

# **Modelling low amplitude air pressure transient propagation in building drainage and vent systems to allow system analysis and control.**

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Abstract.

Low amplitude air pressure transients propagate as a result of any appliance discharge within a building drainage and vent system. The resulting transient pressures may be sufficient to deplete appliance trap seals and provide a cross contamination route into habitable space. These effects may be modelled through the use of established mathematical methods drawn from the wider field of pressure surge control and suppression. This paper will demonstrate the application of these modelling techniques, based on the Method of Characteristics, to local Active Control to minimise the effect of transients on appliance trap seals and as a means of assessing the most appropriate control strategy. The effect of both negative air pressure transients, generated by increases in system water flows, and positive air pressure transients, generated by surcharge events, will be demonstrated, together with the effect of introducing passive venting solutions and / or active solutions based around the use of Air Admittance Valves and flexible containment chambers to minimise positive transients. Historic links to surge control will demonstrate that low amplitude air pressure transients obey the rules of surge propagation, dependent upon the rate of change of flow conditions and the characteristic reflection and transmission properties of system terminations and junctions.

Keywords: transient propagation, vent systems, cross infection, defect identification.

## **1. Transient propagation.**

The prevention of cross contamination via depleted trap seals has been a design consideration over the past 100 years. The invention of the water seal trap in the 18<sup>th</sup> Century - a 'U 'bend' immediately downstream of the appliance with a water depth of 50 - 75 mm - has remained the most effective barrier to sewer gasses. Traps respond to

network pressure so system failure involving cross infection may follow the depletion of trap seals by air pressure transient propagation. Modern design, water conservation and the need to economise demands a re-evaluation of drainage design that recognises the unsteady nature of system flows and the effects of pressure transient propagation. Demands on urban living space that increase system loading due to occupation levels in excess of those envisaged at the design stage, will compromise drainage operation. Pressure transient propagation leading to system failure is associated with destructive forces in complex fluid systems. While the definition of failure is system dependent, the underlying principles of surge propagation, suppression and control remain constant. Transient propagation communicates flow demand - negative transients demand an increase in flow while positive transients reduce flow and increase pressure.

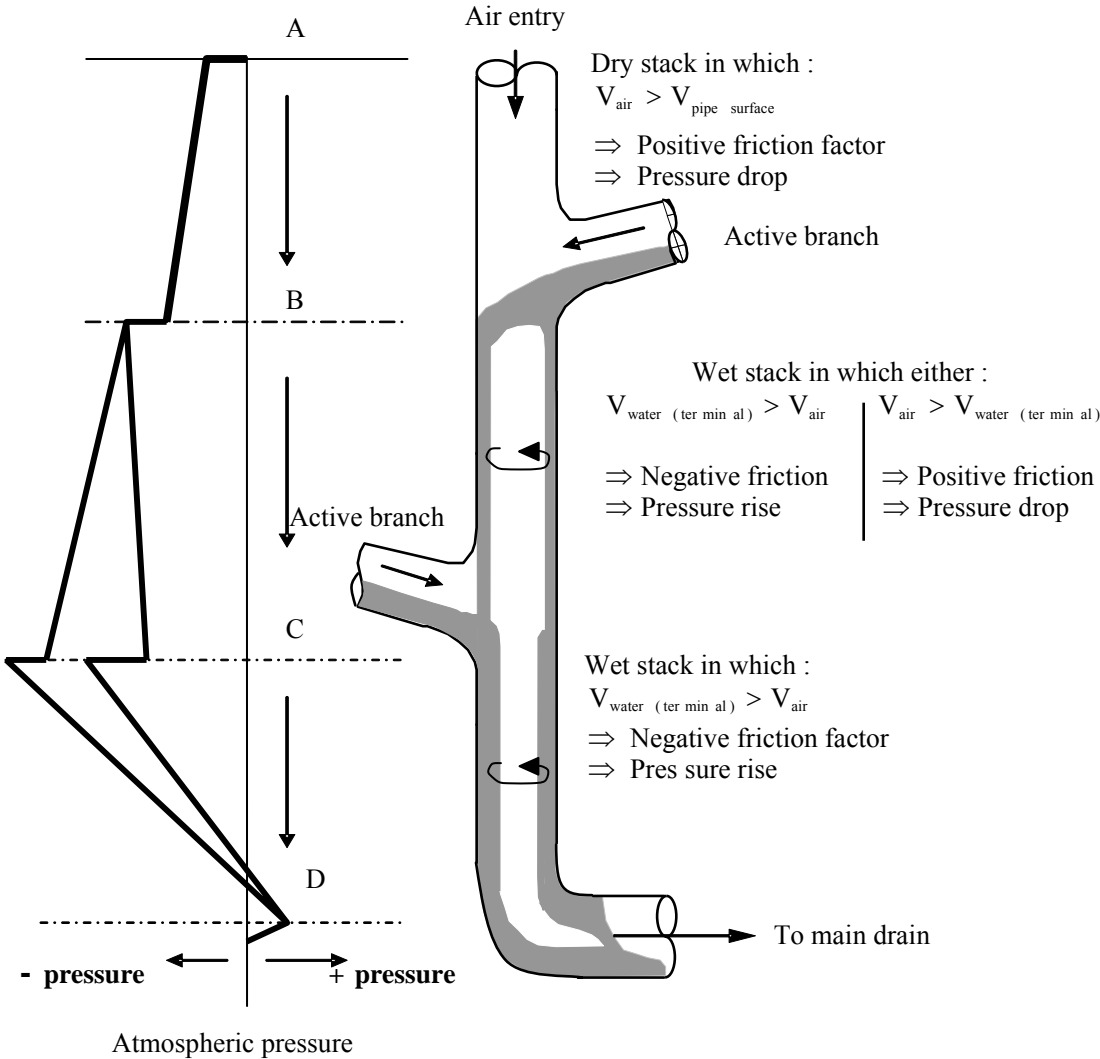
Figure 1 illustrates a single stack conveying appliance discharges as annular water flow, of 6-10 mm thick in stacks up to 150 mm diameter that reaches terminal velocity based on flowrate, stack diameter and roughness, within two floors and entrains air that enters via the open stack termination, generates a frictional pressure drop in the dry stack and pressure losses at discharging branch to stack junction airpath occlusion. Shear forces between the annular water and the air core, due to 'no-slip', generates an entrained airflow. If this airflow exceeds that appropriate to the shear force in any section of the stack the air pressure reduces as the air is drawn past the water film. At stack base the transition to free surface flow generates a water curtain, resulting in the generation of a 'back' or positive pressure. This overall mechanism depends on water flow and network parameters, increasing stack diameter decreases entrained airflow velocity; sweeping the stack base decreases back pressure; sweeping branch entry to the stack reduces airpath occlusion. Negative stack pressure draws trap seal into the system while positive pressure may lead to 'bubble through' from the system to habitable space.

This appreciation of system operation, developed in the UK at BRE and in the US at NBS, was empirical and exclusively steady state, Applications of fluid mechanics analysis in the 1950s, (Lillywhite and Wise 1969), was limited to steady state and remained so until the advent of computer based simulation. Appliance discharges are time dependent and random so the water downflow displays temporal and spatial unsteadiness. Flow conditions also depend on external pressure perturbations from the remainder of the building, the downstream sewer network and wind shear over roof level terminations. While the complex nature of these flow conditions was recognised, the lack of an accessible theoretical basis for design led to 'rule of thumb' practices that ignore the fact that the laws of physics transcend national frontiers.

Drainage systems display classic unsteady flow, variously described as pressure surge or waterhammer. Joukowsky (1900) investigating waterhammer in the St Petersburg Water Works, laid the foundations of modern transient theory, identifying the importance of wave speed and the reflection and transmission of transients at system boundaries that applies to the air pressure transients propagated in building drainage systems due to sudden increases in annular water downflow or reductions in entrained airflow that travel throughout the system. Joukowsky's fundamental relationship

$$\Delta p = - \rho c \Delta u \tag{1}$$

indicates that an increase in airflow of 1 m/s would generate a -40 mm water gauge transient when air density and an acoustic velocity of 320m/s are system characteristics. Equation 1 introduces the first rule of surge protection – reduce the rate of change of the flow velocity.



**Figure 1 - Water and entrained airflows in a drainage vertical stack, illustrating the possible pressure regime established under steady flow conditions. Note concentrated losses at A, B and C and the ‘back pressure’ at D, the sewer entry.**

Interruptions to the airpath may occur at the base of the stack, or at offsets, if a rapidly increasing annular water downflow causes local surcharging. A ‘severe’ positive transient could force air through the appliance trap seal – ‘bubble through’- or displace the trap seal water upwards leaving the trap wholly or partially depleted. Where the

positive pressure displaces the trap seal sufficiently to allow air bubbles to pass through to the appliance, trap seal depletion may occur on cessation of the positive pressure as the trap seal water is allowed to flow into the trap. Once generated a transient will continue to propagate throughout the network displacing every trap seal it encounters until relieved. This introduces the second rule of surge protection – position the relief device between the source of the transient and the item to be protected.

## 2. Mathematical basis for a vent system simulation.

Network air pressure transients depend on the rate of change of water flow and interrupted airflow. Air pressure transient propagation belongs to a family of unsteady flow conditions described by the St Venant equations of continuity and momentum solvable via the Method of Characteristics, introduced in the 1960s, (Lister 1960, Streeter and Wylie 1967). Jack (2000) introduced a ‘pseudo-friction factor’ model of the annular water to entrained air core interface that drives the simulation of combined discharge flows and air entrainment. This analysis includes the case of airflow entrained by high water flows in the lower levels of the wet stack exceeding that appropriate to the water flow in the upper levels. This allows the modelling of increasing pressure in the lower levels and decreasing pressure further up the stack as the air is drawn past the slower moving upper level water film that impedes its passage.

The St Venant equations link mean airflow velocity and wave speed as air pressure and density are interdependent. These quasi-linear hyperbolic partial differential equations are transformed via the Method of Characteristics into finite difference relationships, equations 2 to 5, linking conditions at a node one time step in the future to current conditions at adjacent upstream and downstream nodes, Figure 2.

$$\text{For the } C^+ \text{ characteristic : } u_p - u_R + \frac{2}{\gamma - 1}(c_p - c_R) + 4f_R u_R |u_R| \frac{\Delta t}{2D} = 0 \quad (2)$$

$$\text{when } \frac{dx}{dt} = u + c \quad (3)$$

$$\text{and the } C^- \text{ characteristic : } u_p - u_S - \frac{2}{\gamma - 1}(c_p - c_S) + 4f_S u_S |u_S| \frac{\Delta t}{2D} = 0 \quad (4)$$

$$\text{when } \frac{dx}{dt} = u - c \quad (5)$$

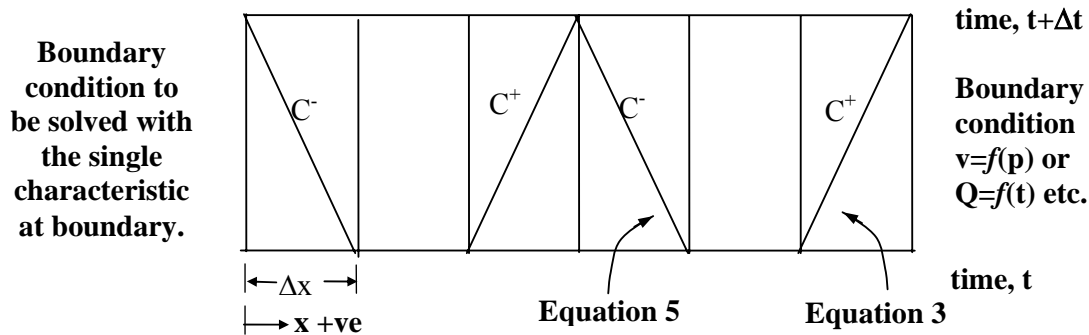
$$\text{where the wave speed } c \text{ is given by } c = (\gamma p / \rho)^{0.5} \quad (6)$$

$$\text{and local pressure is calculated as } p_{\text{local}} = [ (p_{\text{atm}} / \rho_{\text{atm}}) (\gamma / c_{\text{local}}^2)^{\gamma} ]^{1/(1-\gamma)} \quad (7)$$

Time step and internodal distance are governed by the Courant Criterion, defined as  $\Delta t < \Delta x / (u + c)$ . In the dry stack  $f_R$  and  $f_S$  are determined from Colebrook White. In the wet stack they are functions of time, location and annular water downflow and drive the simulation by generating the entrained air flow, Jack (2000).

Only one characteristic exists at each boundary so an additional equation is required at each pipe termination, e.g. airflow vs. pressure for AAVs, constant pressure for open

terminations, zero velocity at dead ends, a combination of these for PAPA<sup>TM</sup>s, partial reflection and transmission coefficients at pipe junctions or the momentum equation describing trap seal motion. An unique feature is the pseudo friction factor that drives the entrained airflow condition, effectively a distributed boundary condition with variable friction factor values at each node. Boundary conditions may be active or passive - pressure relief by vent connection to atmosphere is a passive boundary while active boundaries include AAVs, where inflow depends on local pressure differentials, or variable containment volumes that open in response to local positive pressure.



**Figure 2 - St Venant equations of continuity and momentum allow airflow velocity and wave speed to be predicted on an  $x-t$  grid. Note  $\Delta x < 1.0$  m,  $\Delta t < 0.003$ s.**

### **3. Air pressure transient control and suppression – traditional ‘passive’ venting.**

While the propagation of low amplitude air pressure transients is a natural and unavoidable consequence of appliance discharge to a building drainage system, the protection of appliance trap seals is dependent on the control and suppression designed into the system. From the late 19<sup>th</sup> century, this control and suppression depended upon fixed venting running parallel to the wet stacks. The earliest ‘two pipe’ systems separated foul from general waste flows with each appliance independently vented. In the 1930s the ‘one pipe’ system discharged all appliances to a common wet stack but again separately vented appliances. In the 1970s the UK introduced a ‘single stack’ system that dispensed with separate vents although above 30 floors a parallel vents stack cross connected into the wet stack was introduced. All these designs featured vent stacks smaller in diameter than the wet stack and all represent ‘passive’ control and suppression as there is no interaction between the control mechanism, the fixed in place vent, and the transient. Two basic rules of surge suppression have been identified –

1. Transients may be attenuated by reducing the rate of change of flow velocity. This follows from equation 1 and implies that flow should be diverted in the case of a positive transient or, in the case of a negative transient added through an adjacent inlet.
2. The second basic rule is that the surge alleviation should be positioned between the source of the transient and the equipment to be protected.

While the fixed in place vent solution provide a degree of flow diversion or addition, criteria 1 above, its efficiency in this role is limited by fundamental misunderstandings of the operating mechanism of the vent stack currently embedded in the codes.

Fixed in place vents do not meet the second criteria in any way. The source of any relief to offset the pressure regime imposed on the system by the passage of the transient is the reflection of the transient at the upper open termination of the vent system. Thus the potentially trap seal depleting transient has already passed all the traps to be protected before any relieving reflection can be generated by the open termination. The pressure transient transmission and reflection coefficients at junctions may be determined from the following expressions (Swaffield and Boldy 1993)

$$C_{\text{Transmission}} = \frac{2 \frac{A_1}{c_1}}{\frac{A_1}{c_1} + \frac{A_2}{c_2} + \frac{A_3}{c_3}} = \frac{2}{1 + \frac{A_2}{A_1} + \frac{A_3}{A_1}} = \frac{2}{1 + \frac{A_{\text{Branch}}}{A_{\text{Incoming}}} + \frac{A_{\text{Continuation}}}{A_{\text{Incoming}}}} \quad (8)$$

$$C_{\text{Reflection}} = \frac{\frac{A_1}{c_1} - \frac{A_2}{c_2} - \frac{A_3}{c_3}}{\frac{A_1}{c_1} + \frac{A_2}{c_2} + \frac{A_3}{c_3}} = \frac{1 - \frac{A_2}{A_1} - \frac{A_3}{A_1}}{1 + \frac{A_2}{A_1} + \frac{A_3}{A_1}} = \frac{1 - \frac{A_{\text{Branch}}}{A_{\text{Incoming}}} - \frac{A_{\text{Continuation}}}{A_{\text{Incoming}}}}{1 + \frac{A_{\text{Branch}}}{A_{\text{Incoming}}} + \frac{A_{\text{Continuation}}}{A_{\text{Incoming}}}} \quad (9)$$

It will be seen from equations 8 and 9 that the wave speed in each pipe or duct is included in the coefficient determination, however in the case of low amplitude air pressure transient propagation in building drainage and vent systems the pipework may be taken as rigid and the wave speed in air as constant, simplifying the equations.

Similarly it will be seen that the transmission and reflection coefficients depend upon the identification of the pipe carrying the incoming transient. The junction will present different coefficients for transients arriving along the branch or the continuation pipe. Thus equations 8 and 9 have been re-cast in terms of the pipe carrying the incoming transient (pipe 1 in Figure 3), the branch (pipe 2 in Figure 3) and the continuation pipe (pipe 3 in Figure 3) as this will make calculation of the coefficients easier.

The transmission coefficient at a junction of three equal diameter pipes is 66% of the incoming wave, Figure 4. A -33% reflection of the incoming is also generated. If the branch vent, Pipe 2 in Figure 3, is reduced in diameter then the transmitted wave strength increases – e.g. if the vent is half wet stack diameter then the transmitted wave is increased to 90% of the incoming wave. This offers no reduction in the transient propagating up the wet stack. If the vent has a greater diameter than the wet stack then the vent system starts to have an influence on the transient propagated up the building, e.g. if the vent stack is double the wet stack diameter then the transmission reduces to 33%. Note that the diameter of the cross vent, Figure 3, is as important as the vent diameter in restricting wave attenuation.

All national plumbing suggest equal or smaller diameter vent stacks compared to the wet stack, hence there is a fundamental misunderstanding of the mechanism of surge protection embedded in the design codes.

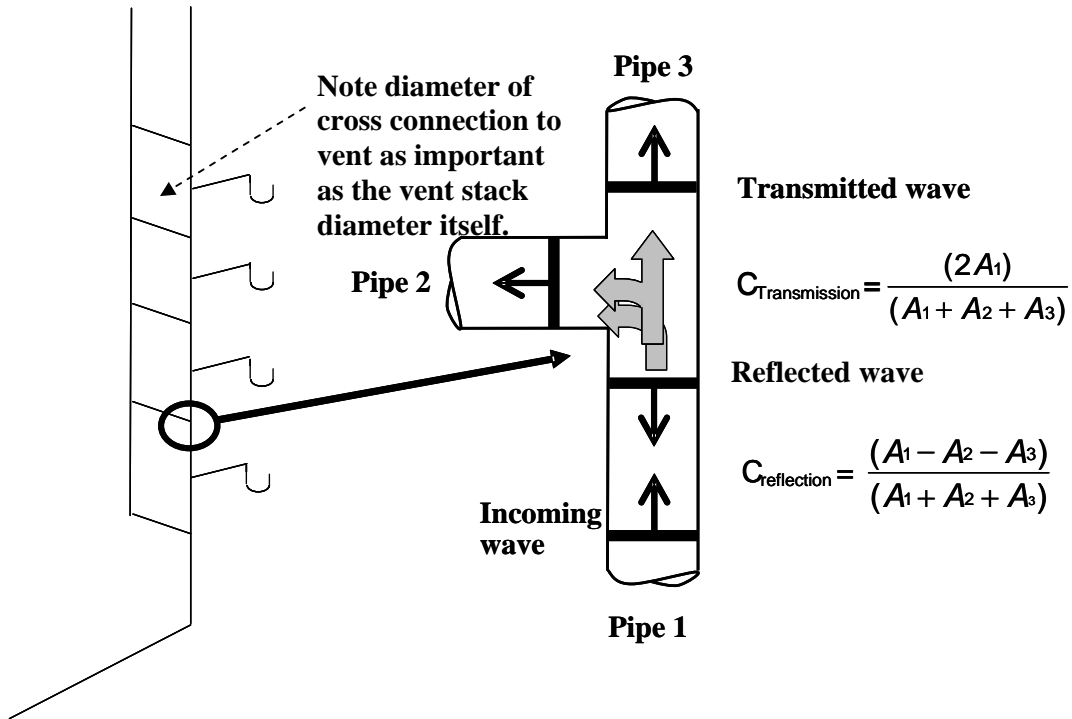


Figure 3 – transmission and reflection of a transient at a three pipe junction.

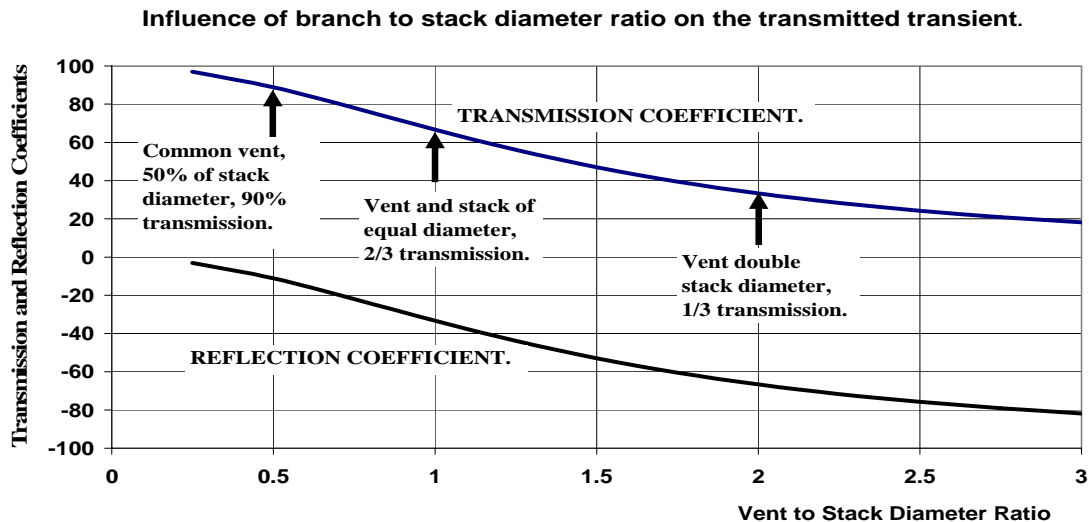
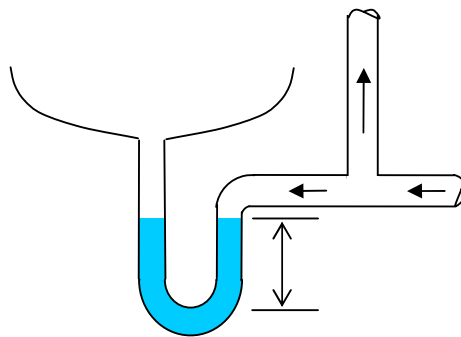


Figure 4 – The transmission and reflection coefficients at a three pipe junction depend upon the relative area ratios of the joining pipes. Figure 3 illustrates the necessary equations defining these coefficients.

It is the ratio of the pipe cross sectional areas that determines the coefficients rather than actual pipe diameters. If the traditional passive venting of individual traps back to the vent stack is considered, Figure 5, then it will be appreciated that a small diameter vent connected into the trap branch will have little effect.



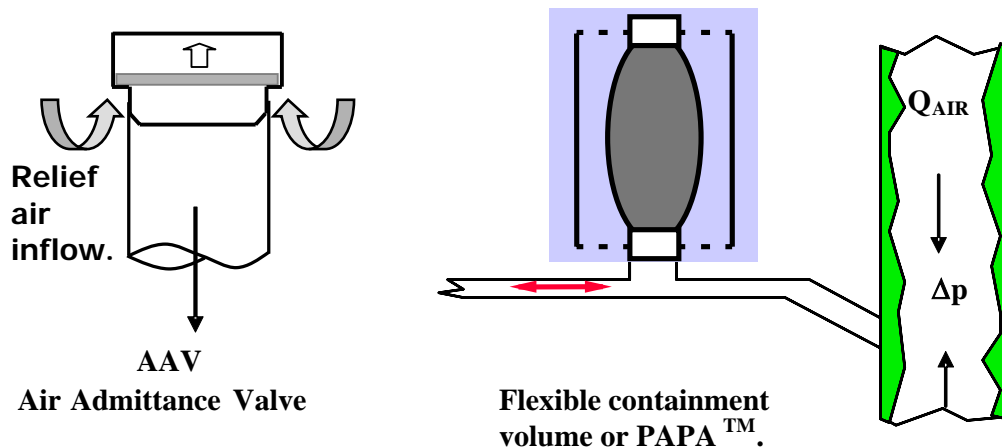
**Diversion of incoming transient depends on area ratio of the vent pipe cross sectional area to that of the trap branch.**

**To be effective in reducing pressure applied to the trap seal the vent should be greater in cross section than the branch.**

**Figure 5 – Passive vent connections applied locally to protect trap seals also require a larger vent diameter to be effective.**

#### **4. Air pressure transient control and suppression – active control.**

The need to minimize external pipework and the advent of taller buildings led to the introduction of the single stack system in the 1970s. Further reductions from the mid 1980s introduced Air Admittance Valves installed within the habitable space to allow inwards air pressure relief. Active transient control extends this approach to include both positive and negative transient suppression to provide trap seal retention and prevent cross contamination of habitable space. Figure 6 illustrates an air admittance valve, AAV, and the positive air pressure attenuator, PAPA™ or flexible containment



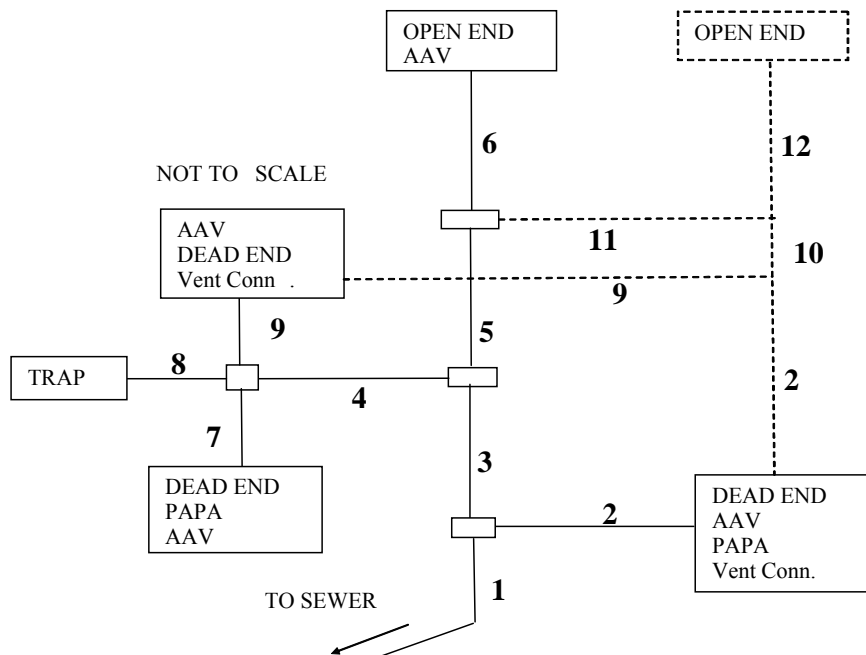
**Figure 6 - Active air pressure transient suppression devices to control both positive and negative surges.**

volume, capable of absorbing transients until pressurized. The principle of operation of the AAV is to open whenever the local air pressure falls below a predetermined level in the local network allowing an air inflow that does not require the transient to travel the whole height of the building to the first roof line open termination

The PAPA™ allows entrained airflow to be diverted into the containment volume and reduces the rate of airflow deceleration by providing a diversion path. The pressure rise associated with the flow stoppage (Swaffield et al 2005) is therefore reduced. Thus it may be appreciated that Active control and suppression meets both the criteria.

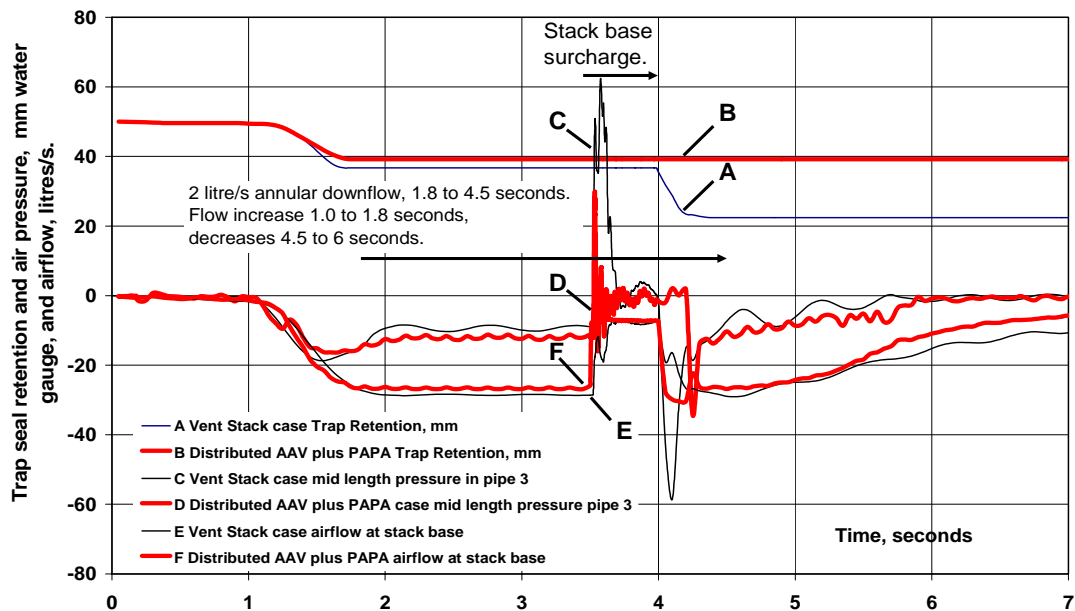
### 5. Evaluation of Active and Passive control and suppression strategies for a simulated network.

Figure 7 illustrates a network that will allow the direct comparison of several design solutions - All stacks and branches 100 mm diameter, the trap is a 50 mm seal and the vent stack is initially 80 mm diameter. Interfloor height is 5 m. The applied water flow is a 2 litre/s flow with a 0.8 rise time from 1.0 seconds. This trial will impose a negative transient on the network and will test the ability of the Active control AAV installation compared to various Passive venting solutions with differing vent stack diameters. The base of the stack is surcharged from 3.5 to 4.0 seconds to impose a positive air pressure transient onto the network to test the ability of the Active control PAPA™ installation compared to various Passive venting solutions with differing vent stack diameters.



**Figure 7 – a drainage and vent system to allow the evaluation of the relative performance of an Active or Passive transient control and suppression strategy.**

Thus this single simulation includes both the possibility of induced siphonage and trap seal loss following a system surcharge dependent on system characteristics. Figure 8 illustrates the system operational conditions for two design cases, namely an Active Control application including distributed AAVs and a PAPA™ at pipe 2 and a traditional scheme using an 80 mm diameter parallel vent. Trap seal water is lost as the imposition of the annular water downflow generates negative stack air pressure. Seal loss is dependent on the waterflow acceleration – 2.5 litre/s<sup>2</sup> is a challenging criteria. Stack base surcharge results in a positive transient propagation, however the inclusion of the PAPA™ Active Control device prevents any additional trap seal loss. The parallel vent system does not control the positive transient and a secondary trap seal loss is experienced. Air pressure values in pipe 3 indicate that Active Control was more efficient at reducing the propagated positive transient following stack base surcharge



**Figure 8 - Active Control through AAV and PAPA™ units compared to a standard parallel vent system.**

Table 1 compares trap seal retention and peak pressure following surcharge for all cases. Active Control results in improved trap seal retention. Introducing AAVs alone reduces the positive transients experienced as the airflow into the network is reduced and so the stack base surcharge acts on a lower entrained airflow, generating a weaker transient. Table 1 indicates that for a parallel vent system to have a similar performance, the vent diameter would have to be twice that of the wet stack diameter at 200 mm, a result justified by the transient transmission relationship for junctions.

Reducing vent diameter increases the transmission coefficient and reduces attenuation. A 200 mm vent stack diameter reduces the transmission coefficient to 0.33 and allows greater diversion of the airflow that would have been brought to rest by the surcharge,

thus conforming to the concept of surge protection already discussed – a similar but less efficient mechanism to that used by the PAPA™ (Swaffield et al 2005).

Network description, Figure 4	Trap seal retention	Trap seal retention	Maximum pressure
	mm water gauge. at 3.5 seconds.	mm water gauge. at 7.0 seconds.	mm water gauge. mid length pipe 3
Parallel Vent Stack, 200 mm dia. with 100 mm dia. cross vents.	45.68	41.25	16.85
Single Stack, Distributed AAV pipes 6, 7, 9, 3, PAPA pipe 2.	39.20	39.20	28.16
Parallel Vent Stack, 200 mm dia. with 50 mm dia. cross vents.	41.82	36.38	22.18
Single Stack, AAV pipe 7 and 9, PAPA pipe 2.	35.08	35.08	18.90
Single Stack, AAV pipe 7 and 9, PAPA pipes 2 and 7.	34.48	34.34	18.39
Single Stack, AAV pipe 9, PAPA pipe 2.	33.49	31.12	20.90
Single Stack, AAV pipe 9, PAPA pipe 2 and 7.	33.54	30.67	18.13
Single Stack, Distributed AAV pipes 6, 7, 9, 2.	39.74	26.74	51.70
Parallel Vent Stack, 80 mm dia. with 50 mm dia. cross vents.	36.70	22.44	62.40
Single Stack, AAV pipe 7 and 9 no PAPA.	35.08	17.44	48.41
Single Stack, PAPA on pipe 2.	28.07	13.32	20.83
Single Stack, AAV on pipe 9.	34.00	12.82	55.94
Single stack, no AAV, PAPA or paralel vent.	27.80	1.58	62.43

**Table 1 - Comparative system performance for various levels of Active Control and parallel vent sizing.**

The modelling capability provided by the Method of Characteristics and the application of pressure surge analysis to building drainage and vent systems presents an opportunity to re-evaluate drainage design to reduce both complexity and labour and equipment costs while providing effective protection against cross contamination via the depletion of trap seals.

## 6. Conclusions.

Building drainage and vent system design relies on codes that in the main have been developed from practice ‘rules of thumb’ or steady state experimental research, much now dated or, as demonstrated by this paper, based on a fundamental misunderstanding of the mechanisms of transient control and suppression based on passive, fixed in place, vent networks – the traditional basis of system venting. There is a need to re-evaluate the design of these networks against current criteria, including water conservation, an escalation in building complexity, increased occupation levels, enhanced concerns as to cross contamination and ever increasing building height. Reliance on codes is no longer sufficient. There is a need to move drainage design into the same arena as other building services system design where validated simulation techniques provide a background to allow designers and consultants to deal with applications that lie outside the specific range of cases dealt with in codes. The Method of Characteristics driven simulations presented in this paper, along with the Active Control design opportunities, provide a basis for this re-evaluation that rests on extensive research as well as drawing on over a century of analysis and practice in the area of pressure surge theory. It is hoped that this paper will encourage the drainage design community to undertake this re-evaluation.

## 7. References.

- Jack, L.B., (2000), Developments in the definition of fluid traction forces within building drainage vent systems, *BSER &T*, Vol. 21, No 4, pp 266 - 273.
- Joukowsky, N., (1900), Uber den hydraulischer Stoss in Wasserleitungsrohen, Memoirs de l'Academie Imperiale des Sciences de St Petersburg, translated by Simin O., *Proceedings American Water Works Assoc.*, Vol 24 pp341-424, 1904.
- Lillywhite, M.S.T. and Wise, A.F.E. (1969), Towards a general method for the design of drainage systems in large buildings. *Journal IPHE.*, Vol. 68, No. 4: p. 239-270.
- Lister, M., (1960) 'Numerical Simulation of hyperbolic partial differential equations by the Method of Characteristics', *In: Ralston, A., and Wilf, H.S., Numerical Methods for Digital Computers*, J. Wiley, New York: p. 165-179.
- Streeter, V.L. and Wylie, E.B., (1967), *Hydraulic Transients*, McGraw-Hill, New York,
- Swaffield J.A. and Boldy A.P. (1993) 'Pressure surge in pipe and duct systems', Avebury Technical, Gower Publishing, p358.
- Swaffield, J.A., Campbell, D.P. and Gormley, M., (2005), 'Pressure Transient control Part II: - simulation and design of a positive surge protection device for building drainage networks', *BSER&T*, 26.3, p. 195-213.

## 8. Nomenclature.

A	Pipe cross section, m <sup>2</sup> .	C <sup>+</sup>	Characteristic equations.
c	Wave speed, m/s.	f	Friction factor
p	Air pressure, N/m <sup>2</sup>	Q	Air/water flowrate, m <sup>3</sup> /s.
t	Time, seconds.	u	Mean air velocity m/s.
V	Stack water, air velocity m/s.	x	Distance, m.
γ	Ratio specific heats.	μ	Viscosity kg/ms.
Δp	Pressure change, N/m <sup>2</sup>	Δt	Time step, s.
Δu	Velocity change, m/s.	Δx	Internodal length, m.
ρ	Density, kg/m <sup>3</sup>	atm	Atmospheric pressure
R,S,P	Nodal points.	t+Δt,t	Conditions at node at a time.



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