Measuring Flowrates in Partially-filled Pipes in Siphonic Roof Drainage Systems

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Abstract: While a variety of flow measurement devices are available to measure the flowrate of water through closed pipe systems, these devices generally only function correctly when the pipes are completely full of water. Accurate measurement of water flowrates in partially-filled pipes is extremely difficult. In siphonic drainage systems, this problem is further compounded by the unsteady flow conditions that occur in the pipework during the priming process. This has been a major obstacle to understanding the performance of these systems in practice. In order to accurately model the priming process in multi-outlet siphonic roof drainage systems, a method of estimating the instantaneous flowrates through the partially-filled individual pipes needs to be developed.

This paper describes an experimental method of determining flowrates in partially-filled pipes using a propeller-type current meter to measure flow velocity and a pressure transducer to measure water depth and a modified version of the continuity equation. A computational model is presented which estimates the unsteady flowrates passing through partially-filled pipework. Overall, the experimental results are promising and correspond well with the model. The results of this study will ultimately be used to develop an unsteady flow model of the priming process in multi-outlet siphonic roof drainage systems.

Keywords: open channel pipe flow, flow measurement, siphonic roof drainage

1. Introduction

Siphonic roof drainage is a highly efficient type of drainage system that is particularly suitable for large buildings and other structures that are taller than approximately four metres in height. These systems were first developed in the 1970s by Ebeling and Sommerhein in Scandinavia [1]. Unlike traditional drainage systems, the pipework of siphonic systems are designed to flow full at their design capacity. Through the use of specially designed gutter outlets, air is purged from the pipework and the pipes quickly fill with water. This process is generally referred to as priming. Once primed, the pipes then experience sub-atmospheric pressure and the driving head is effectively the difference in level between the water in the gutter and the discharge point, which is usually near ground level. This causes significant increases in both the flow velocity and volumetric flowrate compared to traditional systems [2].

The theory and hydraulic performance of siphonic systems experiencing pipe-full, steady, flow conditions is well understood and has been studied extensively [1,3,4-6]. However, the unsteady flow conditions that occur in siphonic systems during the priming process, when the pipes are only partially-filled, are still largely unknown. In order to accurately model the priming process in multi-outlet siphonic roof drainage systems, a method of estimating the instantaneous flowrates in the individual pipes needs to be developed for conditions when those pipes are flowing part-full.

The most appropriate choice of a velocity or flow meter to measure liquid flows in open-channels depends on the purpose of the measurement and the accuracy required. Properly designed flow measurement systems need to be compatible with the process or fluid they are measuring[7,8]. They must also be capable of producing the accuracy and repeatability that are most appropriate for the particular application. As with any flow measurement application, it is necessary to consider the operating constraints in order to be able to select the most appropriate method to use.

Siphonic roof drainage systems are designed to operate with full-pipe flow. The design procedure for siphonic roof drainage systems therefore focuses on single-phase water flow. For the maximum capacity design of a siphonic system this procedure is sufficient[1, 9]. However, as previously mentioned, a method of estimating the instantaneous flowrates that occur in the partially-filled individual pipes during the priming stage is also required to fully understand the complete siphonic drainage process. Because of the large size of siphonic roof drainage systems it is not practical to implement expensive techniques such as laser Doppler velocimetry.

As part of this study, a current meter and a pressure transducer were installed inside a 150mm diameter acrylic pipe that was subjected to a range of flowrates and flow conditions. The instantaneous readings from the current meter and pressure transducer during this flow testing stage were observed and recorded. The two instruments were then calibrated against know flowrates to produce calibration curves. This paper presents results of an experimental method to estimate flowrates in partially-filled pipes using instantaneous readings from a current meter and a pressure transducer in conjunction with the equations of a set of calibration curves.

2. Experimental Set-up

One of the major challenges in estimating flowrates in partially-filled pipes is to accurately determine the flow velocity, particularly at low flow velocities. Low flow velocities are usually encountered in siphonic system pipes during the initial stages of a rainfall event. The average velocity in these early stages is often below 0.1 m/s. This requires a measurement system that can operate accurately at these very low flow velocities. In addition, a measurement system must also be able to operate in the corresponding low flow depths that also occur in the initial stages of a rainfall event.

Various methods and hydrometric instruments are available to measure flowrates in open-channels. One of the most reliable measuring devices for flow velocity measurements in natural and artificial channels is the propeller type current meter. This produces reliable measurement results in both high and low velocity flow and depth situations. In this study we used an OTT C2 current meter, which is based on the simple principle that the rotational speed of the propeller is proportional to the local flow velocity[10]. The rotational speed is determined by the number of revolutions per second made by the propeller and this is then shown on a numerical display[11]. In this study, a flow measurement method using a combination of a propeller type current meter and a piezoelectric pressure transducer was developed.

A variable slope testing rig was constructed for the experimental work presented in this paper. The rig consisted of a 4400mm long, 150mm diameter acrylic pipe, an OTT C2 current meter, a high-accuracy pressure transducer (BCM 430S) and an 80mm diameter (ABB MagMaster) electromagnetic flow meter (EFM). A schematic diagram of the test rig is shown in Figure 1.

The instrument readings from the current meter, transducer and EFM were recorded by a DT82 Data logger that was connected to a personal computer. The EFM was located at the upstream end of the pipe (Figure 1) between two gate valves in a section of 80mm diameter pipe. The high accuracy of the EFM for pipe-full flow conditions was verified separately. The apparatus was therefore designed so that the flow conditions at the EFM were always pipe-full. Water was supplied from a reticulated supply connected to an underground reservoir. The gate valves shown in Figure 1 were used to control the flowrate through the system. A 80mm to 150mm reducer was used downstream from Valve 2 to connect the 150mm diameter acrylic test pipe. This ensured the development of open-channel flow conditions in the acrylic test pipe. A specially designed adjustable weir was installed at the downstream discharge point of the test pipe. This was used to control the depth of water in the test pipe.

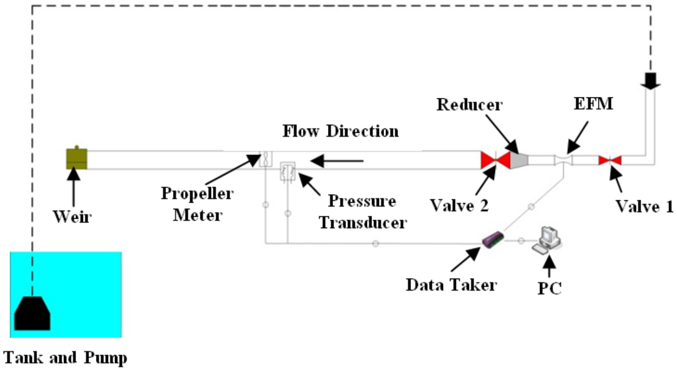

Fig. 1 Schematic of the Experimental Rig

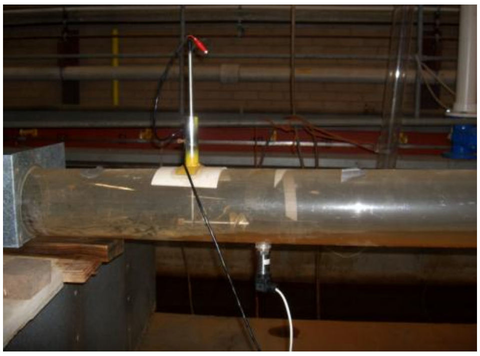

Fig. 2 Current Meter and Pressure Transducer Installed in 150mm Diameter Acrylic Test Pipe

The OTT C2 current meter, with a 50mm diameter anodized aluminium propeller fitted, was installed inside the acrylic pipe. This was held in place by a stainless steel rod as shown in Figure 2. The height of the propeller was set at 1mm above the invert of the acrylic pipe to ensure the current meter would rotate even in the smallest flowrates but would not be affected by sediments in the flow. Although the highest flow velocities in open-channels are generally found at a position of approximately one third of the water level depth below the water surface, in this study, only the velocity of the flow in the vicinity of the current meter was required. The pressure transducer was held in place via a threaded boss that was fitted to the underside of the 150mm diameter pipe, approximately 20mm upstream from the tip of the propeller (Figure 2). The pressure transducer converted the pressure to an electrical signal (using piezoelectric theory) and was calibrated to the depth of the water in the pipe[11].

3. Methodology

For a constant flowrate in a partially-filled pipe, there can be many different combinations of flow velocities and water depths. For example, if the pipe slope is steep enough, super-critical flow conditions will develop producing a correspondingly shallow flow depth. Conversely, if the pipe slope is very mild, deeper, sub-critical flow conditions will develop for the same flowrate. It was therefore necessary to calibrate the test rig under an extensive range of discharge and depth conditions (Figure 1).

In order to calibrate the test rig, the flow behaviour in the acrylic pipe over a range of known flowrates was observed and recorded. The flowrates calibrated in the test rig were all between 3L/s and 15L/s, increasing in 1L/s increments. These calibration flowrates for each test were verified using the EFM. For each test flowrate, a variety of steady flow regimes was generated. This included both sub-critical and super-critical conditions. The test rig slope was first adjusted to produce the required flow conditions and the adjustable weir was used to control the depth of water above the pressure transducer.

The instrument readings from the current meter, the transducer and the EFM for all flowrates were recorded by the DT82 Data logger. Each test was repeated three times to ensure accuracy and repeatability. The data for each flowrate was plotted and a trendline for the line of best fit was added to the chart. The correlation between the data and the trendline was generally very close, with the lowest R^2 value being 0.83. The equations of the trendlines for each data set were then used to develop a set of calibration curves for this test rig. The calibration curves shown in Figure 3 were used to develop a numerical computer model that estimates instantaneous flowrates based on the current meter and the pressure transducer output. For each one second time interval, the model first counts the number of revolutions completed by the current meter and establishes where that number lies on the X-axis of the calibration curve chart (Figure 3). The model then examines the water level corresponding to the transducer reading in order to determine between which two trendlines that value lies on the Y-axis. The model finally uses a weighted average method to interpolate between the two trendline equations to determine the flowrate.

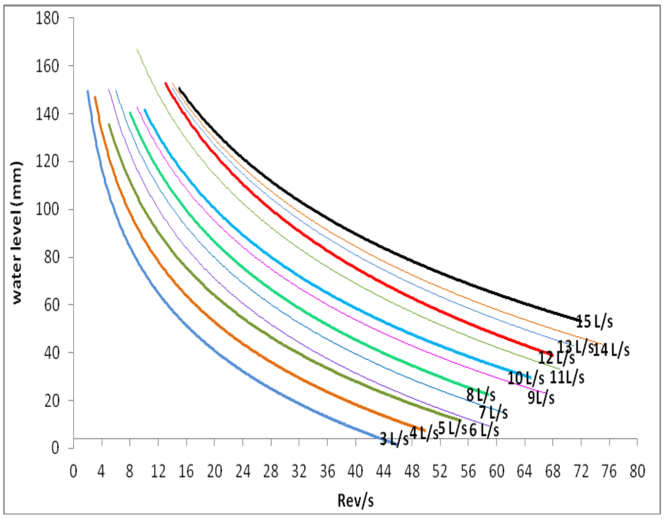

Fig. 3 Calibration Curves for Flowrates from 3L/s to 15L/s.

In order to test the accuracy of the computer model, a range of flowrates and flow conditions was again produced through the test rig. The estimated flowrates generated by the computer model were then compared to the actual flowrates measured using the EFM. The results of this comparison are presented in the following section.

4. Results

A comparison between the flowrates estimated by the computer model and the flowrates measured using the EFM was undertaken using separate experimental tests to the ones described for the calibration procedure. Figure 4 shows both the predicted and the measured flowrates over a 30 minute period. The initial flowrate was 3L/s and this was increased by 1L/s intervals every 5 minutes up to a maximum flowrate of 15L/s. The flowrate was then decreased from 15L/s to 3L/s over a period of approximately 4 minutes.

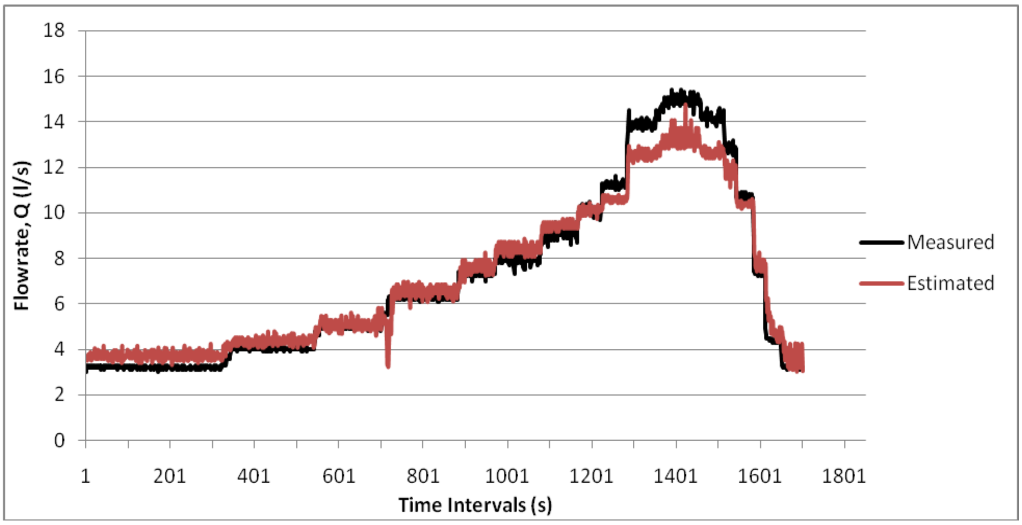

Fig. 4 Comparison of Measured and Estimated Flowrates

5. Discussion

The predicted and the measured results displayed in Figure 4 show that the flowrates estimated using the computer model were slightly higher than those measured by the EFM for flowrates between 3L/s and 10L/s. For flowrates between 10L/s and 15L/s the flowrates estimated using the computer model were slightly lower than the flowrates measured by the EFM. This variation is possibly due to the oscillation effects and unstable flow conditions that sometimes occurred during testing. It could also mean that more variables need to be included in the computer model. This will be examined in a further research study.

To quantify the variation between the measured and estimated flowrates, a statistical analysis of the two data sets was undertaken using a paired t-test analysis. The null hypothesis was that the Measured Q = Predicted Q and the test significance level was set at 5%. The analysis results gave a P value of 0.876 which means there was no significant difference between the flowrates. These results suggest that the computer model developed in this study can be utilised to satisfactorily estimate the flowrates when the siphonic pipework is flowing part-full flowrate in the experimental test rig.

5.1. Disturbance Testing

The experimental measuring method presented in this paper is intended to estimate flowrates in partially-filled pipes using a current meter and a pressure transducer. The method has been shown to produce satisfactory results. However, it is clear that any measuring device that intrudes into the fluid will cause some degree of disturbance of the flow. While this disturbance will probably not have any significant effect on the overall flowrate, it could possibly cause a backing-up effect on the upstream flow conditions resulting in an increase in the water depth. However, for the experiments described in this paper, this backwater effect did not significantly affect the measurement of flowrates. The overall long-term aim of the research presented in this paper is to develop a suitable method of estimating the instantaneous flowrates in an experimental, multi-outlet, siphonic drainage system during all stages of its operation. Providing the flow measuring devices proposed in this paper are installed in the pipework of each of the outlets in the experimental multi-outlet siphonic system, then the disturbance effects caused by the devices will be balanced in that the hydraulic interaction between the outlets will not be affected.

Although the disturbance effects of having flow measuring devices installed in the pipework will not influence the current experimental results, it was decided to quantify these effects for future reference and testing. A new disturbance test rig was constructed for this purpose. The configuration for this new disturbance rig was similar to the one shown in Figure 1. However, a smaller 82mm diameter pipe was used to more closely represent the small diameter pipes that are commonly used in multi-outlet siphonic drainage systems. The current meter was installed inside the 82mm diameter pipe for the disturbance testing.

Two additional piezoelectric pressure transducers were installed in the pipe in order to measure the disturbance effects from the current meter on both the upstream and the downstream water levels. One of the additional pressure transducers was installed one metre upstream from the position of the current meter and the original transducer (midstream). The other additional transducer was installed one metre downstream from the midstream position. The positions of the three transducers are shown in Figure 5.

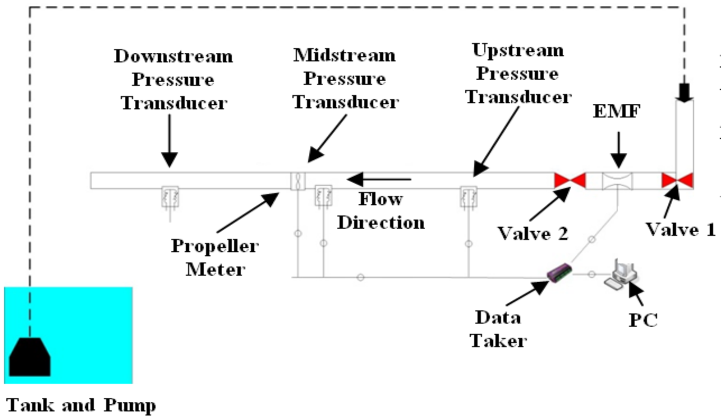

Fig. 5 - Schematic of Disturbance Test Rig

Fig. 6 - Midstream Flow Conditions

A total of nine different steady flow configurations were tested in the disturbance test rig. The nine configurations comprised a combination of three different water depths and three different flow velocities. The three flow depths tested were 33%, 66% and 100% respectively, of the pipe's 82mm internal diameter. The three flow velocities were approximately classified as slow, medium and fast. The slow flow was sub-critical, the fast flow was super-critical and the medium flow was transitional.

In order to measure the disturbance effects that the current meter had on the flow conditions, a slot was cut in the top of the pipe. This allowed the meter to be lifted in and out of the flow, as shown in Figure 6. For each of the nine steady flowrates tested, the procedure was as follows:

1. The three pressure transducer readings were first recorded when the pipe was empty to identify one boundary condition (water level = 0mm);
2. The pipe was then completely filled with water and the three transducer readings were recorded to identify the other boundary condition (water level = 82mm);
3. The required flowrate and flow condition was set up in the pipe without the current meter installed;
4. The three transducer readings (and water levels) were recorded for this flowrate (without the current meter inserted);

5. Without changing any flow conditions, the current meter was then inserted into the flow through the slot in the top of the pipe;
6. The pressure transducer readings (and water levels) were again recorded for this flowrate (with the current meter inserted); and
7. The test was repeated for the next flowrate and flow condition.

The three pressure transducer readings (and corresponding water levels above each transducer) were recorded by a data logger and transferred to a PC for each of the nine steady flowrates tested. The water level measurements above each transducer with and without the current meter installed were then compared. The differences in water level are shown in Table 1.

Table 1 - Water Levels Differences Above Each Transducer (%)

		Transducer Position		
	Water Level	**Downstream**	**Midstream**	**Upstream**
Slow Flow	**33%**	0%	0%	3%
	66%	3%	6%	0%
	100%	15%	1%	0%
Medium Flow	**33%**	0%	10%	3%
	66%	0%	7%	6%
	100%	8%	11%	-1%
Fast Flow	**33%**	0%	14%	5%
	66%	0%	14%	5%
	100%	11%	14%	-6%

The results in Table 1 show that generally, the largest differences in the water levels occurred above the midstream transducer. This was to be expected as the propeller of the current meter was only 20mm upstream of the midstream transducer. There was no apparent consistent trend in any of the water level changes. It is believed that this was due to the wave patterns that developed within the pipework for some flowrates.

While water level differences of 14% may appear relatively large, in reality the effects of the current meter on the overall flowrate were negligible. However, as previously mentioned, as long as the current meter is installed in the pipework for all testing, its effects do not significantly influence the measured flowrates.

6. Conclusions

In order to accurately model the priming process in multi-outlet siphonic roof drainage systems, a method of estimating the instantaneous flowrates through the partially-filled individual pipes needs to be developed. This paper presents the results of an experimental investigation to determine the flowrates in partially-filled pipes using a propeller-type current meter to measure flow velocity, a pressure transducer to measure water depth and a modified version of the continuity equation.

A numerical model was developed that estimates instantaneous flowrates based on the current meter and the pressure transducer outputs. In order to test the accuracy of the numerical model, a comparison between the flowrates estimated by the model and the flowrates measured using an EFM was undertaken. A statistical analysis of the two data sets showed that there were no statistically significant differences between the flowrates, at the 5% level.

These experimental results show that the computer model developed in this study can be utilised to satisfactorily estimate partially-filled flowrates in the experimental test rig.

Although the disturbance effects of the current meter in the pipework did not influence the current experimental results, it was decided to quantify these effects for future reference and testing. The disturbance testing results showed that the largest difference in the water levels above the transducers was 14% and this occurred above the midstream transducer. It has been shown that the proposed flow measurement method is suitable for use in more detailed investigations of multi-outlet siphonic systems, providing the current meters are installed on all outlets.

This method will be further developed in future research investigations in order to accurately model the priming process in siphonic drainage process.

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