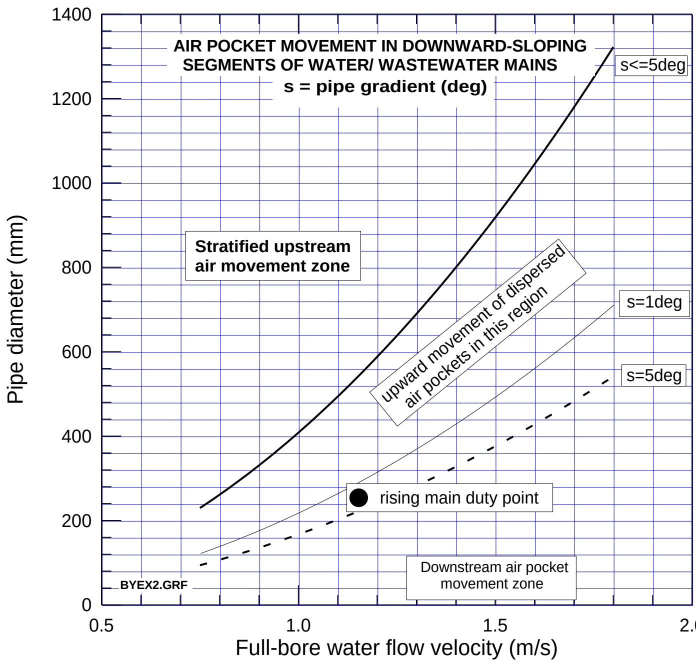

Fig 7 **Example 2 rising main air pocket movement prediction**

One further aspect of this rising main example is noteworthy. As shown in Fig 6, under steady flow operating conditions, the air valves, with the exception of AV3, are predicted to operate at a low positive pressure under steady flow conditions. This requires careful attention to air valve selection, as the low pressure could prove to be operationally problematic due to inadequate sealing performance resulting in leakage at each pumping cycle. In some such circumstances, ventilation columns may be an appropriate alternative to automatic air valves.

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