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Siphonic Roof Drainage

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UNDERSTANDING SIPHONIC RAINWATER DRAINAGE SYSTEMS

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ABSTRACT

Over the past 3 years a UK EPSRC research programme has been underway at Heriot-Watt University investigating siphonic roof rainwater systems. This text aims to report the principle findings of the project to date. A brief description of experimental and numerical aims is given. The priming procedure which occurs in an idealised system is documented. The test procedures employed are described, and experimental results are illustrated. The framework employed to numerically model the ambient hydraulics is described in some detailed. Conclusions are drawn regarding the operational characteristics of siphonic roof rainwater systems.

BACKGROUND

Siphonic roof drainage systems have been in existence for approximately 30 years. In this time, the construction industry has been gradually persuaded by the benefits which these systems offer when compared to the traditional approach. Much of these benefits arise from the fact that systems can become pressurised. However, this condition only arises at the design condition – typically a storm with a return period in excess of 30 years. When the application was being made for the work reported herein, it was recognised that the overwhelming majority of rainfall events any siphonic system would have to drain would be well below the design condition. This, coupled with reports of siphonic system failures, convinced the investigators that this was an area worthy of future research.

AIMS AND OBJECTIVES OF RESEARCH

Siphonic rainwater drainage depends upon the establishment of full bore flow within the pipe network linking roof collection outlets to the storm sewer. The replacement of conventional multiple downpipes by a network of closed conduits offers significant advantages to the building designer, as evidenced by the increasing installation of such systems in buildings such as; airport terminals, large warehouses and prestige office developments. However, the establishment of siphonic action depends upon the matching of the network to the expected storm hyetograph and the maintenance of siphonic conditions throughout the storm event - only one storm matches any particular system. Errors in design may lead to systems operating in an inefficient, non-siphonic mode, or to insufficient capacity (flooding). Generation of negative pressure transients may lead to system failure due to the collapse of pipewalls(1). While siphonic systems have been installed in the UK over the past decade, there is no recognised design standard, and system design is based on steady state calculations which assume a near instantaneous steady full bore entrained air free flow. The aim of the work reported herein was to develop an unsteady flow model which could simulate conditions within an idealised siphonic roof rainwater drainage system driven by a storm hyetograph. This would enable flow conditions within the rainwater drainage system to be represented, simulating, via the method of characteristics finite difference technique, the flow regimes simultaneously present within a simple siphonic drainage system, from initial free surface flow as the storm develops, through a two phase flow stage, while air entertained, or initially present, in the system is flushed out, until the full bore flow design condition is reached. The primary objectives of the project were therefore;

1. Within a laboratory environment, investigate pressure transient generation and propagation within a siphonic system during priming.
2. Establish boundary conditions, both stationary and moving, consistent with developing a numerical model based on the method of characteristics.
3. Develop a computer based design tool, which could provide guidance at the design stage to both system designers and building operators.

DESCRIPTION OF RESEARCH

The programme of research has relied heavily on exploiting industrial links and data generated from a siphonic test facility constructed at Heriot-Watt University to build the initial numerical model. Once a prototype model was obtained, it was further developed and fine tuned using data collected at the Heriot-Watt University facility, installed systems, and using results obtained from test facilities operated by HR Wallingford and elements of the siphonic rainwater industry. The strength of this project has largely been due to the close links made with industry and local system operators, as well as the strong background the investigators have in numerically modelling building drainage systems.

DESIGN CONSIDERATIONS

For any given application, siphonic roof drainage systems are normally designed to cope with the steady state pressures associated with a selected 'design storm', which is normally specified in terms of a steady rainfall intensity (in the UK this is in accordance with BS 6367[2]). Selection of a rainfall intensity at the design stage is based upon the geographical location, and by balancing the risk of failure against the cost of allowing for additional roof drainage capacity[1 & 3]. However, it can be seen that this approach will lead to one of two post installation eventualities each time the system comes into operation:

1. A storm occurs which exceeds the design rainfall intensity

Practically, no matter what design rainfall intensity is selected, this will always eventually occur, and may result in flooding to some extent. Well designed systems make allowance to ensure that any overspill is directed to areas where it can be managed, or any damage caused is limited.

2. A storm occurs which is less than the design rainfall intensity

For any well designed and specified system, the vast majority of the storms encountered will fall into this category. Where rainfall events of quite low intensity are encountered, the system will act hydraulically as a 'conventional' roof drainage system. However, as increasing rainfall intensities are considered partial unsteady de-pressurisation of the system will occur. Tests at Heriot-Watt University have shown that this de-pressurisation results in substantial amounts of air being drawn into the system, this can exceed the volume of water entering the system in some circumstances. The unsteady nature of the flow regime, which has been observed to be cyclic in nature, leads to varying amounts of noise generation, and structural vibration within the system. The structural vibration, conceivably, could lead to physical failure of a component of the system.

CURRENT DESIGN PRACTICE

Currently siphonic roof drainage systems are designed to accommodate a specified storm which fills, and primes, the whole system rapidly with 100% water. This assumption means that the system may be designed easily using elementary steady state hydraulic relationships. The steady flow energy equation is used almost universally[3] as the backbone of the design procedure for siphonic roof drainage systems. The pressure drop between any two points X and Y can be determined using equation 1.

$$\left(H+\frac{Q^2}{2gA^2}+z\right)_{\text{Point X}}-\left(H+\frac{Q^2}{2gA^2}+z\right)_{\text{Point Y}}=\Delta H_{X,Y} \qquad \ldots 1$$

The pressure drop between two points, $\Delta H_{X,Y}$, is accounted for by losses due to the hydraulic resistance of the pipe walls and additional losses due to fittings where these are present.

The design approach outlined above was used to estimate the flow capacity and pressure distribution for a single configuration of the siphonic roof drainage test rig which has been installed at Heriot-Watt University. The test rig is illustrated in Figure 1. There are significant calculated variations in pressure throughout the system, which are dependent upon frictional losses through fittings and changes in static height. On physically testing the system, it was found that the capacity was ~11.75 l/s (plus any air), and pressures between -2.30 and -3.13 m H_20 developed in the horizontal pipe length once the system was primed. These results are broadly consistent with those calculated using Equation 1, where the capacity of the system was computed to be 11.78 l/s (<1.0% difference), and pressures between -2.60 and -2.80 m H_20 were calculated in the horizontal pipe section. The discrepancies which exist between the measured and calculated results may be accounted for by variation in air content and inaccuracies in the estimation of the head loss across fittings.

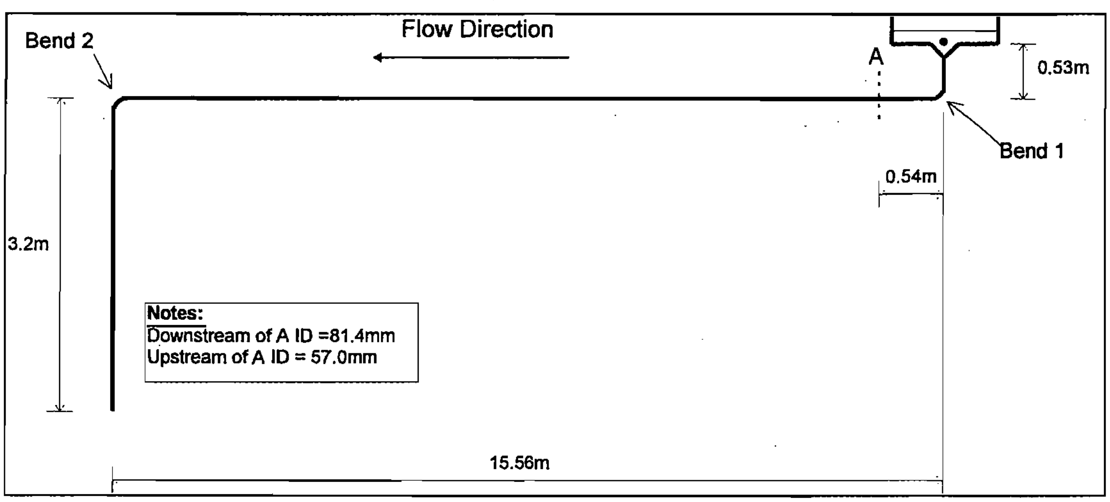

Figure 1 : Schematic diagram of a test rig configuration illustrating the main dimensions.

The unsteady pressure regimes which have been observed to occur within the test rig at Heriot-Watt University, when the system is draining an inflow less than the system capacity, are illustrated by the data presented in Figure 2 and 3.

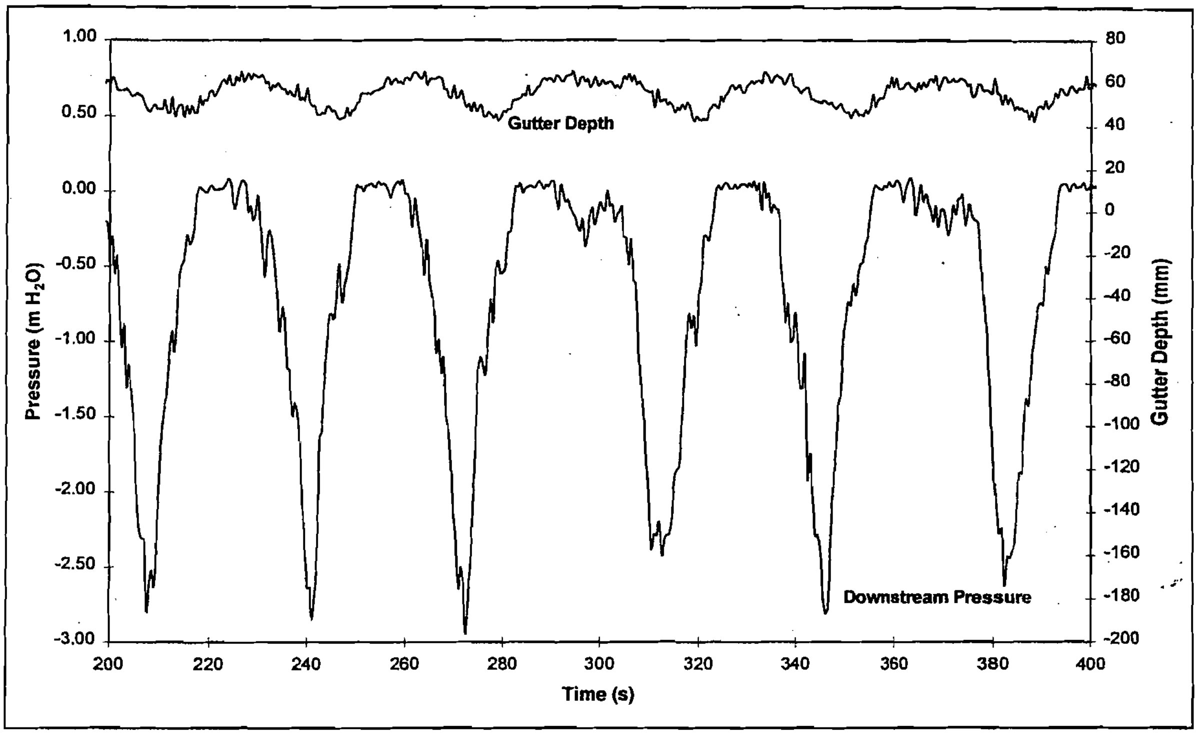

Figure 2 : Ambient pressures in the system for a steady gutter inflow rate of 42% of the measured capacity of the system illustrated in Figure 1. The figure illustrates how, under particular conditions, a cyclic pressure regime may be established in the system. The frequency of the cyclic response of the system is related to the rate of inflow, and the lengths of the horizontal and vertical pipework.

LABORATORY INVESTIGATIONS

The main aim of the laboratory testing was to define just how siphonic roof drainage systems prime at the design condition. Before describing the priming process, it is first essential to define what physically constitutes a siphonic roof drainage system. A basic, idealised, siphonic roof drainage system may be dismantled into three essential components:

1. A single siphonic roof outlet

These units are situated on a roof or gutter surface and allow entry of storm water from the roof surface into the siphonic system. The outlet can be idealised as having an inverted truncated conical cross section with baffle type obstruction near the gutter level. The primary purpose of the baffle is to aid priming by restricting the entry of air into the system.

2. Horizontal pipework

In an idealised siphonic system the horizontal pipework exists to convey the storm water from the outlet to the main drainage stack. Typically, in an installed system, the hydraulic conditions within the horizontal pipework will be influenced by several bends and possibly connections from one, or more, other roof outlets.

3. Vertical pipework

For a siphonic roof drainage system to function properly two pieces of vertical pipework must be present: the first is a small length (0.2-~0.5m) which connects the outlet to the horizontal pipework. The second connects the horizontal pipework to the point of discharge, assumed to be at atmospheric pressure.

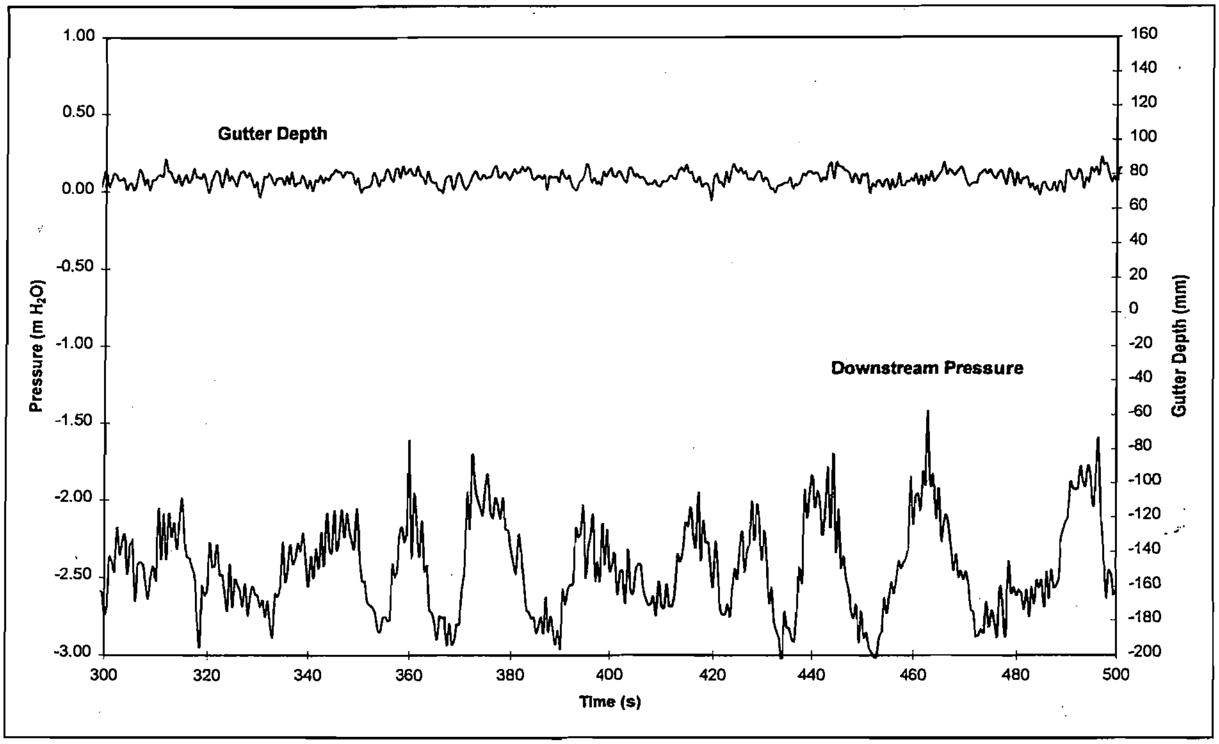

Figure 3 : Ambient pressures in the system for a steady gutter inflow rate of 81% of the measured capacity of the system. The figure illustrates how even when the inflow to the system is approaching the design condition ambient flow conditions are far from steady.

Priming of the Test Rig

Understanding the priming action within a siphonic test rig is of fundamental importance. If, for what ever reason, an installed system cannot prime at the design rate of inflow the system will fail to meet its design criteria. The priming action described in this section will consider the hydraulic conditions which prevail in a siphonic system where the inflow to the roof gutter 'instantly' is equal to or greater than the observed inflow capacity of the test rig (i.e. the design condition). To analyse the priming action of the test rig, pressures were recorded at several points along the horizontal pipework at data sampling rates from 10 - 1000Hz, flow depths in the gutter were measured using pressure transducers at a similar frequency. Additionally, as the entire system was transparent, flows were analysed by eye, with the aid of still photography and using an EPSRC Loan Pool high speed video camera (up to 500 frames per second).

The priming procedure observed may be deconstructed into the elements listed below:

1. Initial gutter inflow

The first step in the priming procedure is for the water depth in the roof gutter to slowly increase. Initially the pressures in the siphonic system pipework were equal to ambient atmospheric pressure (plus the flow depth). Flow in the vertical pipework at this stage was observed to be annular. Flows in the horizontal pipework were observed to be sub-critical. As the depth at the roof outlet increases, the inflow to the system was also observed to increase – resulting in supercritical flow occurring at the start of the horizontal pipework, and the observed formation of a distinguishable hydraulic jump just downstream (Figure 4a).

2. Importance of Bend 1

As Figure 1 indicates, a short section of vertical pipe is attached to the siphonic roof outlet. This short length of pipe then connects, via bend 1, to the horizontal part of the test siphonic system. Laboratory tests have indicated that if only a single vertical length of pipe is connected to the siphonic roof outlet (i.e. no horizontal pipework is included in the system), the hydraulic resistance is insufficient to allow the development of full bore flow in the vertical section - irrespective of the depth of flow in the roof gutter.

3. Hydraulic jump

As the flow slowly increases with time the jump gradually moves towards the downstream end of the horizontal pipe. Simultaneously, the downstream (subcritical) depth of the jump slowly increases. Eventually a rate of inflow is reached where the depth downstream of the hydraulic jump is equal to the pipe diameter, at this juncture full bore flow has developed in the horizontal pipework (Figure 4B). At the instant that the depth downstream of the hydraulic jump becomes full bore, a volume of air becomes lodged between the jump and the upstream end of the horizontal pipe (above the supercritical flow). Simultaneously, full bore flow conditions then propagate downstream along the horizontal pipework and eventually reaches bend 2 and the stack.

4. Main vertical pipe

When full bore flow conditions reach bend 2 the vertical pipe begins to fill. As full bore flow develops in the main length of vertical pipe, the mass of water in the pipe causes de-pressurisation of the flow in the upstream pipework (i.e. the ambient pressure falls below atmospheric pressure). This causes the inflow into the system to increase. This increased inflow causes the full bore flow to develop at the upstream end of the horizontal pipe. The air pocket (described above) then moves along the horizontal pipework at the ambient velocity of the flow (Figure 4C). When this air pocket passes bend 2 and enters the vertical pipe (Figure 4D) it causes a partial re-pressurisation of the entire system (i.e. ambient pressures increase towards atmospheric pressure). However, once the air pocket leaves the vertical pipe the system can become fully primed - other than the presence of small amounts of entrained air which enter the system (normally less than 5%).

Figure 5 shows data collected for a typical priming event in the test rig. Each of the zones delineated in the figure are described in Table 1.

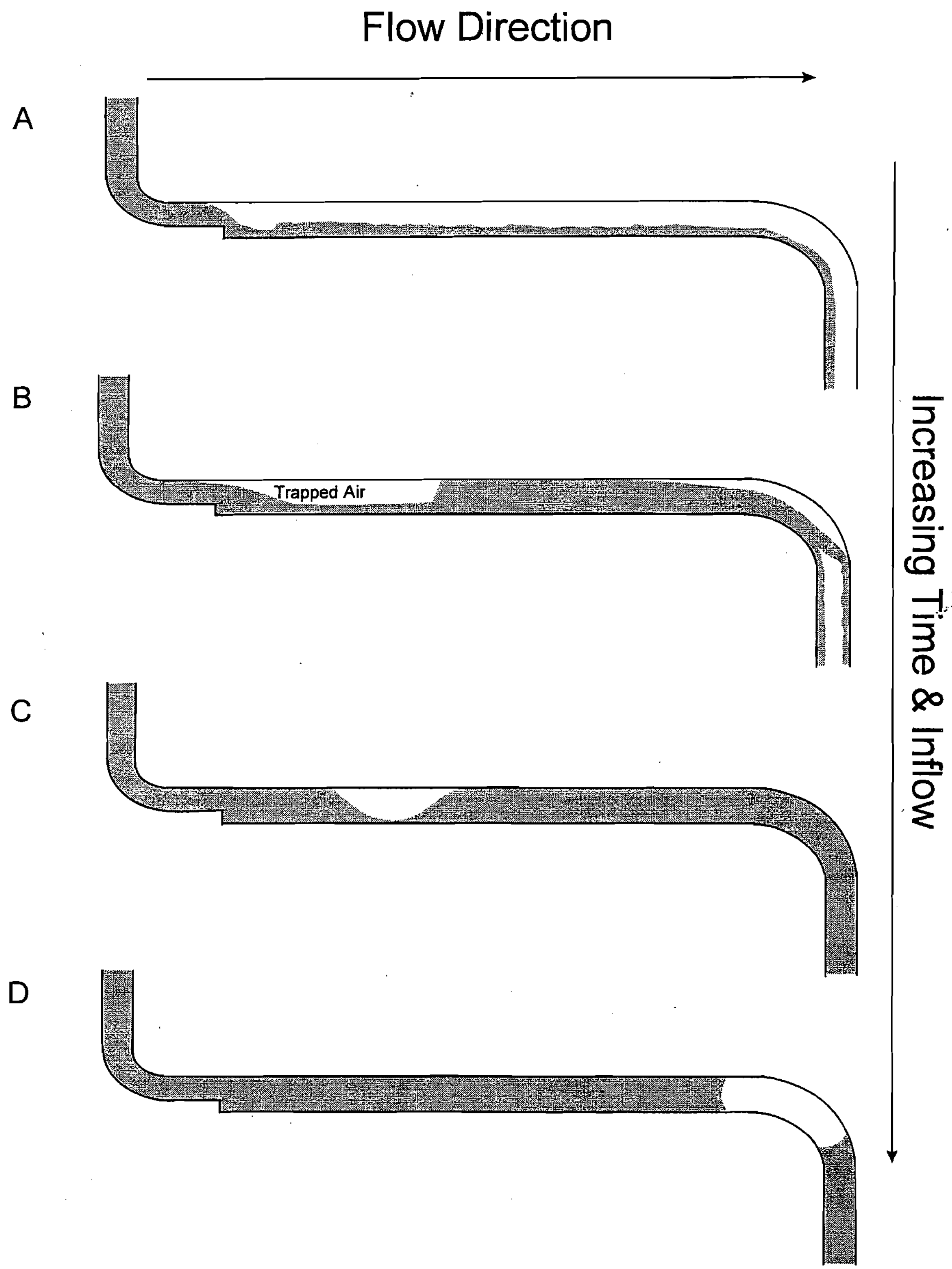

Figure 4 : Movement of trapped air within the system during priming.
(The figure assume the roof outlet is fully submerged and the inflow contains no air).

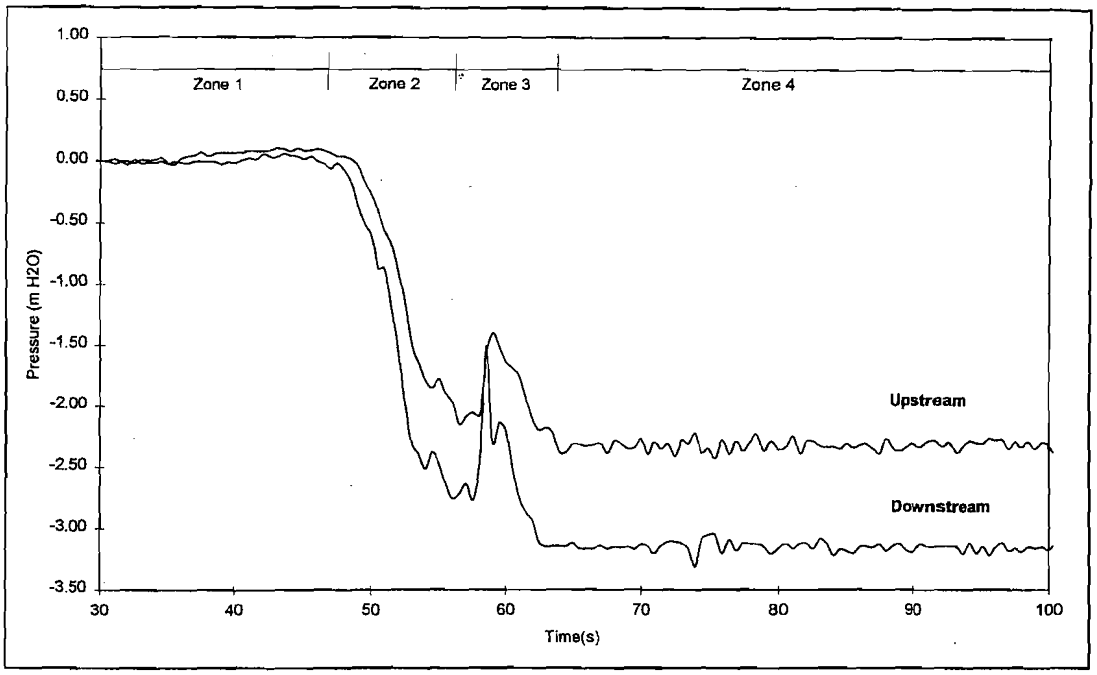

Figure 5 : Ambient pressures in the system during priming. It can be seen that the flows within the system move quite quickly from a free surface flow condition to full bore flow. The figure clearly shows that the re-pressurisation is generated at the downstream end of the system, and then propagates towards the upstream end. This is indicated by the time lag observed between the observation of the re-pressurisation at the downstream and upstream pressure monitoring points.

Zone	Description
1	Development of full bore flow in the horizontal pipework
2	Filling of main length vertical pipe
3	Re-pressurisation caused by air pocket
4	System primed

Table 1 : Zone descriptions, as delineated in Figure 5.

AIR INDUCTION INTO SIPHONIC SYSTEMS

Within siphonic roof drainage systems there are three principle entry routes for air into the system flow, and these may be listed as follows;

1. Air which existed within the system before the rainfall event considered began.
Before there is any inflow into a siphonic system, the volume within the pipework is almost entirely filled with air. Well designed systems allow this air to exit from the system both via the roof outlet, as the inflow gradually builds, and via the discharge point to the sub-surface system – propelled by the energy of the flow.

2. Air which is held within the inflowing rainwater.
Due to the turbulent nature of runoff from roofs and the flow within the roof gutters, large amounts of air can be entrained within the inflow to the system.

3. Air which is drawn directly into the system via the siphonic outlet.

Each of the siphonic system outlets available currently is specifically designed to inhibit the formation of a vortex. The formation of a vortex is inhibited, in most cases, by placing an obstruction, the geometry of which varies, over the main entry to the system. However, some air does enter the system via small vortices or due to reduced flow depths. It is this mode of entry of air to the system which causes the severest problems. This is due to the fact that if a large pocket of air is drawn into the system, it can cause a sudden local depressurisation which then propagates through the entire when it reaches the main vertical stack.

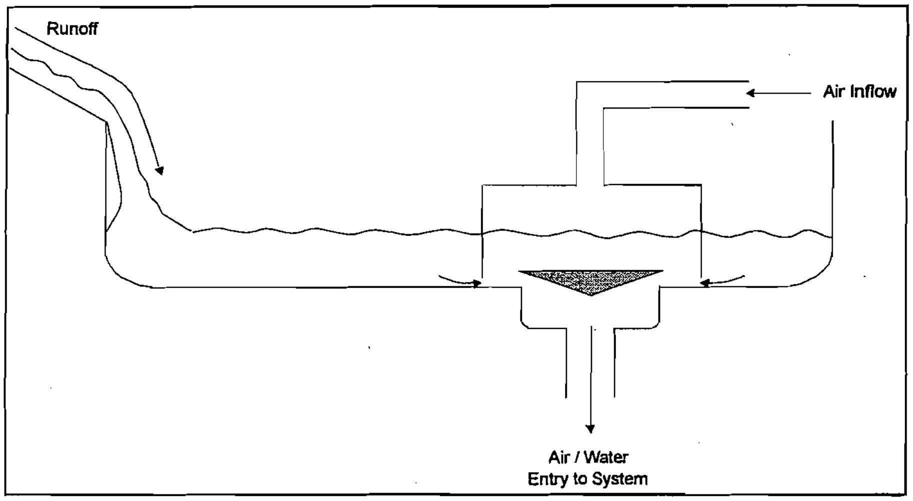

Figure 6 : Mechanism employed to measure the volumes of air entering the test rig. The air intake was instrumented to measure air flow rates at 100Hz.

Measurement of the Levels of Air Entering the System

To quantify the amount of air entering the test rig via the roof outlet, and entrained within the inflow the straightforward experimental set-up illustrated in Figure 6 was constructed(4). The methodology employed consisted of sealing off the outlet from the atmosphere other than via a single instrumented air inlet. This allowed the time varying levels of air flow rate entering the system to be accurately recorded. Any additional air in the system inflow after priming may then be assumed to be that entrained within the inflow. The test rig was then operated at varying levels of inflow, and hence different levels of gutter depth. The data represented in Figure 7 was obtained when the inflow into the gutter was set at 88% of the measured, fully primed, system capacity. As the inflow is approaching the capacity of the system there is initially an excess of inflow into the system gutter (i.e. gutter inflow> gutter outflow via the roof outlet), a situation develops which allows the system to operated at the fully primed running pressure - by 60 seconds (Figure 7) – the average pressure was computed to be –3.09 m H_2O (standard deviation = 0.023 m H_2O, 0.74%). However, there is insufficient inflow to the gutter to sustain this (i.e. gutter inflow < gutter outflow) and by 100 seconds (Figure 7) the system pressure drops to an increasingly unsteady running pressure, this was computed to be –2.37 m H_2O (standard deviation = 0.092 m H_2O, 3.88%) – this is a drop of 27.3%. The data in the plot also indicates that air was entering the system directly via the roof outlet at an average rate of 0.027 l/s, this volume flow rate would then expand to 0.036 l/s at Bend 2 - insignificant when compared to the water flow rate. Visual observations during the test indicated that the level of air in the system was far higher than indicated by these measurements, revealing that a significant amount of air entered the system due to entrainment within the system inflow, via the turbulent flow within the gutter.

The data represented in Figure 8 was obtained when the inflow into the gutter was set at 42% of the measured, fully primed, system capacity. It can be seen from the plot that the system running pressure is unsteady, and that it is varying cyclically. The average running pressure was measured to be –0.58 m H_2O (standard deviation = 0.77 m H_2O, 132.6%). Where the inflow of air directly into the system is concerned, the main difference in this test run is that air is primarily drawn into the system only when the system running pressure drops below –0.15 m H_2O. Above this pressure the plot shows very little air entering the system directly, although a proportion will still enter entrained within the gutter inflow.

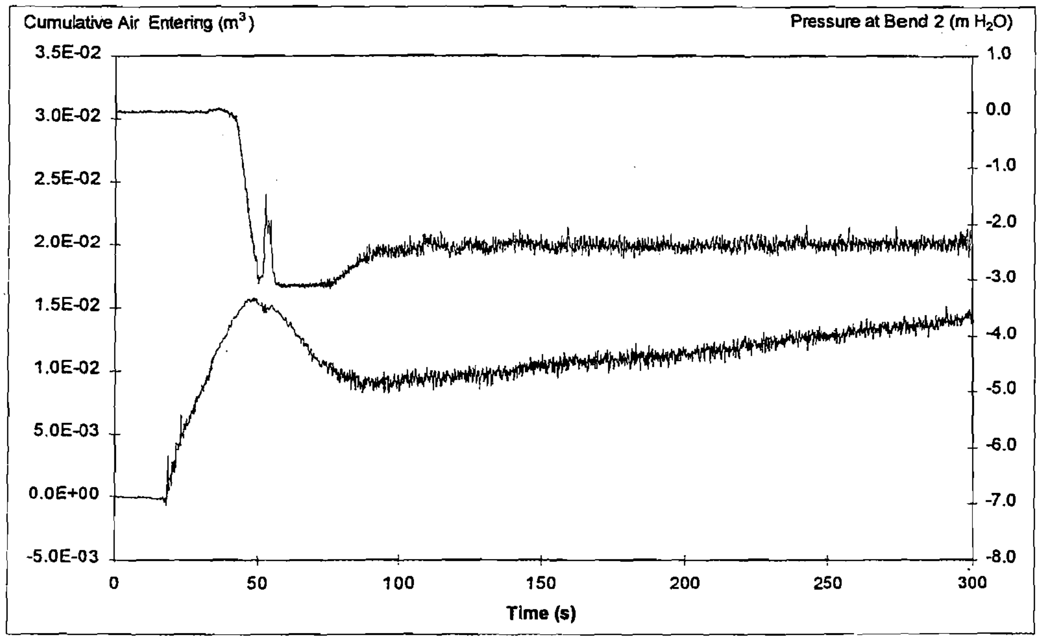

Figure 7 : Pressure and air inflow data for the system operating at 10.4 l/s.

NUMERICAL REPRESENTATION OF SIPHONIC RAINWATER SYSTEMS

The transitory flow conditions within the siphonic roof drainage systems may be simulated by numerical solution of the defining equations of momentum and continuity, augmented by representations of the boundary conditions within the system. A numerical model, "SIPHONET"[5 & 6], has been devised which represents the priming of the system as a whole. The priming procedure which SIPHONET represents consists of depicting the replacement of the homogenous air/water mixture downstream of the jump with the low air content flow entering the system. The key point in the priming phase occurs when the low air content flow fills the stack, as this then leads to the de-pressurisation and priming of the system. The movement of discrete pockets of air from the point of entry to the point of discharge can also be tracked, and any influence on the internal pressure regime is computed. The remainder of this section of the discussion gives an overview of the process employed within the numerical model to represent the priming procedure.

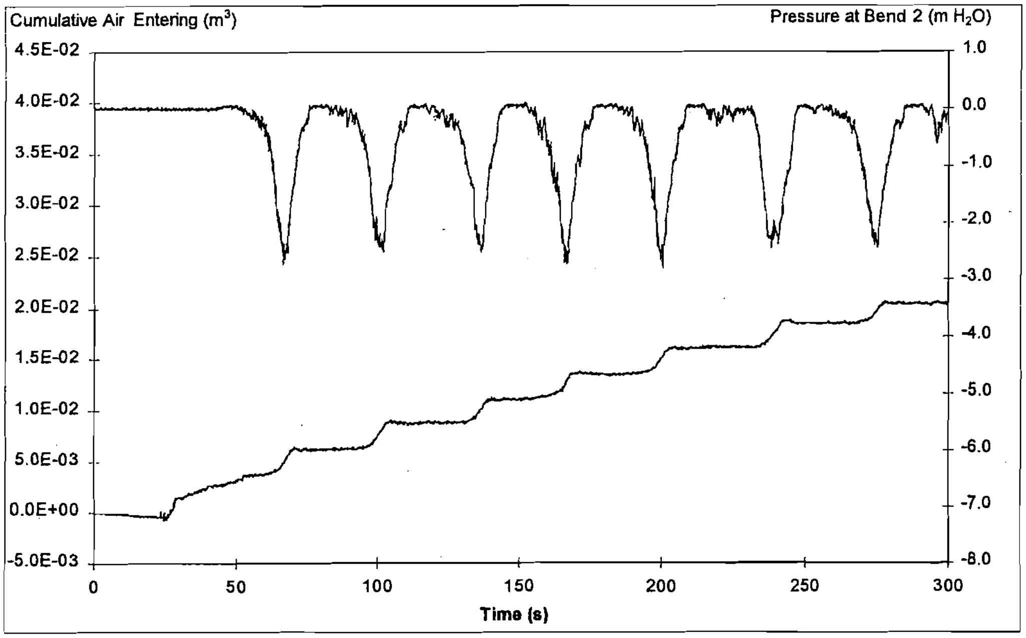

Figure 8 : Pressure and air inflow data for the system operating at 5.0 l/s.

The first step in the modelling process is to represent, numerically, the initial free surface flow conditions and the initiation of full bore flow via the formation of a hydraulic jump. Once this has been established within the model, it then becomes possible to calculate the initial pressures throughout the system (t = 0 condition). All the data required to run the main numerical section of SIPHONET have now been computed. The hydraulics within the system may now be represented and solved using the quasi-linear hyperbolic partial differential equations of continuity and momentum, Equations 2 and 3, expressed in terms of two dependant variables - velocity and pressure head (V and H respectively). These equations may then be solved using the method of characteristics[7, 8 & 9]. Using this method, the pipeline is divided into N sections (N+1 nodes) of equal length, Δx. Values of discharge and head are known at each node at t=0, as detailed above. The solution framework normally employed to solve the hydraulic conditions present in the horizontal pipework is illustrated in Figure 9, where points A and B represent two points in space and time (nodes i-1 and i+1 at t=0) where discharge and pressure head are known, and point P represents the intermediate node, i, at t=Δt. The next step in the calculation procedure is to determine the Q and H at each calculation node at t=Δt (Δt is determined using Equation 4 - the Courant Criterion), this is done by communicating the hydraulic conditions from adjacent nodes for the previous time step to the calculation point. This is accomplished by applying the characteristic Equations (Equations 5 & 6 which are valid along C^+ and C^- respectively) and intersect at point P.

$$V\frac{\partial V}{\partial x}+\frac{\partial V}{\partial t}+g\frac{\partial H}{\partial x}+\frac{fV|V|}{2m}=0 \qquad \ldots 2$$

$$\rho c^2\frac{\partial V}{\partial x}+V\rho g\left[\frac{\partial H}{\partial x}+\sin\alpha\right]+\rho g\frac{\partial H}{\partial t}=0 \qquad \ldots 3$$

$$\Delta t \leq \frac{\Delta x}{V+c} \cong \frac{\Delta x}{c} \quad (when\ c >> V) \qquad \ldots 4$$

$$V_p = V_A - \frac{g(H_p - H_A)}{c_A} + g\sin\alpha_A \Delta t - \frac{f_A V_A |V_A| \Delta t}{2m_A} \qquad \ldots 5$$

$$V_p = V_B + \frac{g(H_p - H_B)}{c_B} + g\sin\alpha_B \Delta t - \frac{f_B V_B |V_B| \Delta t}{2m_B} \qquad \ldots 6$$

At each end of the pipe length considered in Figure 9 only one of the characteristic equations is available (i.e. at the upstream end only the C^- characteristic, and at the downstream end only the C^+ characteristic). Therefore for a solution to be reached at these points, additional relationships must be formulated which represent Q and H at the upstream and downstream boundaries. The system exit boundary consists of setting the pressure to atmospheric at the point of exit. Whilst the entry relies on an empirical relationship which relates flow depth to outlet type.

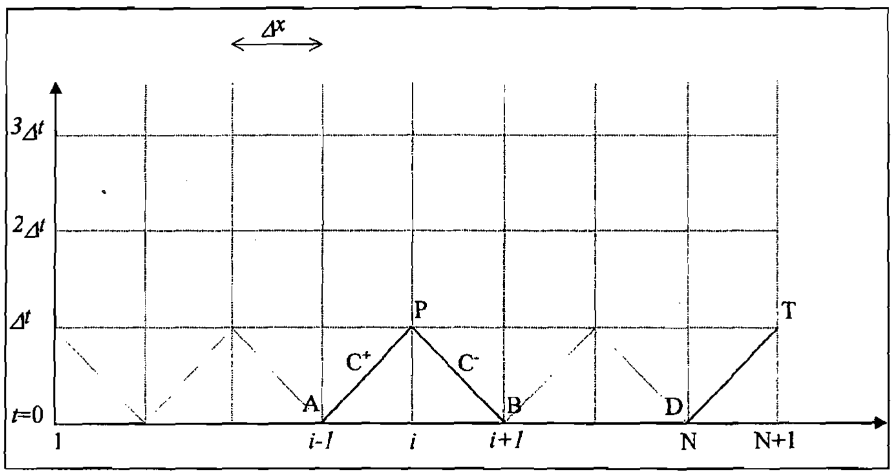

Figure 9 : Details of the normal application of the method of characteristics.
(Note : For clarity only alternate nodes are represented.)

Any flow entering the system during the priming phase after full bore flow has been established is assumed to contain 0.1% air as the roof outlet is fully submerged. The flow downstream of the jump is assumed to be a homogeneous air/water mixture between adjacent nodes. The propagation velocities between internodal reaches may now be computed using Equation 7[a]. It can be seen that the propagation velocity will not be equal throughout the system, and that the flow velocity may also approach the propagation velocity under some conditions. For the horizontal pipe length, this consideration was found not to be important. However, as the air content of the flow significantly influences the ambient pressures within the vertical stack, the influence that the air content has on the propagation velocity here must also be taken into account. This, therefore, results in a variation in wave speed between the component pipe lengths within the system and between inter-nodal sections. Therefore if Δt is selected using the highest wave speed,

[a] Although the equation includes the effect of the pipe material, this is known to be limited when the flow contains entrained air[(9)].

sections of the system may exist in which the Δt time step is significantly smaller than that prescribed by the Courant Criterion (Equation 4).

$$c = \frac{\rho_m}{\dfrac{1-y}{K_f} + \dfrac{y}{K_g} + \dfrac{DC'}{Ee}} \quad \ldots 7$$

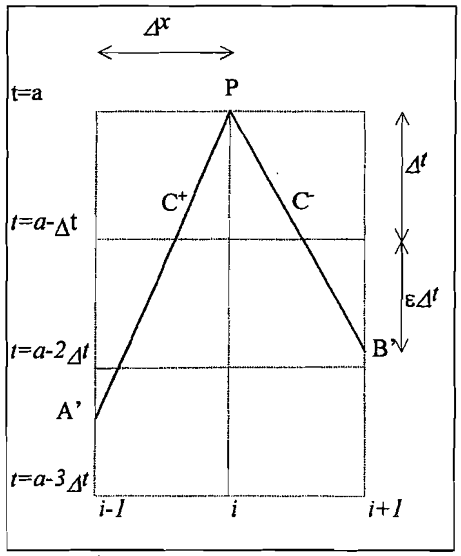

Figure 10 : Details of the application of the method of characteristics using time line interpolation. (Note : For clarity only alternate nodes are represented.)

Using time line interpolation, the level of Δt is set within all the system elements modelled using the highest propagation, resulting in the lowest value of Δt. Determination of H and Q is undertaken as illustrated in Figure 9 for the horizontal pipework as here the propagation velocity is that used to set Δt. As the propagation velocity is lower in the stack it means that it takes longer than Δt for pressure changes to be communicated to point P from adjacent nodes. Depending on the amount of air in the flow the propagation and flow velocities may also become comparable, therefore the approximation represented in Equation 4 is invalid. These factors mean that if nodes *i-1* and *i+1* are still to be used in the determination of Q and H at the point in time and space P, the known values of Q and H at these nodes must be obtained more than Δt before the time plane in which point P exists. This situation means that the solution method outlined in Figure 9 must be modified, and time line interpolation may be introduced to solve the characteristic equations for Q and H in the successive Δt time solution planes. Figure 10 illustrates the time line interpolation method as applied to this condition. Time line interpolation means that rather than using the previous time step, and communicating the conditions at that juncture to the current time step, data is conveyed from a position m+ε time steps[b] prior to the current position where the characteristic lines (C^+ and C^-) cross preceding and subsequent nodal planes respectively.

[b] Where m is an integer greater than 1, and ε is a real number greater than zero and less than one.

The solution structure is now in place and SIPHONET can now begin solving for Q and H at each node for each successive time step. SIPHONET also tracks the movement of the air pocket lodged upstream of the hydraulic jump, as it moves through the system at the ambient flow velocity, and the volume is adjusted according to the gas law as it moves through the system at computed $V\Delta t$ spatial intervals. As the air pocket enters the stack the resultant reduction in the flow density within the stack generates a partial re-pressurisation of the system. The pocket then causes a de-pressurisation as it exits the system. At this juncture the system is judged to be primed.

Figure 11 compares output from SIPHONET, and data collected from the test rig. However, despite these simulation results laboratory work is underway to augment the understanding of the rate at which air enters the system at varying rates of inflow and depths of gutter flow. Once these data have been integrated into "SIPHONET", simulation of 'real' storms (time varying gutter inflow) in the test rig will be attainable.

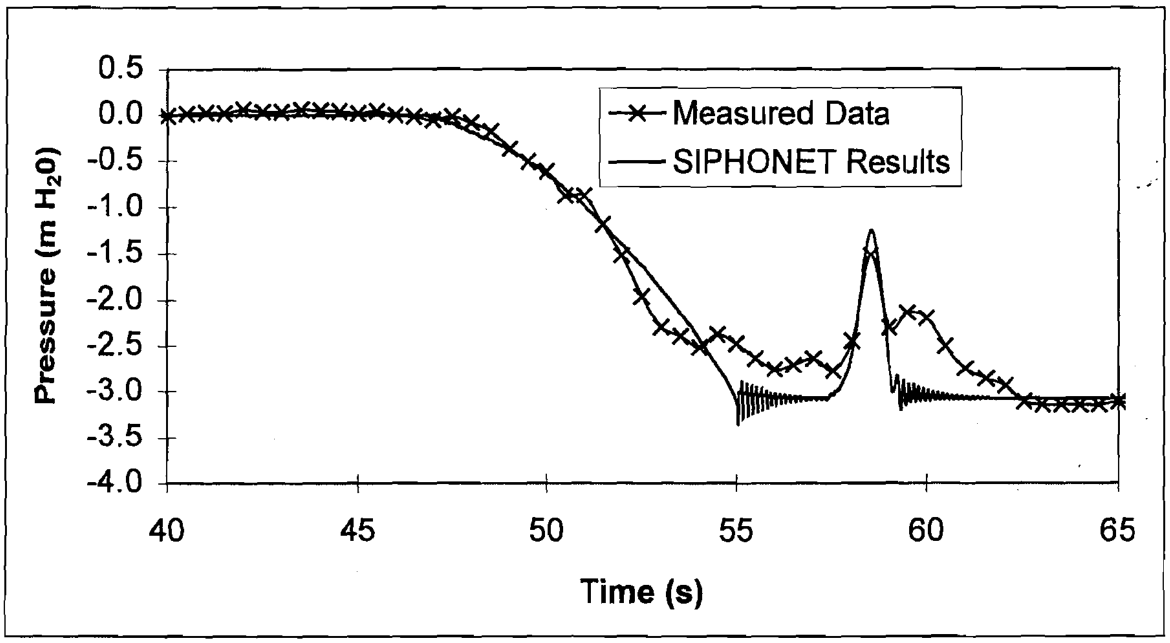

Figure 11 : Computed and measured pressures at bend 2 during the priming of the siphonic roof drainage system illustrated in Figure 1.

CONCLUSTIONS

- Due to the benefits which siphonic systems have, they are draining an increasing proportion of UK commercial roof space.
- There are weaknesses in the current design approach employed by designers.
- Arguably weaknesses, and installation problems, have resulted in a number operational failures.
- With the aid of the European siphon rainwater drainage industry a siphonic test facility has been established at Heriot-Watt University.
- A method has been establish which may be used to quantify the amount of air entering the test rig

- The priming the siphonic test rig has been described.
- Data collected, illustrates how when the systems operate below the design capacity the flow regime is unsteady.
- A numerical model has been devised which can represent the priming of a siphonic roof rainwater system.

Like all good research the programme reported herein has raised as many questions as it has answered. So much so that EPSRC has decided to invest a further 3 years funding in the siphonic roof rainwater research undertaken at Heriot-Watt University.

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