Design criteria for siphonic roof drainage systems

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Summary

Design criteria for siphonic roof drainage systems

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A key feature of siphonic roof drainage systems is that they are designed to flow full bore and thereby make maximum use of the available head between roof and ground level in overcoming the flow resistance of the pipes and fittings. This allows the development of high flow velocities in the pipes and produces correspondingly high flow rates. The full-bore flow can also give rise to sub-atmospheric pressures within the system; these pressures can produce a suction effect at the outlets and increase their flow capacity compared with conventional outlets of similar size. The outlets are usually of a special design and fitted with a baffle to minimise the amount of air that is drawn into the system when operating at high flow rates.

Siphonic systems were originally developed in Finland and the first major installation in the UK was in 1985/6. The systems are now widely used for large shed-type buildings and also for buildings with unusual structures such as airport terminals and sports stadia. Several proprietary siphonic systems are now available, having different designs of roof outlet and individual computer design packages for sizing the pipework components. Although generally based on the same hydraulic principles, the different systems have evolved somewhat different design criteria and installation practices. To help identify best practice and provide specifiers with increased confidence about the characteristics and design procedures for siphonic systems, it was decided after consultation with the UK siphonics industry to prepare a draft guidance document that would be proposed for publication as a British Standard. To assist the preparation of this document, the Department of Trade and Industry provided part-funding for a collaborative industry project under its Partners in Innovation scheme. The drafting was carried out with the assistance of a Project Steering Group representing specifiers, architects, drainage consultants, academic researchers, professional and trade organisations, and the manufacturers and/or suppliers of all the proprietary siphonic systems currently available in the UK. The draft text is fully consistent with the general performance requirements for siphonic systems given in European Standard BS EN 12056-3 (2000) but provides detailed recommendations on hydraulic design criteria, installation, testing and maintenance.

This report complements the proposed Standard and provides detailed background information explaining the basis of the new hydraulic design criteria that are proposed. The principal topics covered are:

- Hydraulic design principles
- Balancing requirements for siphonic systems
- Minimum allowable flow velocities
- Speed of priming of systems
- Minimum allowable pressures.





Glossary

Cavitation :	Phenomenon involving the formation and subsequent sudden collapse of vapour cavities in a liquid, with the cavities forming when the local pressure within the flow reduces close to that of the vapour pressure of the liquid.
Collector pipe :	Horizontal pipe installed below roof, gutter or floor that collects and conveys flow from the tailpipes of roof outlets.
Conventional system :	Non-siphonic system in which the pipework between roof level and ground level is designed to flow part full with internal pressures at or above atmospheric pressure.
Downpipe :	Section of vertical pipe in pipework connecting collector pipe to siphon break or to point of discharge from siphonic system.
Full-bore flow :	Flow conditions under which the water (and any entrained air carried by the water) occupies the full cross-section of the pipe.
Primary system :	Fittings and pipework designed to drain a roof or gutter under more frequent rainfall conditions.
Priming :	Process by which water entering a siphonic system is able to remove air from the pipes and cause the system to flow full bore to the point of discharge.
Secondary system :	Fittings and pipework designed to drain a roof or gutter under less frequent rainfall conditions, or in the event of a failure of the primary system, and completely independent from the primary system.
Siphon break :	Point in a siphonic system where the pipework is designed to maintain the internal pressure at atmospheric pressure; or, the point of discharge of a siphonic system into a manhole or chamber that connects to a separate site drainage system.
Siphonic system :	Piped system in which the outlets and pipework enable the system to flow full bore under design conditions and make use of the total head available between the outlets and the discharge point.
Siphonic outlet :	Fitting at the entrance to a roof drainage system to permit rainwater to drain from a roof or gutter and designed to exclude air entering the pipework.
Tailpipe :	Section of vertical and possibly horizontal pipework connecting roof outlet to horizontal collector pipe.



Notation

			<u>Units</u>
A	=	cross-sectional area of flow	m^2
В	=	surface width of flow	m
d_P	=	internal diameter of pipe	m
ΔE_{12}	=	loss of specific energy of fluid between two points (1 and 2)	J/kg
F_R	=	Froude number of flow (see Equation (5.1))	_
g	=	acceleration due to gravity	m/s^2
h	=	static pressure head at a point in the fluid	m
h_I	=	pressure head at inlet to system	m
h_E	=	pressure head at end point of system	m
h_{min}	=	minimum allowable pressure head in system (above vacuum)	m
h_{vp}	=	vapour pressure of water (in equivalent water head)	m
h_0	=	atmospheric pressure head	m
Δh_B	=	reduction in pressure head between centreline and inner wall of pipe bend	m
Δh_L	=	localised loss of energy head at pipe fitting	m
Δh_{12}	=	loss of energy head between two points (1 and 2)	m
H_A	=	available head acting on system	m
H_T	=	total head losses in pipes and fittings along flow path between inlet to siphonic system and end point of the system	m
i_F	=	frictional head loss gradient (m loss of head per m length of pipe)	_
k_P	=	roughness value of pipe	mm
р	=	static pressure at a point in the fluid	N/m ²
Q_D	=	design flow capacity of siphonic system	L/s
Q_{in}	=	combined flow capacity of tailpipes during initial filling stage	L/s
Q_T	=	flow capacity of tailpipe acting siphonically	L/s

r	=	centreline radius of curvature of pipe bend	m
T_F	=	filling time of siphonic system	S
V	=	mean velocity of fluid at point	m/s
V_E	=	velocity of flow discharging from end point of system	m/s
ΔZ	=	difference in vertical level between the inlet and end point of system	m
Δz_{12}	=	vertical height of point 1 above point 2	m
ζ	=	dimensionless head loss coefficient for pipe fitting	_
θ	=	angle of inclination of pipe below horizontal	0
ν	=	kinematic viscosity of water	m ² /s
ρ	=	density of fluid	kg/m ³
σ	=	cavitation index of flow (see Equation 7.2)	_
$\sigma_{\rm I}$	=	incipient cavitation index	_
Φ	=	volume of collector pipe and downpipe to point of discharge from siphonic system	L



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Figure

Figure 1 Minimum flow velocity for air pocket movement in horizontal and downward sloping pipes (from Lauchlan et al, 2004)

Appendix

Appendix A Membership of Project Steering Gr	oup
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1. Introduction

In a siphonic roof drainage system, the pipework is designed to flow full bore and thereby make maximum use of the available head between roof and ground level in overcoming the flow resistance of the pipes and fittings. This allows the development of high flow velocities in the pipes and produces correspondingly high flow rates. The full-bore flow can also give rise to sub-atmospheric pressures within the system; these pressures can produce a suction effect at the outlets and increase their flow capacity compared with conventional outlets of similar size. The outlets are usually of a special design and fitted with a baffle to minimise the amount of air that is drawn into the system when operating at high flow rates.

By contrast, the pipework of a conventional roof drainage system is designed to flow only partly full of water in order to prevent the pipes being subjected to sub-atmospheric pressures that they are not intended to withstand. As a result, outlets in a large building may have individual vertical rainwater pipes that discharge into an underfloor gravity drainage system within the building. Alternatively, if a collector pipe is installed at a high level to receive flow from a series of outlets, this pipe must be laid with a fall in order to ensure that it flows partly full and does not cause backing-up of water at the outlets. The requirement for the level of the collector pipe to vary along the length of a building can be inconvenient in terms of efficient use of the roof space.

In a siphonic system, the ability of pipework to flow full bore enables the collector pipe to be installed horizontally and to drain a larger area of roof than if the same section of pipe were used in a conventional system. In this way, flow from a large number of outlets can be drained to a single downpipe adjacent to an outer wall of the building, which avoids the need for an expensive underfloor drainage system. These particular features of siphonic systems make them an attractive option for large industrial, commercial and public buildings where maximum flexibility of the internal space is required.

Siphonic systems were first developed by Mr Olavi Ebeling in Finland and the first major installation in the UK was at Stansted Airport in 1985/6. The systems are now frequently used for shed-type buildings and are also often selected for buildings with unusual structures such as airport terminals and sports stadia. Several proprietary makes of system have been developed in Europe and the UK, with each company manufacturing one or more designs of outlet with individual shapes of bowl, leafguard and air baffle. The sizing of the large number of pipework components in a system to obtain the required flow capacity is a complex procedure, and the various manufacturers of outlets have therefore developed their own computer design packages. As a result, specifiers and drainage consultants are not usually able to carry out their own design checks of siphonic systems in the same way that they can for conventional systems.

Siphonic systems need to be self-priming, that is the flow conditions within the pipes during the initial filling stage have to be sufficiently energetic for them to be able to transition quickly to full-bore flow and thereby respond to high intensity storms of short duration. Once the system is operating siphonically, the overall head losses to individual outlets need to be in a satisfactory degree of balance so that the outlets can handle the required flow rates from their individual catchment areas. If, for example, an outlet at the upstream end of the collector pipe has too little flow capacity, it could cause localised ponding in the gutter or roof; conversely, an outlet close to the vertical downpipe might have excess flow capacity, which could cause it to suck air and partially de-prime the system. During siphonic operation, sub-atmospheric pressures will occur in parts of the pipework so it is necessary to ensure that the pressures do not become low enough to result in pipe collapse or cavitation damage. Although the leafguard and air baffle of a siphonic outlet will prevent large debris entering the system, smaller sediment such as grit, silt and organic material is likely to be washed into the horizontal collector pipe. It is therefore necessary to ensure that flow velocities sufficient to erode any deposits will occur frequently enough (on a statistical basis) during the life of the system.

To help ensure satisfactory performance, the developers of the various proprietary systems have evolved their own sets of hydraulic design criteria covering factors such as:

- suitable (and non-suitable) types of pipe fitting (e.g. bends, junctions, reducers, increasers, etc.)
- head loss coefficients for pipes and fittings
- minimum flow velocity
- minimum pressure
- allowable imbalance in head losses between outlets
- speed of priming of system.

The limiting flow values have been developed from a combination of established hydraulic theory, experimental studies carried out by the individual companies and experience gained from their previous installations. Although most of the proprietary systems are designed in accordance with the same general hydraulic principles, there are currently certain differences between the numerical values adopted and the ways in which they are applied. In the UK several of the systems have received accreditation from the British Board of Agrément (BBA) who checked their design, manufacturing and installation procedures.

In 2000 European Standard BS EN 12056-3 (BSI, 2000) was published covering the layout and calculation of gravity roof drainage systems for buildings. Most of the Standard is concerned with the design of conventional systems, for which formulae and graphs are given for direct calculation of the flow capacities of gutters, outlets and rainwater pipes. For the first time, the Standard also specified general requirements concerning the performance of siphonic roof drainage systems. Section 6.2 in the Standard briefly lists thirteen factors to be considered in design but does not indicate how siphonic systems should be sized or specify any numerical limits for use in the hydraulic calculations (apart from setting a minimum internal pipe diameter of 32 mm).

During the drafting of BS EN 12056-3, the UK had proposed to the CEN Task Group that the document should include more detailed requirements on the specification and design of siphonic systems. However, the complexity of the issues involved prevented a consensus being reached within the limited time available. Following publication of BS EN 12056-3, discussions within the UK construction industry therefore identified the need for a separate British Standard on siphonic systems that would be compatible with the generalised requirements in EN 12056-3 but provide more detailed guidance on the factors necessary for their satisfactory use. The main benefits to be derived from the publication of such a Standard were considered to be:

• Collation of current best practice relating to the design, construction, installation and maintenance of siphonic systems



- Setting of minimum design requirements and limiting values to help ensure that systems are designed in accordance with appropriate hydraulic principles
- Establishment of a level playing field between different proprietary systems
- Increased understanding of siphonic systems by specifiers, contractors, building owners, and other parts of the construction industry, leading to:
- Increased confidence in the selection and use of siphonic systems.

Part-funding to assist the preparation of a proposed British Standard on siphonic systems was provided by the Department of Trade and Industry (DTI) under its Partners in Innovation (PII) research programme. This PII project was carried out by HR Wallingford (HRW) in association with Mr N J Price of Whitby Bird (WB). To oversee and review the drafting of the proposed Standard, a Project Steering Group (PSG) was established with representatives from specifiers, architects, drainage consultants, academic researchers, professional and trade organisations, plus the manufacturers and/or suppliers of all the proprietary siphonic systems currently available in the UK. The membership of the PSG is listed in Appendix A.

At the start of the work, a questionnaire was prepared by HRW and WB and used to collect data from manufacturers, suppliers and other specialists on current best practice relating to the design and installation of siphonic systems. After collation and review, this information provided an important reference source for the preparation of the proposed Standard. After detailed discussion and review by the PSG, the draft document was submitted to Committee B/505 of the British Standards Institution (BSI) in March 2004 with a request that it be taken forward as the basis of a new British Standard.

The purpose of this report is to provide a background reference to the recommendations on the hydraulic design of siphonic systems given in the draft Standard (Version FD4) that was submitted to BSI in March 2004. The topics covered in this report are:

- Hydraulic design principles (Chapter 2)
- Establishment of design criteria (Chapter 3)
- Balancing of systems (Chapter 4)
- Minimum allowable flow velocities (Chapter 5)
- Speed of priming (Chapter 6)
- Minimum allowable pressures (Chapter 7)
- Conclusions (Chapter 8).

It should be noted that a published BSI Standard on siphonic roof drainage systems may differ in its recommendations from those in the draft document (Version FD4) to which this report refers.

2. Hydraulic design principles

2.1 APPLICATION OF BERNOULLI EQUATION

Flow conditions within a siphonic roof drainage system can be calculated using the fundamental Bernoulli equation which relates changes between the potential, pressure and kinetic energies of the fluid and takes account of energy losses due to frictional resistance and turbulence in the pipes and fittings.

Most but not all proprietary siphonic systems are sized on the assumption that all the pipes in a system are flowing 100% full of water at the design flow rate, which is determined from the specified design rainfall intensity for the building and the catchment area drained by the system. This assumption implies that the system will be able to self-prime, i.e. the flow entering the system will be able to remove all the air that is initially within the pipes at the start of a design storm event. (See the Glossary at the beginning of this report for definitions of terms relating to siphonic roof drainage systems).

Applying the Bernoulli equation to the flow of a fluid of constant density under steadystate conditions between two points in a siphonic system gives:

$$\left(p_{1} + \frac{1}{2}\rho V_{1}^{2}\right) - \left(p_{2} + \frac{1}{2}\rho V_{2}^{2}\right) = \Delta E_{12} - \rho g \,\Delta z_{12}$$
(2.1)

where:

p = static pressure at a point in the fluid (in N/m²) $\rho = \text{density of fluid (in kg/m³)}$

V = velocity of fluid at point (in m/s)

 ΔE_{12} = loss of specific energy of fluid between points 1 and 2 (in J/kg)

g = acceleration due to gravity (= 9.81 m/s²)

 Δz_{12} = vertical height of point 1 above point 2 (in m).

Static pressure is the ambient pressure within the flow, which in the case of a straight section of pipe might be measured by means of a pressure tapping installed flush with the wall.

Equation (2.1) can be expressed in terms of pressure head as follows:

$$\left(h_{1} + \frac{V_{1}^{2}}{2g}\right) - \left(h_{2} + \frac{V_{2}^{2}}{2g}\right) = \Delta h_{12} - \Delta z_{12}$$
(2.2)

where:

h = static pressure head at a point in the fluid (in m) Δh_{12} = loss of energy head between points 1 and 2 (in m).

Equation (2.2) is the basis of most current computer design packages for siphonic roof drainage systems. Application to each section of pipe or fitting in turn enables the variation in static pressure head along a system to be determined.



Assuming that a siphonic system is flowing at its maximum capacity without any water surcharging the roof outlets, application of Equation (2.2) between an individual outlet and the downstream point of discharge from the siphonic system gives:

$$H_T = \Delta Z + h_I - h_E - \frac{V_E^2}{2g}$$
(2.3)

where:

- H_T = total head losses in pipes and fittings along flow path between inlet to siphonic system and the downstream end point of the system (in m)
- ΔZ = difference in vertical level between the inlet and end point of system (in m)
- h_I = pressure head at inlet to system (in m)
- h_E = pressure head at end point of system (in m)
- V_E = velocity of flow discharging from end point of system (in m/s).

The depth of water above a siphonic outlet in a gutter or flat roof is normally very small compared with the height of the building and can be neglected when applying the Bernoulli equation to determine flow conditions within a system. On this basis, h_I can effectively be assumed to be equal to the value of atmospheric pressure head; if for convenience, the pressure heads in the system are calculated using atmospheric pressure as the datum, the value of h_I can then be put equal to zero.

The pressure head acting at the downstream end of a siphonic system may not necessarily be equal to atmospheric pressure. Site drainage systems are usually sized to cater for storms of lower rainfall intensity than roof drainage systems. Surcharging of a site system during a high intensity storm may therefore exert a positive pressure head at the end point of the siphonic system and reduce its capacity below that achievable if it were able to discharge freely. If the first access chamber or manhole into which a siphonic system discharges is fitted with a suitable ventilated cover, it can be assumed that the surcharge head will not exceed the difference in level between the cover of the chamber and the centre of the pipe cross-section at the point where the flow discharges into the chamber. For these reasons, it is convenient to define the head difference acting on a siphonic system as the available head, H_A (in m), given by:

$$H_A = \Delta Z - \left(h_E - h_0\right) \tag{2.4}$$

where h_0 (in m) is the value of atmospheric pressure head and $(h_E - h_0)$ is the amount of surcharge head. If it is certain that the site drainage system cannot surcharge the end point of the siphonic system, or if a satisfactorily ventilated siphon break is installed at that point, the surcharge head can be assumed to be zero.

It is important to note that the Bernoulli equation as expressed in Equations (2.1) and (2.2) gives only an averaged description of flow conditions within a siphonic system. It does not provide any information about the magnitude of turbulent pressure fluctuations within the flow. Also, it does not take account of the effects of flow curvature on values of local pressure within pipe fittings. The centripetal acceleration experienced by flow within a bend produces a pressure gradient across the flow, with the pressure being lower on the inside of the bend than on the outside. The pressure calculated from the Bernoulli equation is likely to be a reasonable estimate of the mean pressure along the centreline of the bend but higher and lower pressures will occur at other points in the

flow. Similarly, flow separation at irregularities such as pipe joints or in expansion sections (i.e. pipe increasers) will produce fast rotating eddies within which the pressure can be much lower than in the surrounding flow.

Another reason why values of pressure calculated using the Bernoulli equation may not be completely reliable is that it is normal practice to assume that pipe fittings (such as bends, junctions, reducers, increasers) produce point losses of head, while the losses due to friction at the pipe walls are considered to be distributed uniformly along the length of the pipes. Even though the total head loss within a system may still be assessed satisfactorily, the local pressure values and the location of the points where the losses occur may not correspond precisely with predictions. This is particularly the case where the distance between fittings is small since the local flow conditions can then become very complex (see for example Miller, 1990).

2.2 ESTIMATION OF HEAD LOSSES

Frictional head losses in pipes can be calculated using any formula that is suitable for the type of pipe being considered. The Colebrook-White equation (HR Wallingford and Barr, 1998) is particularly suitable because it has been validated for a wide range of flow conditions and pipe materials, and BS EN 12056-3 (BSI, 2000) states that it shall be used if there is a dispute concerning appropriate values of head loss for design.

The Colebrook-White equation for frictional losses in pipes flowing 100% full of water can be written in the form:

$$i_F = \left(\frac{V^2}{8gd_P}\right) \left\{ \log_{10} \left[\frac{k_p}{3710 \, d_p} + \frac{1.775 \, v}{\sqrt{\left(g \, i_F \, d_P^3\right)}} \right] \right\}^{-2}$$
(2.5)

where:

 i_F = frictional head loss gradient (m loss of head per m length of pipe)

V = velocity of flow (in m/s)

g = acceleration due to gravity (= 9.81 m/s²)

 d_P = internal diameter of pipe (in m)

- k_P = roughness value of pipe (in mm)
- v = kinematic viscosity of water (= 1.14×10^{-6} m²/s at 15° C).

An iterative method of solution is required to find the head loss gradient, i_F , from Equation (2.5) because this quantity also appears on the right-hand side of the equation.

The value of the roughness parameter, k_P , depends on the surface texture of the pipe walls, the effects of any irregularities or beads at joints, and the distance between successive joints relative to the pipe diameter. When they are new, plastic pipes such as polyethylene are intrinsically very smooth and can be expected to have values of the order of $k_P = 0.006$ mm to 0.06 mm (see HR Wallingford and Barr, 1998). However, over the design life of a building (typically 20 years or longer), the pipes in a system are likely to become hydraulically rougher due to ageing of the pipe material, roughening of the walls due to grit or silt carried by the flow, and deposition of fine sediment or organic material washed into the system and accumulating in the horizontal pipes during periods of low flow. For these reasons, use of a minimum roughness value of $k_P = 0.15$ mm is suggested when determining the design flow capacity of a siphonic system. [In a parallel context, it may be noted that UK surface water sewers intended for adoption by sewerage undertakers must be designed for a roughness value of $k_P = 0.6$ mm (see Sewers for Adoption, Water UK / WRc, 2001). This value applies irrespective of the pipe material used and is significantly higher than the pipes would have when new. A somewhat lower design value of k_P is appropriate for siphonic systems because the size and quantity of sediment entering them is likely to be less than in sewers, even though the latter are laid at gradients that are intended to avoid sediment deposition].

When a siphonic system is flowing 100% full of water, the local head loss, Δh_L (in m), at a pipe fitting can be determined from the formula:

$$\Delta h_L = \varsigma \frac{V^2}{2g} \tag{2.6}$$

where ζ is a non-dimensional head loss coefficient. Values of this coefficient for bends, junctions, reducers and increasers are given in standard references such as Idelchik (1986) and Miller (1990) and can also be established from suitable tests.

Since proprietary designs of siphonic outlet differ in geometry, the draft Standard recommends that the appropriate value of ζ for each design should be determined using a test procedure given in Annex B of the draft. This procedure differs from the one currently described in UK National Annex NF of BS EN 12056-3 and has been checked experimentally for its suitability. Since existing Annex NF is only advisory, the UK will be able to withdraw it on publication of a separate British Standard on siphonic systems.

2.3 CALCULATION PROCEDURE

The usual procedure for designing a siphonic system is as follows:

- Determine a suitable layout for the pipework and select/estimate likely pipe sizes
- Based on the design rainfall conditions and roof catchment areas, calculate the required flow rate through each component of the system
- Calculate the head losses in the various components of the system
- Find the total head loss along each flow path through the system, i.e. from a siphonic outlet at roof level to the downstream point of discharge from the system
- Check that the total head loss for each flow path does not exceed the available head and is also close enough to this value to allow balanced operation of the system. Also, check that allowable limits on minimum velocity and pressure within the system are not exceeded
- If these design criteria are not met, revise the layout and/or sizes of the pipes and repeat the above procedure.

When applying the Bernoulli equation to calculate the flow conditions within the system, it is recommended to start the calculations at the downstream end and work in the upstream direction to the siphonic outlets at roof level. The reason for doing this is to avoid the possibility of obtaining an unsafe estimate of the minimum pressure in the system. Most systems are designed so that the total head loss along each flow path is somewhat less than the available head (partly because standard pipe sizes make it impossible to obtain an exact match). The unused portion of the available head is termed the residual head for that flow path. If the calculations were to start from the outlet and work in the downstream direction, the pressure head predicted at the point of

discharge would exceed the true value by the amount of the residual head. This causes all the calculated values of pressure within the system to appear higher than they actually are. The recommended procedure of calculating from the downstream end will cause the pressure values to be underestimated (i.e. made more negative), but this errs on the safe side when checking that the limit on minimum pressure is satisfied.

Another point that should be noted when applying the Bernoulli equation concerns the way in which the kinetic energy of the flow (i.e. the velocity head, $V^2/2g$) is taken into account. Although some of the available head is used to accelerate flow as it enters and travels through a siphonic system, the kinetic energy only becomes a loss if and when it is dissipated in turbulence downstream of the exit point from the system. An exit loss coefficient should not therefore be included in the analysis when determining flow conditions within a siphonic system. Thus, applying Equation (2.2) to the most downstream section of the system (with point 2 being the point of discharge), gives:

$$\left(h_{1} + \frac{V_{1}^{2}}{2g}\right) - \left(h_{E} + \frac{V_{E}^{2}}{2g}\right) = \Delta h_{12} - \Delta z_{12}$$
(2.7)

where h_E is the pressure head acting at the end point of the system, and $V_E^2 / 2g$ allows for the kinetic energy of the flow prior to any losses farther downstream.

2.4 PERFORMANCE OF SYSTEMS WITH AIR/WATER FLOW MIXTURES

In order to fulfil its function, a siphonic system needs to be able to perform satisfactorily at all rates of flow up to its maximum design capacity. This requires that the system should not cause the depth of flow in a gutter or on a roof to be greater at an intermediate flow rate than at its design capacity.

At low flow rates, a siphonic system will behave in the same way as a conventional one, with the pipes flowing only partly full of water and at atmospheric pressure. At higher rates of flow, some of the pipes in the system will transition to flowing full bore while others will still be flowing partly full, with local or continuous air pockets remaining in some pipe lengths. During this transitional condition, pressures within parts of the system may start to become sub-atmospheric. A further increase in flow rate will cause the whole system to flow effectively full bore but with some air still being drawn in through the siphonic outlets and transported along the system in the form of bubbles. At this point, the system can be said to have primed, with a continuous column of bubbly liquid connecting the outlets to the downstream discharge point at or below ground level. The system is then acting siphonically with the ability to generate significant subatmospheric pressures within the pipes. Further increases in flow rate entering the system cause a corresponding reduction in the amount of air transported through the system until at a certain point the pipes are flowing 100% full of water. The system cannot accept any more flow without causing significant surcharging above the outlets. As an indication, if a system is flowing 100% full of water with an available head of 10 m, an increase of 1% in the flow rate would ultimately cause water to surcharge above the outlets to a depth of about 200 mm (assuming that the flow rate is maintained constant for a long enough period and overtopping of the gutter or roof does not occur first).

Laboratory testing of siphonic systems indicates that some layouts are able to operate with a partial air/water mixture in an approximately steady condition of full-bore flow. Other layouts behave in a cyclical manner with the system first priming and flowing

nearly 100% full of water; if the flow rate drawn by the outlets then exceeds the rate of supply, the water depth in the gutter or roof will decrease and allow more air to be sucked in through the outlets. This partially de-primes the system, causing a loss of flow capacity and a consequent increase in water depth in the gutter or roof. Beyond a certain point the increased depth cuts off the intake of air and allows the siphonic system to prime again. The reasons why different systems can behave in different ways are not yet properly understood but may be linked to the detailed layout of the pipework and the internal geometry of the siphonic outlets. There is an interesting analogy with siphon spillways used in dams and river control structures, where "blackwater" siphons can exhibit a cyclical behaviour while "whitewater" or air-regulated siphons can operate in a more stable way with varying proportions of air and water (see, for example, Webber, 1965, and Novak et al, 2001).

Some siphonic systems are sized on the basis of allowing a mixture of air and water to occur at the design rate of flow. This is a feasible option because siphonic systems have to be able to operate satisfactorily in this condition since the great majority of storm events experienced by an installed system will produce flow rates below the maximum design capacity. However, sizing a siphonic system so that it operates full bore at its design flow rate with an air/water mixture is more complex than designing it assuming the system is 100% full of water. It is possible to apply the Bernoulli equation in Equation (2.1) if the air/water mixture is effectively homogeneous so that it can be considered to behave as a single fluid with a density less than that of water. However, the following factors need to be satisfactorily taken into account in the design process:

- *Effect of air on the flow resistance of pipes and fittings.* On the one hand, the presence of air may reduce the effective viscosity of the fluid, but on the other hand the air will reduce the flow area of the water and thus increase the velocity of the water in contact with the walls of the pipe.
- *Effect of changes in pressure on the volumes of air bubbles in the pipes.* If, for example, the volumetric flow rate of air entering a system at atmospheric pressure is equal to 10% of the water flow rate, and the absolute pressure at a point within the system reduces to 30% of atmospheric pressure, the air bubbles will become larger and cause the volumetric flow rate of air to increase to about 27% of the water flow rate (assuming rapid adiabatic expansion of the air without transfer of heat).
- Ability of different outlets in a system to draw different amounts of air. This will give rise to a variation of density of the bubbly liquid along the length of the system, with changes in pressure producing additional variations in its average density.

Generalised design procedures for sizing the pipework in such systems should be based on physical principles governing the behaviour of air/water mixtures and should be checked against data from experimental tests to ensure that the various assumptions are valid.

Siphonic systems that have been designed with an allowance for air have generally been sized on the basis that the proportion of water in the system should not be less than 60% in order for the system to flow full bore and develop a siphonic action. The exact limit is likely to vary with the pipe layout and the flow velocities in the system, but experimental data obtained by May and Escarameia (1996) provide some support for a limiting water to air ratio of about 60 : 40.

3. Establishment of design criteria

3.1 GENERAL

The Bernoulli equation described in Chapter 2 can be used to predict the flow capacity of a pipework system but it does not follow that the system will automatically be able to self-prime and develop a satisfactory siphonic action. It is, therefore, necessary to apply additional criteria in the design process relating to the degree of balancing, minimum flow velocity, speed of priming, and minimum pressure.

Most manufacturers of proprietary systems have carried out experimental studies on their systems to develop new types of siphonic outlet and to check performance against design predictions. Much of this experimental data has remained confidential to the manufacturers, but the results of some research studies have been published and are in the public domain, see for example: Arthur and Swaffield (2001a, b); Bramhall and Saul (1999); Hanslin R (1993); May and Escarameia (1996); Sommerhein (1991, 1999); Swaffield *et al* (1998); Wright *et al* (2002). Over the period that siphonic systems have been in use, the manufacturers and designers have also gained considerable experience of some of the practical issues and design limits that can affect performance.

Despite the data and experience that have been accumulated, it remains the case that no direct measurements have probably been made on large siphonic installations where the flows conditions approach some of the limits beyond which performance would be unsatisfactory. Carrying out in-situ tests of large systems is normally impractical because of the difficulty of providing, maintaining and measuring large rates of flow (of the order of 50 - 200 l/s) at roof level. Monitoring performance under natural rainfall conditions can be useful but installation of the necessary instrumentation is often not Also, the probability of straightforward or acceptable to the building owner. experiencing a storm close to the design maximum during a typical monitoring period of one to three years is not very high if the system has been designed to cater for storms with return periods of 100 years or more. Experience gained from the large number of installations existing around the world can help in identifying satisfactory design criteria, but it is not possible to determine how many of the systems have actually experienced flow rates at or near the design capacity and how many of them would then have operated close to the limiting flow conditions. Like conventional roof drainage systems, some siphonic systems have failed in use and not provided the expected degree of protection against flooding, but it has not always been possible to determine with certainty the reasons for failure.

It follows from this summary that there is currently some uncertainty about the exact hydraulic design criteria that should be applied to ensure satisfactory operation of siphonic systems. The problem is also complicated because practically every installed siphonic system is unique in some respect and small differences in layout have sometimes been shown to have a large effect on performance. In setting design criteria for the proposed British Standard, it is therefore appropriate to adopt a certain degree of caution while taking balanced account of available experimental data on siphonic systems, data from other related areas of hydraulics, and direct experience gained by manufacturers, designers and installers of siphonic systems.

3.2 FACTOR OF SAFETY

Current design practice for siphonic systems is usually (but not necessarily always) to make maximum use of the available head so that the design flow capacity is as close as possible to the design rate of rainfall run-off from the roof. Also, the outlets are assumed to be in a clean state with no allowance made for possible clogging by debris.

This contrasts with the situation for conventional systems where BS EN 12056-3 (2000) provides all the equations and graphs necessary for the hydraulic design. The methods for calculating flow capacity in the various components contain in-built safety factors as follows: 10% for hydraulically short gutters; somewhat more than 10% for longer gutters; an average of 7% to 15% for open outlets with orifice-type flow; and an average of approximately 50% for open outlets with weir-type flow (due to significant variability in the test data). More details can be found in May (1982) and May (2003). To allow for possible clogging at conventional grated outlets, BS EN 12056-3 assumes fairly arbitrarily that the effective flow capacity will be only 50% of that of an open sharp-edged outlet with the same top diameter.

In order to make the performance requirements for the two types of system more comparable, it is therefore proposed that a safety factor of 10% should be incorporated in the design of siphonic systems. This should be done by first calculating the flow rates that would be produced by the design rainfall intensity and then increasing these values by 10%. This increase should also be applied to the design calculations for the gutters, which should be carried out in accordance with BS EN 12056-3; in this case the extra 10% allows for some limited clogging of the outlets by debris. This allowance is less than specified for conventional grated outlets, but this partly reflects the fact that the proposed British Standard stresses the importance of carrying out regular and effective maintenance of outlets and gutters of siphonic systems. Also, the 50% figure mentioned above for conventional grated outlets allows for the combined effects of the bars and partial clogging, whereas the 10% allowance for siphonic outlets relates only to the clogging.

For a siphonic system, the additional 10% flow capacity can be catered for by suitably increasing the size of the pipework. On average, this would lead to pipe diameters being about 3.5% larger than they would without the application of the safety factor; in practice, this is likely to result in the larger pipe sizes being increased in length relative to the smaller sizes. However, as an alternative, it is possible for a designer to provide the additional flow capacity by means of separate overflows if these can be incorporated satisfactorily within the overall layout of the building. The overflow system can take the form of high-level weirs, chutes through parapets, separate conventional outlets, or a separate siphonic system. If a building is equipped with separate primary and secondary siphonic systems, the additional discharge capacity may be allocated to the secondary system.

4. Balancing of systems

The aim of balancing a siphonic system is to ensure that, under design conditions, the flow capacities of the individual outlets are satisfactorily matched to the amounts of rainfall run-off draining to them from the roof. If this is not done, outlets that have a lower capacity than required will not be able to accept all the flow approaching them and will divert some of it towards outlets of higher capacity. More seriously, outlets that have too much capacity when the system is siphoning will tend to draw in additional air; this may partially de-prime the system and reduce its overall capacity below that predicted.

The degree of imbalance is determined by assuming the required rates of inflow to the outlets and calculating the total head loss along each flow path connecting an outlet to the downstream point of discharge from the siphonic system (see Section 2.3 for more details). The value of the available head minus the total head loss along the flow path is termed the residual head for that outlet.

For a siphonic system designed to flow 100% full of water at the design condition, it is recommended that no outlet in a system should have a negative residual head (i.e. none should be below its required flow capacity). Also, the difference between the largest and smallest residual heads at the outlets should not exceed 1.0 m or 10% of the available head, H_A , acting on the system (see Equation 2.4), whichever is the smaller. If the 10% limit applies, this will ensure that the flow capacities of the outlets do not differ by more than about $\pm 2.5\%$ from the target values of flow rate. This level of redistribution of flow between outlets in a system can probably take place without causing a significant increase in water depth in a gutter or on a flat roof.

If a larger degree of imbalance between outlets were to be accepted, careful consideration would be necessary to ensure satisfactory performance. As explained above, there would be a risk of outlets with excess flow capacity sucking air into the system. Also, the cumulative effects of flow redistribution need to be determined quantitatively in systems that drain gutters. If the outlets with insufficient capacity are located predominantly near the upstream end of the system (which is often the case in long systems), the rate of flow in the downstream sections of gutter can be considerably higher than if the flow capacities of the outlets were well matched to the pattern of incoming flow from the roof. It should be noted that BS EN 12056-3 (2000) does not provide any specific recommendations on how to calculate increases in water depths in gutters resulting from flow redistribution.

5. Minimum allowable flow velocities

A siphonic system will only be able to achieve the flow capacity predicted by the Bernoulli equation if it is able to self-prime and remove the air that is initially in the pipes whilst also preventing new air being drawn in through the outlets. For this to happen, flow velocities in the pipes during the filling stage need to be high enough to create turbulence and cause local sealing of sections of pipe. This produces air pockets that can be transported downstream by the action of the flowing water, while turbulence such as that created by hydraulic jumps at junctions between tailpipes and horizontal collector pipes can entrain air directly into the flow. Flow mechanisms involved with the priming process are described by Wright *et al* (2002). If the flow velocities are too low, it is possible that a system may never prime or that it will not be able to respond quickly enough to deal with high-intensity storms of short duration.

Flow velocities in siphonic systems also need to be high enough to prevent the longterm build-up of deposits of sediment and other debris in the sections of horizontal pipe. Deposits can cause significant increases in local head loss due to their blockage effect and their greater surface roughness compared with the pipe walls. The avoidance of sediment deposition in site drainage systems and sewers is an important factor affecting their hydraulic design. Detailed guidance on minimum self-cleansing velocities in sewers and drains is given in CIRIA Report 141 prepared by Ackers *et al* (1996). For surface water sewers and drains carrying "medium" sediment loads of 50 mg/l, recommended minimum velocities (expressed in terms of pipe-full velocity) vary from 0.67 m/s for a 150 mm diameter pipe to 0.79 m/s for a 450 mm diameter pipe. Sediment loads in roof drainage systems are likely to be smaller than in sewers and drains, but velocities of this order are still necessary to erode deposits that may have formed during periods of low flow.

Definitive guidance on minimum flow velocities needed to remove air from horizontal pipes is not currently available but experimental data indicate that this is a more severe design criterion for siphonic systems than the requirement to prevent the build-up of sediment deposits.

As mentioned above, the formation of a hydraulic jump within a pipe is an efficient means of entraining and removing air. To create a turbulent jump, the upstream flow needs to be supercritical with a Froude number, F_R , not less than about 1.5, that is:

$$F_R = \sqrt{\frac{BV^2}{gA}} \ge 1.5 \tag{5.1}$$

where:

B = surface width of flow (in m) V = velocity of flow (in m/s) $g = \text{acceleration due to gravity (= 9.81 m/s^2)}$ $A = \text{cross-sectional area of flow (in m^2).}$

If, as an example, the pipe is assumed to be flowing half-full, Equation (5.1) can be expressed in the form:

 $V \ge 0.94 \sqrt{g d_P}$

(5.2)

where d_p is the internal diameter of the pipe (in m). This formula indicates minimum velocities in the range of 0.8 m/s to 1.5 m/s for pipe diameters between 75 mm and 250 mm.

Another factor to be considered is the minimum velocity needed to move air pockets along a horizontal pipe. This is also a significant factor affecting the operation of pumping mains because, if the air cannot be transported and removed at air valve chambers, it will reduce the flow capacity of the main and may cause damaging pressure fluctuations. Minimum flow velocities specified by water companies for the design of pumping mains are generally in the range of 1.0 - 2.0 m/s with some variation according to pipe diameter.

A review by Lauchlan *et al* (2004) of available information on air problems in pipelines includes a comparison of experimental data on minimum velocities needed to cause movement of air pockets in horizontal and downward sloping pipes. The results are shown in Figure 1, from which it can be seen that there is a fair degree of scatter between some of the different studies. Overall, it appears that the minimum pipe-full velocity increases with increasing pipe diameter and that values for horizontal pipes (with angle of inclination of $\theta = 0^{\circ}$) can be expected to be given approximately by the following relationship:

$$\frac{V}{\sqrt{g \, d_P}} \approx 0.4 \, \text{to} \, 0.6 \tag{5.3}$$

This suggests minimum velocities could lie in the range 0.35 m/s to 0.5 m/s for 75 mm diameter pipes and increase to between 0.65 m/s and 0.95 m/s for 250 mm diameter pipes. These values relate to the initiation of air pocket movement. In order to assist rapid priming of siphonic systems, air pockets need to be removed from collector pipes within a short time (typically less than a minute) so minimum design flow velocities will need to be somewhat higher.

Taking account of the information discussed in this section, it is suggested that a minimum flow velocity of 1.0 m/s under design conditions should be specified for tailpipes and sections of horizontal pipe longer than 1 m. Some siphonic companies currently use lower values, but these are understood to have been determined on the basis of self-cleansing requirements. As explained, it is likely that the requirement for rapid removal of air from horizontal pipes is the more critical design criterion.

A separate issue is the minimum flow velocity that should be specified in vertical downpipes. High velocities are needed during the filling stage because this creates a suction effect that increases flow rates in the collector pipe and assists the initiation of priming. There is a general consensus within the siphonic industry that the minimum velocity for downpipes under design flow conditions should be in the range of 2.0 - 2.4 m/s, and after discussions with the Project Steering Group it was decided that a minimum limit of 2.2 m/s should be proposed for the British Standard.

6. Speed of priming

Application of suitable minimum flow velocities in design will help ensure that siphonic systems are capable of priming but the values do not themselves allow the speed of priming of individual systems to be estimated. Arthur and Swaffield (2001a) developed a numerical flow model of siphonic systems that has a capability of simulating the filling process, but this is currently a research tool and is not used for routine design of systems.

Analysis by siphonic manufacturers of data obtained from laboratory tests of their systems suggests that there may be some correlation between the priming time and a notional filling time for the system. This approach can help to identify potential problems in large systems that may not be able to fill and prime quickly enough to deal with high-intensity storms of short duration. The approach is also useful in highlighting the importance that the flow capacity of the tailpipes plays in the priming process.

BS EN 12056-3 (2000) requires that roof drainage systems (both siphonic and conventional) should normally be designed to cater for 2-minute duration storm events having a return period (or frequency of occurrence) appropriate to the standard of protection required for the building. This 2-minute event may often be part of a longer storm, which would allow more time for a siphonic system to fill and prime. However, the most critical case would occur if the peak design intensity were to occur at the start of a storm when the pipework is practically empty of water.

Definition of the priming time is not straightforward because storage of water in each component of the system (gutters, tailpipes, collector pipe, downpipe) introduces a time delay in the overall response. Starting from an assumed empty condition, the flow depth in the gutter has to build up before significant flow can enter the outlets. Following that, there will be a further delay while the tailpipes fill; however, due to the small diameter of the tailpipes this is likely to take only a few seconds during heavy storms. The bend and junction fittings in tailpipes will normally enable them to prime rapidly, so within a short time the tailpipes should be acting siphonically and discharging water freely into the horizontal collector pipe. Provided, the flow velocities in the collector pipe are high enough (see Chapter 5), air will be removed from the system while the siphonic outlets act to prevent the entry of new air at roof level. This enables the collector pipe to fill until at a certain stage the flow rate is sufficient for it to run full bore; as mentioned in Section 2.4, this can typically occur when the water to air ratio in the system reaches a value of about 60 : 40. Full-bore flow enables the system to make full use of the available head and respond quickly to changes in the flow rates entering at the outlets. The critical factor is therefore the period required for the filling of the collector pipe and downpipe. Taking account of the normal design storm duration of 2 minutes, it is suggested that this filling time should normally not be greater than 60 seconds.

This description of the priming process is very simplified, but in the absence of suitable experimental data it appears to provide a reasonable basis for evaluating the filling time. The calculation procedure recommended in the draft Standard is based on the following analysis.

(a) Assume that the tailpipes have primed and are flowing 100% full of water and discharging into the collector pipe, initially at atmospheric pressure.

- (b) Calculate the initial flow capacity, Q_T (in L/s), of each tailpipe assuming that it is acting like a miniature siphonic system. Add together the values of Q_T for all the tailpipes in the system to find the total flow rate, Q_{in} (in L/s), entering the collector pipe at the start of the filling stage.
- (c) Let the design capacity of the whole siphonic system when fully primed be Q_D (in L/s). It is assumed that full-bore conditions in the pipework will first occur when the flow rate reaches a value of 0.6 Q_D .
- (d) Let the filling time for the collector pipe and downpipe be T_F (in seconds). At the start of this time, the inflow rate from the tailpipes is Q_{in} but as the collector pipe fills, a suction effect will develop that enables the outlets to draw in more flow.
- (e) At the end of the filling time, the whole system is assumed to be flowing full bore (as an air/water mixture) with an inflow rate to the collector pipe of 0.6 Q_D and an outflow rate from the downstream end of the system also of 0.6 Q_D .
- (f) The total volume of water entering the collector pipe during the filling time can be approximated by $(Q_{in} + 0.6 Q_D) T_F/2$. On the same basis, the total volume of water leaving the system in this time is equal to $0.6 Q_D T_F/2$. The net volume of water stored in the collector pipe and downpipe during this period is therefore $Q_{in} T_F/2$. This will be equal to 0.6Φ , where Φ is the total volume (in litres) of the collector pipe and downpipe from the siphonic system:

$$T_F = \frac{1.2\,\Phi}{Q_{in}}\tag{6.1}$$

As discussed above, it is recommended that the value of the filling time, T_F , for a siphonic system should normally not be greater than 60 seconds. If a longer time cannot be avoided, measures should be taken to ensure that the water which is not able to enter the siphonic system during the design storm can be safely stored in the gutter or roof without risk of flooding or leakage into the building.

7. Minimum allowable pressures

7.1 GENERAL

When a siphonic system is fully primed, the flow within the pipes may generate significant negative (i.e. sub-atmospheric) pressures. The lowest values generally occur near the downstream end of the collector pipe as a result of high flow velocities and the cumulative loss of energy head along the horizontal section of pipe (see Equations (2.1) and (2.2)). After the flow turns downward into the vertical downpipe, the static pressure normally begins to increase because the gain in pressure energy due to the drop in level exceeds the frictional losses in the downpipe. As a general rule, the higher the building and the greater the available head acting on the system, the lower the pressures in the system may potentially become.

According to the Bernoulli equation, there would appear to be no limit below which the static pressure in a siphonic system can fall. In practice, however, the pressure in a liquid cannot normally fall below its vapour pressure because at this limit the liquid will vaporise and form vapour-filled cavities (equivalent to boiling). The vapour pressure increases with temperature, and in the case of water, for example, it has values of 17 mbar at 15°C and 43 mbar at 30°C, measured above vacuum (i.e. absolute zero pressure); these values are equivalent to water heads of 0.17 m and 0.44 m above vacuum, respectively.

In a siphonic system, it is important to consider negative pressures for two reasons. Firstly, if cavities of water vapour form in the flow they can significantly reduce the predicted flow capacity, cause vibrations and noise, and potentially result in serious damage to the pipes (see Section 7.2). Secondly, pipes have considerably lower strengths when subjected to negative pressures than to equivalent positive pressures. This is because negative internal pressures produce compression forces in the pipe walls that are enhanced if the walls deflect asymmetrically. This can lead to a buckling mode of failure, whereas positive pressures produce symmetrical tensile stresses in the pipe walls. Pipe collapse is not a specifically hydraulic issue, but designers of siphonic systems need to ensure that the pipes they use are capable of withstanding the expected negative pressures, including an allowance for turbulent pressure fluctuations that may be imposed on the mean static values (as determined from the Bernoulli equation). In the case of flexible materials like polyethylene, the pipe walls may gradually deflect (i.e. "creep") under load, leading eventually to collapse under even quite small negative pressures. The time/deflection characteristics therefore need to be considered when selecting an appropriate wall thickness for these types of pipe.

7.2 CAVITATION

Cavitation will occur in flowing water when the local or instantaneous static pressure falls to the inception pressure, which is usually slightly below the vapour pressure of the water. Initially, a cloud of tiny cavitation bubbles forms and these will grow in size the longer they are subjected to pressures below the inception pressure. The cavities are carried downstream by the flow and as soon as they enter a region of higher pressure, they will collapse very quickly and violently. The collapse produces noise and, more importantly, very high impact pressures if the cavities are adjacent to solid boundaries. Lesleighter (1983) measured collapse pressures equivalent to 15,000 atmospheres, which explains why cavitation is capable of damaging the very strongest materials. Metals and brittle materials are easily eroded, with the cavitation causing a characteristically pitted surface. Flexible materials such as polyethylene are generally more resistant and tend to suffer surface roughening rather than deep pitting. Damage does not usually occur immediately after the onset of cavitation, but appears to require a certain incubation period; in the case of metals this may be due to the time required to work-harden the surface and remove protective oxide layers. Reviews of available information on cavitation relevant to hydraulic applications are given by May (1987) and Falvey (1990).

Cavitation in fast flowing water usually occurs when the mean ambient pressure is well above vapour pressure. There are two reasons for this.

Firstly, local curvature of the flow, such as occurs in pipe bends and junctions, can reduce the pressure significantly below the average value. A simplified analysis of flow in a bend indicates that the mean static pressure head on the inside of the bend will be lower than on the centreline by an amount, Δh_B (in m), given by:

$$\Delta h_B \approx \left(\frac{d_p}{r}\right) \left(\frac{V^2}{2 g}\right) \tag{7.1}$$

where:

V = mean velocity through bend (in m/s) g = acceleration due to gravity (= 9.81 m/s²)

g = acceleration due to gravity (= 9.81 d_P = internal diameter of pipe (in m)

r = centreline radius of curvature of bend (in m).

As an example, a flow velocity of 6 m/s through a bend with a relative curvature value of $r/d_P = 2$ would produce a pressure head difference between the centreline radius and the inner radius of the bend of about 0.9 m. More sharply radiused bends and higher flow velocities would produce larger local pressure drops.

The second reason why cavitation can occur when the ambient pressure is well above vapour pressure is flow turbulence. Flows in siphonic systems are naturally turbulent, but the intensity of fluctuations in velocity and pressure can be significantly increased by surface irregularities at the walls and by flow separation. Irregularities such as beads or steps at pipe joints, or rapid increases in pipe diameter, create fast-rotating eddies within which the pressures can be much lower than ambient. If these reductions in pressure approach the vapour pressure of the water, cavities will form inside the eddies and be carried downstream to a point where the pressure increases and causes them to collapse. Lopardo *et al* (1985) compared model and prototype data on cavitation in stilling basins, and estimated that cavitation first occurred when the turbulent fluctuations were sufficient to cause the instantaneous pressure to fall to the vapour pressure for more than 0.1% of the time. Fluctuations with such a low frequency of occurrence can have large magnitudes and are the reason why cavitation can still occur when the mean ambient pressure in a flow is well above the value of vapour pressure.

7.3 CAVITATION INDEX

The potential for cavitation to occur in flowing water can be determined from the value of the cavitation index, σ , defined as:



(7.2)

$$\sigma = \frac{2g\left(h - h_{vp}\right)}{V^2}$$

where:

h	=	mean static pressure head at reference point in flow
		(absolute value measured above vacuum)
h_{vp}	=	vapour pressure of the water (in m head of water)
g	=	acceleration due to gravity (= 9.81 m/s^2)
\overline{V}	=	mean velocity at reference point in flow

Measurements of the flow conditions at which cavitation first occurs with different types of joint irregularity or pipe fitting are used to determine limiting values of cavitation index. If the value of σ in Equation (7.2) determined by the flow conditions is less than the limiting value for that particular type of fitting or irregularity, cavitation will occur.

Siphonic systems contain a large number of different pipe fittings, and irregularities at joints can vary according to the type of pipe used and the standard of jointing. Each of these cases will have a different value of cavitation index below which cavitation will occur. It is therefore not possible to specify a particular value of σ that will guarantee the avoidance of cavitation in all possible cases, unless this value were set so high as to render the general use of siphonic systems impractical.

Most experimental studies of cavitation have concentrated on identifying for different flow configurations the limiting values of σ below which cavities will first form (termed the point of incipient cavitation). However, significant damage does not normally occur until the value of σ falls to about 80% of the limit for incipient cavitation. Also, as mentioned in Section 7.1, a certain incubation period is normally necessary before damage actually starts. Therefore, the risk of cavitation directly causing pipe failure in siphonic systems may not be very great except in systems that frequently operate full bore or for extended periods. However, it should be noted that some pipe materials may be more liable to suffer cavitation damage than others (see May (1987) for further details).

A more serious consequence of cavitation in siphonic systems may be the adverse effect it has on the flow conditions. If flow cavitates in a pipe fitting such as a bend, the pressure will be unable to fall as low as would otherwise be the case. Also, the formation of the vapour cavities will cause some restriction of the water flow and thereby increase the local head loss. As a result, cavitation is likely to prevent a siphonic system achieving the maximum design capacity predicted from the Bernoulli equation. In addition, cavitation may produce strong pressure fluctuations that affect the smooth running of the system and reduce the margin of safety of the pipes against collapse.

Typical values of the incipient cavitation index, σ_I , for different types of irregularity or pipe fitting are as follows:

• Sudden step into the flow: $\sigma_{I} = 1.0 - 1.7$ for step heights between 1 mm and 5 mm (Liu, 1983).

- Chamfer facing into flow (with angle of 45° or steeper): $\sigma_I = 2.3$ (Novikova and Semenkov, 1985).
- 90° bends: $\sigma_I = 2.4 4.5$ for pipe diameters between 75 mm and 300 mm (Tullis, 1981); $\sigma_I = 1.1$ for bends with a radius of curvature equal to the internal diameter (Kudriashov *et al*, 1983).

Taking account of this information and of the various other factors discussed above, it is suggested to assume a typical value for incipient cavitation of $\sigma_I = 1.5$, with serious effects not occurring until the cavitation index falls to 80% of this value, which corresponds to a limiting value of $\sigma = 1.2$. Substituting this value in Equation (7.2) gives the following relationship between flow velocity and the minimum allowable value of pressure head, h_{min} (relative to vacuum), in a siphonic system:

$$h_{\min} = 0.061V^2 + h_{\nu p} \tag{7.3}$$

where *h* and h_{vp} are in m head of water and *V* is in m/s.

For a water temperature of 25° C and a flow velocity at the point of minimum pressure not exceeding 6 m/s, Equation (7.3) gives a minimum allowable pressure head of 2.5 m absolute or -7.8 m below standard atmospheric pressure. This is slightly more severe than current industry practice, which is typically based on use of a minimum pressure value between -8 m and -9 m relative to atmospheric pressure.

8. Conclusions

The information contained in this report provides an explanation of the various hydraulic design criteria which are included in a draft document that is proposed for publication as a new British Standard on siphonic roof drainage systems.

Well-established experimental data are not yet available on some of the complex topics covered so in proposing suitable design criteria it has been necessary to use a combination of theory, data from laboratory studies of siphonic systems, information from other relevant branches of hydraulics, and the practical experience gained by manufacturers and designers of siphonic systems from the large number of systems that have been installed worldwide.

The following design criteria for siphonic systems are proposed:

- (a) The minimum value of Colebrook-White pipe roughness for determining the flow capacity of systems should be $k_P = 0.15$ mm.
- (b) A safety factor for siphonic systems should be provided by increasing the design rates of run-off by 10%; these increased rates should also be used for sizing gutters drained by siphonic systems (to allow for possible partial clogging of outlets).
- (c) Systems should be designed so that the residual heads at siphonic outlets are zero or positive. The difference between the largest and smallest residual head in a system should not exceed 1.0 m or 10% of the available head, whichever is the smaller.
- (d) The minimum velocity in tailpipes and horizontal sections of pipe (longer than 1 m) should not be less than 1.0 m/s under design conditions.
- (e) The minimum allowable velocity in vertical downpipes should not be less than 2.2 m/s under design conditions.
- (f) The filling time of a system calculated from Equation (6.1) should not be greater than 60 seconds, unless suitable measures are taken to safely store the excess runoff occurring during the design storm without flooding or leakage.
- (g) Pressures in siphonic systems under design conditions should not be lower than -7.8 m water head below atmospheric pressure provided the flow velocity at the critical point does not exceed 6 m/s. For other conditions or buildings at high altitude, reference should be made to Equation (7.3).

It should be noted that the design criteria proposed in this report may not necessarily be the same as those contained in a published Standard.

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Figure





Minimum flow velocity for air pocket movement in horizontal and downward

sloping pipes (from Lauchlan et al, 2004)

Figure 1





Appendix



Appendix A Membership of Project Steering Group

Membership of Project Steering Group

<u>Chairman</u> Mr Frank Dales	Dales Fabrications Limited
<u>Members</u> Dr Scott Arthur	Dept of Civil and Offshore Engng, Heriot-Watt University
Mr Robin Bowler	Pick Everard
Mr Ian Boyd	Carillion plc (Representing Institute of Plumbing)
Mr Martyn Bramhall	Fullflow Group Limited
Rev Peter Caplin	Association of Building Component Manufacturers Ltd
Mr Peter Caplehorn	Scott Browrigg
Mr Ian Fellingham	Arup Research & Development
Mr Steve Garside	Aquaphonix
Mr Tony Grayson	Sapoflow Limited
Mr Colin McAllister	Ross ADT
Mr John Purser	Dallmer Ltd
Mr Gordon Puzey	Arup Research & Development
Mr Alan Robertson	HBG Design Ltd
Mr Martin Shouler	Building Research Establishment
Mr Peter Snoad	Geberit Ltd
Dr Per Sommerhein	Sommerhein A B
Dr Malcolm Wearing	CRM Rainwater Drainage Consultancy Ltd
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