Use of Flow Measurement Devices in Restricted Environments

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Abstract

Measuring flow rates in wastewater pump stations (WWPSs) is important for planning, pump protection and quantifying overflows. The replacement of flow meters is a costly exercise, which normally includes bypassing the pump station, excavation and confined space entry. A cost-effective alternative is installing a clamp-on ultrasonic flow meter (USM) on the accessible pipework within the WWPS, but this can result in the upstream straight pipe length being outside manufacturer's recommendations. This project investigates the general behaviour of clamp-on USM in a confined environment, focussing on its application in a dry well type 40 WWPS. USM performance is predicted by numerical calculations based on Computational Fluid Dynamics (CFD), and evaluated using experimental results from a test rig simulating actual pump station pipework. Results confirm the improvement in accuracy as the USM is moved away from a tee. Installation orientation is found to have significant impacts, with the angular dependence diminishing with increasing distance from the tee.

1. Introduction

Water Corporation measures flow rates in wastewater pump stations (WWPSs) for planning, pump protection and quantifying overflows. Presently, only 20-30% of WWPSs have flow meters. Retrofitting of in-line flow meters is expensive, and normally requires bypassing the pump station, excavation and confined space entry. In the example of Slade St WWPS (type 180), the cost of mobilising and demobilising the equipment is estimated at $70,000, equivalent to the capital cost of two pumps for a lower-capacity pump station.

A cost-effective alternative is installing a clamp-on ultrasonic flow meter (USM) on the accessible pipework in WWPSs. This can, however, result in the upstream straight pipe length being outside the meter manufacturer's recommendations. As USMs are typically calibrated for a fully developed flow profile, the highest reading errors are expected close to flow disturbance sources, and should decrease with increasing downstream distance. Stoker (2011) tested a commercial USM installed at various locations downstream of a single bend. The maximum error shifts recorded were -16% (1.5D), -10.5% (3.5D), -8.5% (5D) and -5.0% (10D) at a Reynolds number (Re)=250,000. Since the flow field has an asymmetric structure while the USM acts as a line sensor, the accuracy of USM readings is also subject to variation due to installation orientation.

This project investigates the general behaviour of clamp-on USMs in confined environments, focussing on their application in dry well type 40 WWPSs. The objectives include:

1. Build reliable CFD models for the pipework sections of interest, to improve understanding of the flow field downstream of disturbances and to predict the expected accuracy of a USM.
2. Design, construct and commission an experimental rig for USM testing.
3. Perform laboratory experiments to investigate the real-life response of a clamp-on USM at different distances from the fitting, and under other installation variations.

2. Methodology

2.1 CFD Simulation

A commercial CFD package Ansys Fluent is used to simulate and visualise the fluid behaviour in various scenarios in a type 40 sewerage pump station with a design flow rate of 20 L/s. Pipe sections where a clamp-on USM could be installed are considered, specifically two risers and a horizontal pipe section connected to pressure main. The results of the simulation will support understanding of flow behaviours and provide data for the accuracy analysis. The model results are to be validated against the experimental results, to establish whether CFD can be used instead of experiments in future investigations.

The geometry of the CFD model is obtained from engineering drawings stored in AquaDraw. Mesh refinement continues until the key parameters (pressure difference, velocity/TKE profiles) change less than 1% with each additional refinement. The mesh has been refined to two million elements. Inlet boundary condition is the outlet velocity profile from a model of a fully opened swing check valve with 3.6 million mesh elements.

In addition, model results have found that check valve inlet turbulence intensity (TI) is a key parameter affecting velocity profiles at areas of interest. A typical 10% TI was experimentally measured at a centrifugal pump discharge (Flack et.al 1992), which has been applied as an approximation. The solution is calculated using k-epsilon turbulence model, with second-order discretisation method and coupled solution algorithms.

Two baseline tests were designed to determine the reference flow profile under different Re (flow rate=10, 20, 30, 40 L/s at nominal pipe diameter, DN=150 mm) and pipe roughness. Three modelling tests were run to predict the accuracy level of USM readings at positions outside manufacturer's recommendations. Key testing parameters include the downstream distance from a tee, installation orientation and distance between transducers.

The model results are used to calculate profile factor (PF), equivalent to a correction constant in USM measurements. PF captures the difference between line velocity along the ultrasonic path and area average velocity across the pipe. The PF value is heavily affected by the shape of the velocity profile. USM manufacturers often apply a theoretical PF factor calculated using fully developed profile measured by Nikuradse. Thus, the deviation from a reference fully developed PF should characterise the reading error expected from flow profile disturbance.

2.2 Pilot Test Rig Development and Experiments

A pilot test rig has been built to simulate a typical type 40 dry well WWPS with a design flow rate of 20 L/s and 150 mm DN. With the scaling ratio of 1:3, the rig pipe diameter is scaled down to match the line velocity of the pump station. Due to safety, time, practicality and cost considerations, factors such as water quality, pipe material and inlet pumps are not included in this experiment. The test rig design is shown in figure 1 below.

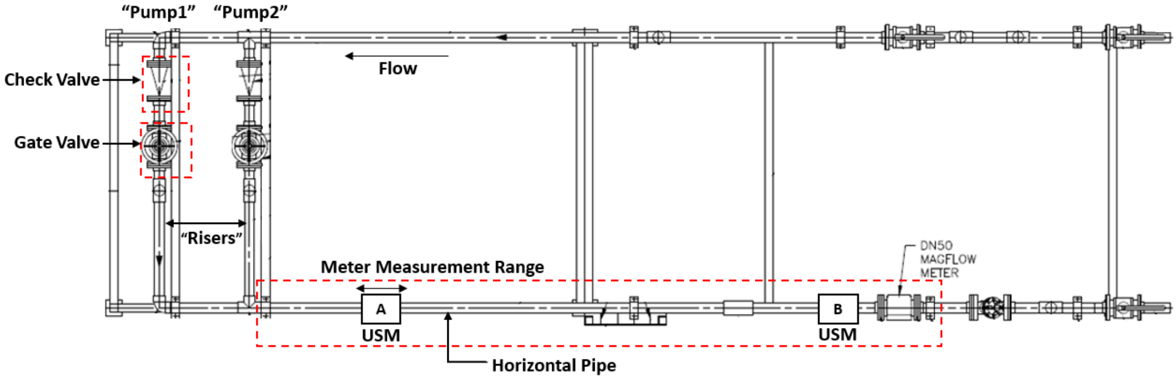

Figure 1 A top view of the pilot test rig used in experimental tasks, USM-A is the meter under testing, USM-B and the magflow meter act as reference measurements.

A magnetic flow meter (magflow) calibrated to ±0.2% uncertainty is used as the reference. Two commercial USMs with an accuracy of ±2 % are used for testing. The performance of USM is quantified by the percentage difference between USM-A readings and magflow. The rig is a closed system, where potable water stored in a 200 L tank is circulated by a 4.5 L/s pump. Two major tests were conducted in the experiment:

- Test A: USM-A is installed at 2D (pipe diameter), 5D, 10D, 20D, 30D and 55D (next to USM-B) away from the tee piece on the horizontal pipe.
- Test B: USM-A is installed at 3.5D, 9D,17D and 24D downstream from check valve on each riser.

At each location, the test was run at flows of 2.7 L/s and 2 L/s, swapping the duty pump line (pump 1 and pump 2). Two installation configurations (one ultrasonic path – "diagonal", two ultrasonic paths – "reflection"), and different orientations considered are shown in figure 2.

In addition, Test C is designed to investigate the orientation effects of USM. USM-A is rotated from 0° to 360° (anti-clockwise looking towards upstream) with a 45° interval. 0° installation is when both transducers are in the same plane as the pipework.

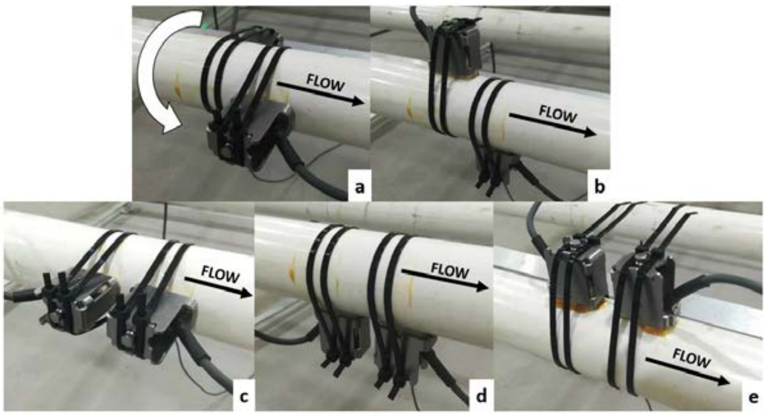

Figure 2 Installation configuration and orientation in Test A and B. a) diagonal, 0°. b) diagonal, 90°. c) reflection, 0°. d) reflection, 90°. e) reflection, 270°.

3. Results and Discussion

3.1 Full-Scale Theoretical CFD Analysis

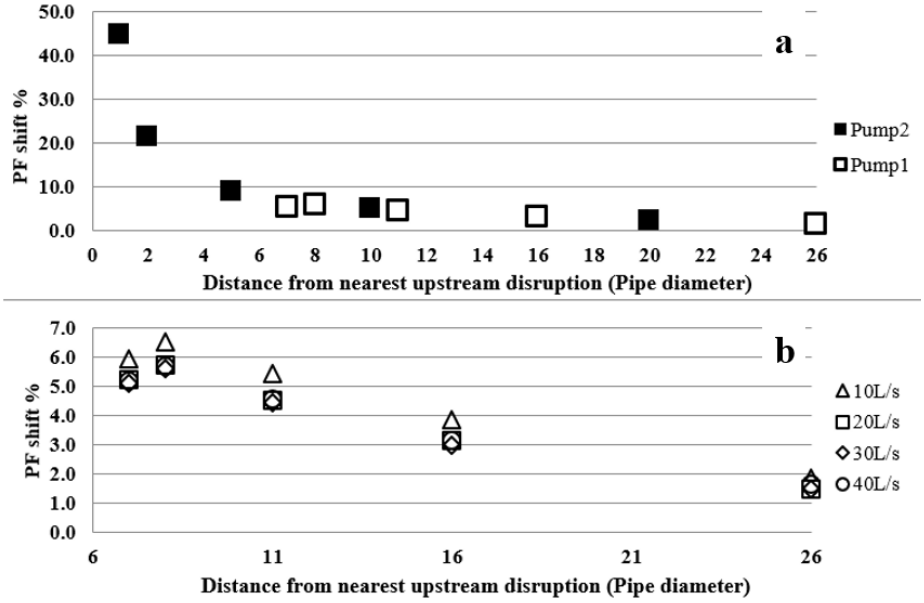

Figure 3 PF deviation from a fully developed profile, with varying distance from the nearest upstream disruption, diagonal 0 ° (in-plane) installation. a) for different duty pumps, b) for different flow rates, pump1.

Percentage profile factor shift decreases as the USM is installed further away from the tee, which implies that the flow profile is restored and approaching to a fully developed state. The worst case is found for pump 2 at 1D downstream of the tee with a maximum 45% PF shift at a flow rate of 20 L/s in a new cement-lined pipe. A much lower PF shift% is seen when pump 1 is running, as pump 1 is connected to a bend and 7D further to the USM installation next to the tee piece. The difference becomes insignificant from 10D onwards.

Flow rate is found to have little effect on the result, other than a minor decrease in PF with increasing flow rate (Re). Lynnwroth (1979) stated PF is reduced about 1% per order magnitude increase in Re, which confirms the CFD prediction. Effects of flow rate also become less significant as USM moves away from flow disturbance sources.

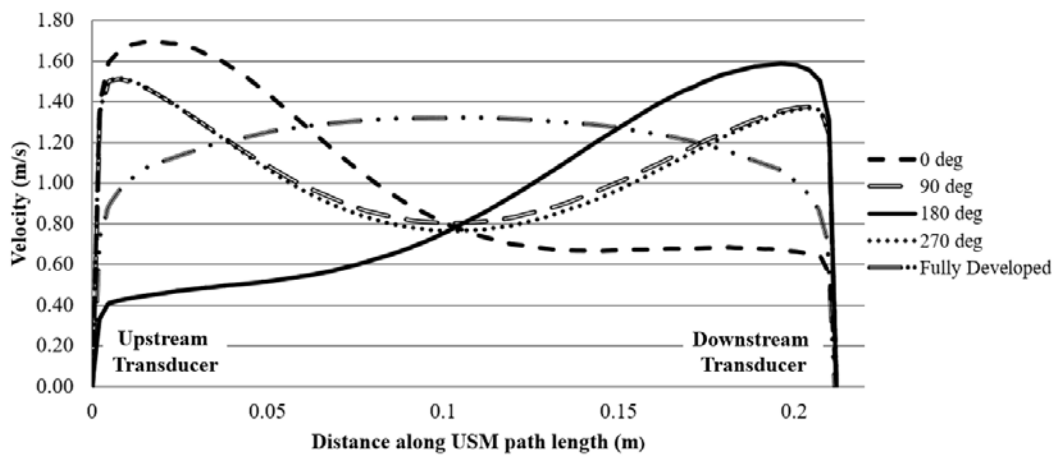

Figure 4 CFD predicted velocity profile, D=150mm, average velocity=1.13 m/s

3.2 Test Rig Experimental Results

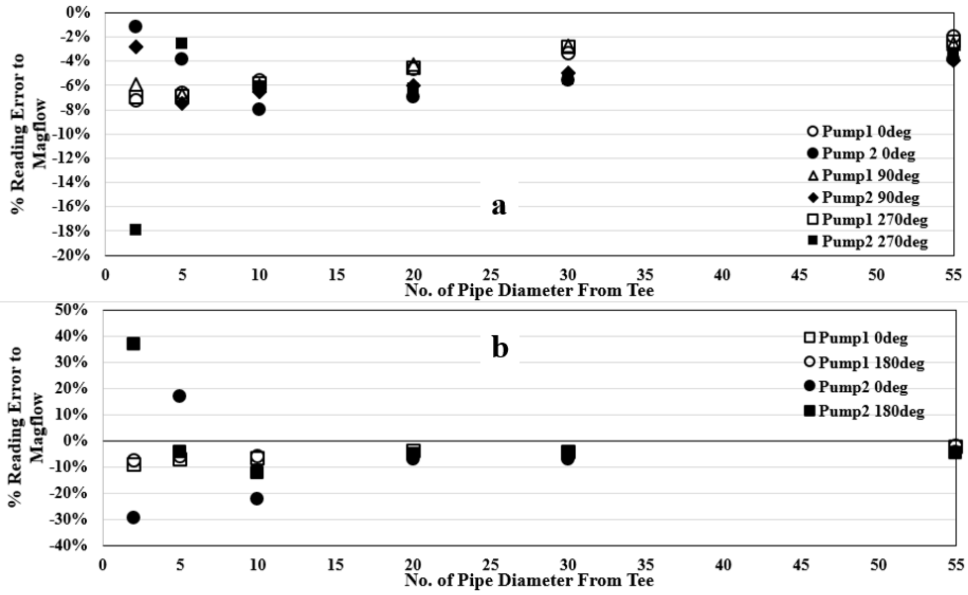

Figure 5 Percentage reading error compared to Magflow along the horizontal pipe from tee at 2.7 L/s, a) Reflection configuration b) Diagonal configuration.

Similar to the CFD results, pump 1 readings are more accurate than that of pump 2 and the difference tends to disappear when USM is moved along the horizontal pipe. The worst results are found for pump 2 at 2D downstream. The installation orientation is confirmed to have a significant effect on the readings in both reflection and diagonal configurations. Readings become less dependent on the orientation angle as the number of pipe diameter increases, which implies a more symmetrical velocity profile is expected. In addition, an improvement of accuracy (~+40% to -30% for diagonal, ~1% to -18% for reflection) when the number of USM paths increases, which is consistent with the literature (Ruppel and Peters 2014) and manufacturer's recommendations.

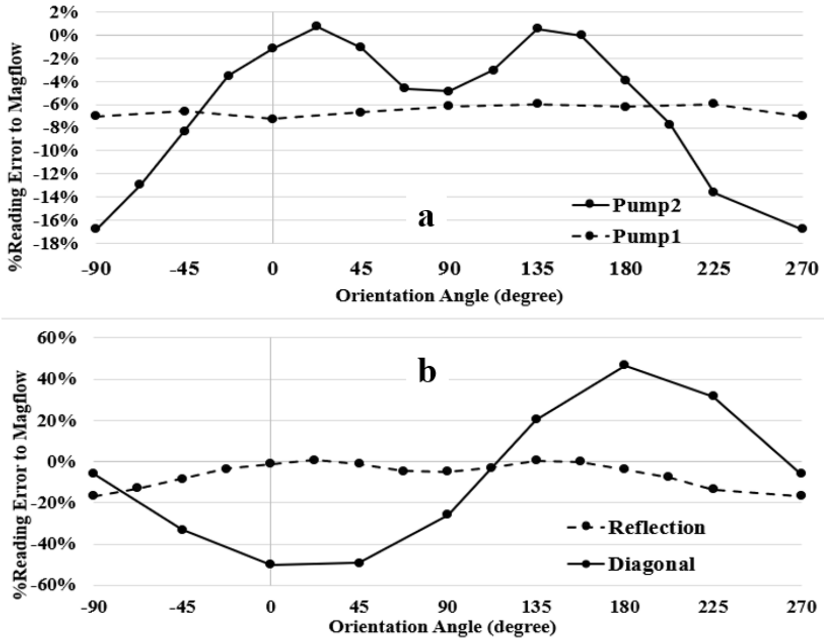

Figure 6 Percentage reading error to Magflow for full span installation orientations at 2D, 2.7 L/s a) Reflection configuration, pump 1 v.s. pump 2, b) Pump 2, Reflection v.s. Diagonal configurations.

A clear periodic nature can be observed in both configurations when the installation orientation is varied, proving that the disturbed flow profile is likely to be approximately symmetrical at 90° (off the plane of pipework). As the measuring principle of a transient time USM is based on the proportionality of the measured time interval and averaged velocity (Stoker 2011), a positive measurement can be caused by an unusually large transient time difference. In an example of 180° in figure 4, the ultrasonic signal is first speeded up by the disturbed profile when it travels downstream and then slowed down traveling upstream. The large time difference thus leads to a positive value at 180° in figure 6 (b).

4. Conclusions and Future Work

The reading of USM is found to be influenced by the shape of the velocity profile that the ultrasonic path travels through. Both CFD modeling and experimental results confirm that the USM becomes more accurate further away from a flow disturbance source. USM installation orientation significantly affects the accuracy particularly when it is installed close to the tee. Accuracy can be significantly improved with more ultrasonic paths.

A better understanding of the relationship between flow profile and reading error is necessary to fully explain the periodic nature of orientation effects. A reliable CFD-based calculation method needs to be further investigated to make CFD an effective tool in USM performance prediction. Results from an upcoming field USM trial in an existing pump station will extend the understanding of USM behaviors, considering non-ideal factors such as pipe aging and water quality, and the data collected will be useful for possible future CEED projects.

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6. References

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