



*Drainage
Research
Group*

Building Drainage Waste and Vent systems: Options for efficient pressure control

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Summary

There are few real mysteries remaining about the mechanisms at play in building drainage and vent systems. This has been well understood from the beginning of modern sanitary engineering at the end of the 19th Century. The description of Building drainage and vent system operation is best understood in the context of engineering science in general and fluid mechanics in particular.

Early researchers in the field were well aware of this and many examples of the application of sound fluid mechanics are available as evidence. Much research has been carried out since the end of the World War II, where, particularly in Europe, extensive reconstruction work prompted the quest for more efficient approaches to drainage and vent system design.

At the center of the system's integrity is the water trap seal, which stops foul air from entering a habitable space from the sewer. The water trap seal is usually 1½ or 2 inches in depth depending on the fixture it is protecting.

It comes as a surprise to many that the flow of air is as important, if not more important, than the flow of water, to the safe operation of the drainage system. This air flow is 'induced' or 'entrained' by the flow of water. The unsteady nature of the water flows causes pressure fluctuations (known as pressure transients) which can compromise water trap seals and provide a path for sewer gases into the habitable space.

Transients can be dealt with by a combination of careful design and the introduction of pressure relief devices as close to the area of concern as possible. Long vent pipes can be an inefficient way of providing relief due to friction in the pipe. Distributing air supply inlets using AAVs around a building provides an efficient means of venting and it reduces the risk of positive transient generation. AAVs do not cause positive pressure transients, they merely respond to them by closing, and hence reflect a reduced amplitude wave.

In tall buildings parallel vent pipes can only provide a small relief path for a positive pressure transient (approx 1/3 if the vent pipe is the same diameter as the main vertical stack) thus a wave will still propagate throughout the rest of the system that could compromise water trap seals. The introduction of a positive air pressure transient alleviation device provides a means to ‘blow off’ pressure surges as close to their source, thereby protecting water traps. Attenuation of up to 90% of the incident wave can be achieved, thus protecting the entire system. There is little that can be done for a system experiencing a total blockage, generating excessive static positive pressures in the drainage system. In such circumstances the lowest water trap seal will ‘blow’ providing relief for the whole system. This will occur regardless of the method of venting employed.

In validated test simulations air admittance valves (AAVs) have been shown to provide as least as good protection for water trap seals as a fully vented system, and in tall buildings in some circumstances, even better. The fully engineered designed active control system utilizing AAVs for negative pressure relief and Positive Air Pressure Transient Attenuators (PAPAs) for positive transient relief is shown to be an effective method for balancing the need for safety and efficiency while maintaining functionality invisible to the user.

1. Introduction

1.1 A historical perspective.

To most people the building drainage system lurking beneath their pristine ceramic and stainless steel appliances presents a mystery beyond their usual 'need to know'. How their sink full of soapy water gets from their newly refurbished kitchen island to the municipal treatment plant is of little or no interest, and likewise, few people ponder the similar journey from the WC, bath or bidet in the bathroom; until that is, they are suddenly faced with a foul smell from 'somewhere down there' or are met by a filling WC bowl which keeps on filling and pours onto the new floor covering. The mystery surrounding the drainage system suddenly deepens on the presentation of an unfeasibly costly repair bill.

In truth there are few mysteries about the operation of a building drainage system. The underlying principles governing the flows of all fluids (water and air) have been well described and indeed applied to the building drainage system for both design (making the system work) and forensic analysis (finding out why it didn't work) for many years. It is worth remembering that while humans have many cultural taboos surrounding the bathroom, which have contributed to the myths surrounding the drainage system, there is a strong scientific basis for the movement of waste by means of water which has a long tradition, going back thousands of years. However our concern is with modern systems and therefore developments over the last 120 - 150 years are relevant.

The age in which the innovation of safe and practical building drainage and plumbing were at the cutting edge of technology was in the late 19th Century. Many of the important factors of maintaining the system's integrity by preventing sewer gases from entering living spaces, the water trap seal and system venting, had already been introduced and much work on improving the system's response to the inevitable pressure fluctuations encountered in a fluid transport system were well under way. This work was initially carried out by Scientists and notable Engineers of the time. In the U.K. the water trap seal was invented by Cummings as early as 1775⁽¹⁾. Cummings was an Engineer and a watchmaker and resurrected the idea of a flushing

WC originally invented by Harrington in the 17th Century. While much of the parts of the system had been around for some time it wasn't until the mid 19th Century that any impetus existed to sort out the poor sanitary conditions in large towns and cities. In 1842 Edwin Chadwick, an English civil servant, published his '*Report into the Sanitary Conditions of the Labouring Population of Great Britain*'. This report initiated a process of reform which prompted investment in sanitation as a public health priority in the slum conditions created by the rapid expansion of British cities as a result of the Industrial Revolution. Such was the importance of sanitation at the time that even the eminent Scientist/Engineer, Osborne Reynolds, whose work on turbulent flow was seminal and still considered central to any discussion of fluid dynamics today, was moved to write a paper on 'Sewer Gas and How to Keep it Out of the House' ⁽²⁾, which dealt with sanitation in the slums of Manchester, England in the late 19th Century.

While this work was continuing in Europe, in the United States, Architects, Scientists and Engineers were facing their own growth problems as immigration from Europe and rapid economic expansion provided the driver for a building boom. Work (reported by) a notable Engineer, George Waring in his book '*How to drain a house, practical information for householders*',⁽³⁾ highlights the depth of knowledge available at the time.

While some of Waring's approaches are outdated, his writings did show that he had a firm grasp of the link between what was going on in the drain and its relation to fluid mechanics. The following extract illustrates this well;

“Efficiency [of the vent system] is due entirely to the admission of air fast enough to supply the demand for air to fill the vacuum caused by water flowing through some portion of the pipe beyond the trap, it is not only a question of having an opening large enough to admit air, but of having an adequate current led freely to the opening.....A one inch pipe, for example may admit air fast enough, while a longer pipe of same diameter, or a smaller pipe of the same length would not do so”

Waring, 1895 pp 101-102

What Waring is suggesting here is the importance of pipe friction and the necessity to analyze the problem in a time – dependent and dynamic way. This is a crucial point and one which has driven much of the computer based systems modeling carried out in the past 30 years. Building drains carry unsteady flows which mean that they are rapidly changing and cannot be analyzed using simple calculations based on steady, unchanging flows, which are often used for the slower moving public sewer networks.

A contemporary of Waring, the Boston Architect J. Pickering Putnam went further in his 1911 book '*Plumbing and household sanitation*'⁽⁴⁾ in which he doubts the necessity for any venting on properly designed systems with anti-siphon traps – he even suggests the use of mechanical air vents in close proximity to water traps in order to overcome siphonage problems^(4,p169). Putnam's conclusions followed years of experimentation on water trap seals and venting arrangements based on sound fluid mechanics principles. The point raised by Waring above was further promoted by Putnam following a series of experiments on pipe friction carried out by the *Massachusetts Institute of Technology (MIT)*^(4,p254). Putnam's 718 page book concludes with a paper delivered to the 44th annual convention of the American Institute of Architects in San Francisco, Jan 18, 1911, entitled '*Better Plumbing at half the Cost*' in which he suggests a single pipe system for multi-storey buildings based on an economic argument and the years of experimentation and experience of the author.

This work on the single pipe system was further investigated in the U.K by the Building Research Station in the 20 years or so following World War II. Again, the driver was a rapid expansion in building projects as the war torn country was rebuilt. Work published by Wise in 1957⁽⁵⁾ concluded that the single pipe system (known as the single stack system in the U.K.) was a robust, safe and economical option and that, if properly designed, building drainage systems do not require every trap to be vented.

Against this historical background this report will explain some of the long established principles of the operation of building drainage waste and vent systems, and will illustrate options for effective venting using the modern method of computer

based simulation to represent and predict the rapidly varying flows found in building drains.

1.2 Water in building drains

When a WC is flushed or a bath or lavatory is emptied, the water flows in the horizontal part of the drainage system and carries with it solids from the WC or, perhaps solids which had deposited in the pipe from a previous flush. When this water reaches a vertical stack pipe, it pours in, in a curved fashion until it strikes the back wall of the vertical pipe.⁽⁶⁾ The water

then swirls around the inner surface and falls down the pipe, under gravity, clinging to the pipe wall, this is called annular water flow (see figure 1). The water film on the inner surface of the pipe is surprisingly thin, even at high flow



rates producing little more than $\frac{1}{4}$ inch film thickness. The solids fall, under gravity, in the core of the pipe.

Figure 1 Water discharging from a branch
Heriot-Watt University

1.3 Air in building drains

While most people are aware of the presence of water in a building drain, because this is what the user is trying to get out of their house or office, few are aware of the important role played by air in the system. Of these two important fluids (air and water) it is the regulation and control of the air flow which poses the greatest challenge for designers, installers and code authorities alike. The whole process isn't helped by the general lack of understanding surrounding the subject. So, how does air come to play a role at all in the building drain.

When water starts to flow in a pipe, as described above, air is entrained along with it. This phenomenon is more marked when water falls down the vertical drainage pipe, where air is drawn down from the upper termination.⁽⁷⁾ This is due to the shear between the water and the air which acts to produce an airflow. The air pressure,

which is assumed to be atmospheric at the upper termination (where the air comes from) is subject to 'losses' on the way down the pipe. These losses can be due to separation (at the termination itself), friction (in the dry part of the pipe) or simple pressure drop across a branch to stack junction when water is pouring in.

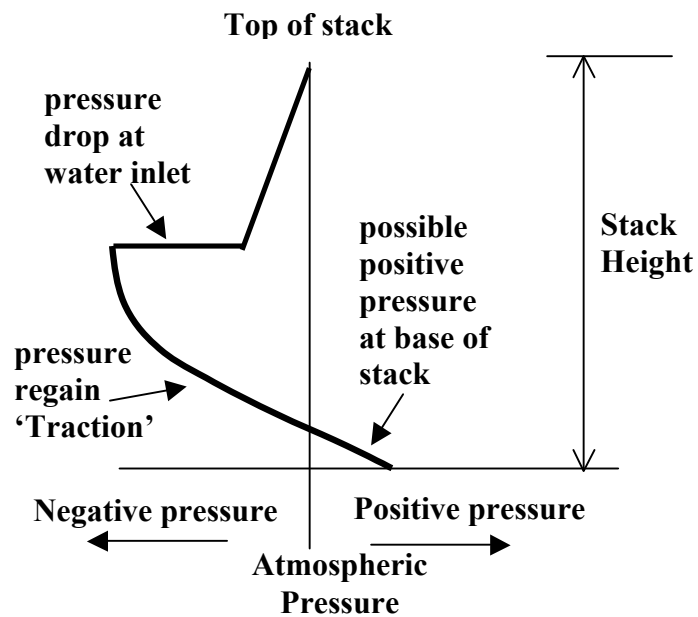


Figure 2 Pressure Profile in the Stack

These losses reduce in the pipe to sub - atmospheric and therefore place a suction force on a portion of the system.

The pressure in the pipe below the discharging branch follows a different pattern. Since the water induces an air flow the dominant force on the air is traction rather than friction⁽⁸⁾. This has a tendency to make the air pressure move in a positive direction (or a reduction in suction pressure) this moves the pressure back towards atmospheric at the base of the stack. This pressure at the base of the stack can go above atmospheric pressure in certain circumstances, this is known as back pressure.

The pressure profile usually associated with this process is shown in Figure 2. It must be remembered that this is only a representation of the pressure 'signature' associated with a specific event at a single point in time, it is in effect a 'temporal snapshot' of the pressure distribution in the vertical stack, and is probably best applied to taller buildings. In reality this profile will change rapidly with time sending pressure transients up and down the stack communicating these changes as described below.

It is very useful to measure pressure in drainage systems in terms of 'head' - Where pressure is referred to as an equivalent water depth, for example 'column inches of

water’, or simply inches of water. The advantage of using depth of water as a reference for air pressure is that a suction pressure of 2 inches of water will remove a trap 2 inches deep and is therefore a useful equivalence.

1.4 The requirements of a well designed system

Put simply, the main requirement of a well designed system is that it should operate without the user being aware of its existence. However, this is a tall order and there is therefore a need to more fully specify some requirements which can lead to the ‘invisible system’. The following requirements are essential in achieving a safe, usable and reliable drainage system;

- The system should remove all waste as quickly as possible
- Long horizontal pipe runs must be self-cleansing
- There must be minimal loss of water trap seal to ensure there is a barrier for the ingress of sewer gases

Other requirements which are less critical are

- Minimal noise from the system
- Minimal Odor from the appliance side (WC design)
- Ease of maintenance

Code regulations were essentially designed in order to ensure that installations meet these requirements, and to protect inhabitants against any possible health risks from contact with contaminated fecal material. In developed industrialized countries the majority of installations meet these standards and the health risks from drainage systems are still very low. As with most fields of engineering, sanitary equipment and techniques have benefited from scientific and engineering research which has improved understanding of system operation and helped develop new innovative and cost-effective ways of achieving the goal of safe, reliable drainage systems with no increase in health risk.

2. Pressure transients in plumbing systems

2.1 What are pressure transients?

Any discussion on the challenge of draining a building would be incomplete without reference to air pressure transients, but what are they? Pressure transients are very simply the physical communication of a condition at one point in a system to another point. This means that if there is an event at point A then this information is communicated to point B some distance away by means of a pressure wave. The wave moves much faster than the air in which it travels and can move in any direction, not necessarily in the flow direction. In a pipe the speed at which an air pressure transient travels is the acoustic velocity, approx 1050 ft/sec. A negative transient communicates a need for more air and represents a suction force while a positive transient communicates the need to reduce the air flowing and represents a pushing force. A negative transient can be caused by air leaving the system (hence the need for more air) and a positive transient can be caused by the air reaching a closed end (stop the air there's no escape route)

An analogy may help to visualize how this works in practice. Imagine driving along a highway at rush hour when cars are traveling at a modest 40 MPH nose to tail. The road is long and winding with a slight incline, it is dark so the stream of taillights can easily be seen for several miles ahead. At some point in the journey, a car, now out of sight, is forced to stop. The driver is forced to apply the brakes. At this time you are still traveling at 40 MPH. Up ahead in the distance you can see the brake lights illuminating as drivers respond to the event out of sight. The 'wave' of brake lights works its way back through the traffic until you are forced to apply your brakes and stop. The illuminating lights are analogous to a pressure transient communicating to you that there has been an event up ahead (which you can't see) and that you must stop. This "positive" type pressure wave travels much faster than the 40MPH that you were traveling at before braking (although in this case the speed of the wave is determined by the response of drivers to seeing brake lights up ahead). When the road is cleared up ahead the reverse happens as brake lights go out and drivers find themselves with a space to drive into as the car in front moves away. Again the information to move is communicated by the "negative" type pressure wave.

It is interesting to consider the consequences if the car speed is increased. If the cars were traveling at 70 MPH and the first car stopped abruptly then there is a good chance of a pile up, the driving equivalent of a Jowkowsky type pressure surge. [Jowkowsky determined that the magnitude of a pressure surge is dependent on the product of the velocity of the fluid, its density and its wave speed]

2.2 What do these pressure transients do in a building drainage system?

A negative transient will attempt to suck water out of a water trap seal. The pressure may not be sufficient to completely evacuate the water in one go, but the effect can be cumulative. Positive air pressure transients cause air to be forced through the water seal from the sewer side to the habitable space inside.

2.3 How to overcome pressure transients?

The need to communicate an increase or decrease in the air flow and the finite time that this takes is central to the requirements of providing a safely engineered drainage system. The absolute key to maintaining a state of equilibrium in a drainage system is to provide pressure relief as close to the source of an event as possible. In the case of our stream of traffic above, a diversion around the road blockage as close to the blockage itself would cause the minimum amount of disturbance. The point raised by George Waring in 1884 (see Introduction above), referring to the relief of suction pressures is still true; air must be provided as fast as possible and long pipe runs mean a time delay and subsequently a possible compromise of water trap seals.

3. Designing for best practice

3.1 Alleviating negative transients

As described above, negative transients are the system's way of communicating the need for more air. This call for air can be caused by a number of phenomenon;

- A branch pipe filling up with water (full bore flow) cause siphonic action to produce a vacuum into which the water from a trap seal is sucked.
- The pressure losses associated with water falling down a vertical stack will induce negative transients which will propagate around the system at the speed of sound. Some of these transients can be of sufficient suction pressure to evacuate water from a trap seal (induced siphonage).
- Any increase in airflow (for whatever reason) will produce negative air pressure transients in the system as the need for more air is communicated to the termination (where the air comes from).
- Air leaving the system will cause a negative transient (either into the sewer or from any other interface point e.g. the top of the stack)

The most efficient way of dealing with this call for increased airflow is to simply answer it as quickly as possible. This means providing the extra air as quickly as possible. In a drainage system this equate to having a termination as close to the point of need as possible, in effect distributed venting using AAVs allows this to happen in the most efficient way. If a trap is 30 ft away from an air inlet to the system then it will delay the arrival of air and quite possibly compromise a water trap seal.

If this is the case then why do people not experience foul odors on a regular basis in a fully vented system? Well, as mentioned earlier, work carried out by Wise in Post-War Britain, proved that if pipework was set to the correct slope and was of sufficient diameter to carry required loads over a specified distance, trap seals would not be compromised⁽⁹⁾. This system (the single stack or one pipe system) has operated very successfully in Europe for 50 years with little increase in risk to system integrity.

Distributed venting provides alternatives for modern building design where distances from appliance to the sewer may be longer than those anticipated 50 years ago.

3.2 Alleviating Positive Pressure Transients

If negative pressure transients are a call for more air then positive pressure transients are a call to stop sending air. Because pressure transient analysis follows a set of well defined rules (remember there are no real mysteries) their source can be established and are given below;

- Changes in the water/air flow rate produce positive as well as negative air pressure transients
- A sudden closure at a system termination, for example a surcharge in the sewer, resulting in a stoppage of the airflow out of the system will cause a positive pressure wave to be produced and propagate throughout the system
- A Blockage or major clog in the system

Positive pressure transients travel at the same speed as negative pressure transients, the speed of sound, and represent a deceleration force on air and water in its path. So, the consequences of a positive air pressure transient reaching a water trap seal would be that air is blown through the trap into the building (at best) or all the water in the trap is forced into the habitable space.

It is important to note here that a positive pressure wave, produced at the base of a drainage stack, will not be alleviated by an open top on the stack. This is because the pressure wave must travel the length of the stack in order to escape the building at the top. It will meet water traps on the way which, if it has sufficient pressure, will blow and so relieve the system into the habitable space.

Again the best way to provide relief against positive air pressure transients is to locate a pressure relief device such as the PAPA as close to the source as possible. So in the case of a transient produced at the base of a stack, relief is needed at the bottom, not at the top. Parallel vent pipes only divert a portion of the wave and will provide best relief if the diameter of the vent pipe is equivalent to the diameter of the stack. But this will only reduce the magnitude of the pressure by 1/3. In laboratory tests PAPAs have been shown to reduce the magnitude of a positive air pressure transient by up to

90%^{(10),(11)}. Effectively the device allows the diversion of the airflow and its gradual deceleration – another example of the cars on the highway analogy.

Do AAVs produce positive air pressure transients? Quite simply No. AAVs respond to positive air pressure waves by closing and simply reflect a % of the incident wave. AAVs will also produce a small negative transient as the inflow is closed off.

The magnitude and ferocity of positive air pressure transients can be limited by distributing the air venting around the building. Since the magnitude of a positive air pressure wave is a function of the velocity of the airflow stopped, and hence airflow rate itself, it is better to reduce the risk of stopping a large flow by installing a number of air inlets with small airflows around the building, thereby limiting the magnitude of any potential air pressure transient produced. This is best done by installing AAVs around the building.

4. Building Case Studies

4.1 Modeling flows in drainage networks

Research and analysis of real building drainage systems is complicated by the difficulty in obtaining data from ‘live’ buildings. Most areas of engineering employ some form of modeling technique in research and development in their ‘look and see’ approach to development. In DWV research there are few models capable of dealing with the complex time dependent transient flows. The computer model AIRNET is such a model and as far as the authors are aware, the only validated model^{(8),(12),(13)} capable of such a complex task. At the heart of the AIRNET model is the mathematical technique known as the method of characteristics. The technique allows the propagation of waves to be predicted along the length of a pipe at different time steps. This is a very powerful and unique way to ‘look and see’ what is actually going on inside a building drainage system, the simulations in this section were carried out using AIRNET.

4.2 Two story building

As stated above, a two story building drainage system can operate sufficiently well with minimal additional ventilation as long as it is designed and installed properly. This is borne out by reference to the installation shown in Figures 3 and 4 below. The building represents a fairly common house with a number of bathrooms and a group branch in a kitchen / laundry area. The simulation was run in two different scenarios.

1. System with open top
2. System with an AAV at the top of the stack

A discharge flow rate was simulated from the top floor consisting of a combined flow from a WC and a bath. This discharge was simulated from the upper floor and the effect on the water trap indicated by shading was recorded from the output data. It can be seen from the bar graph that little water has been lost as a result of the operation of system devices in either scenario.

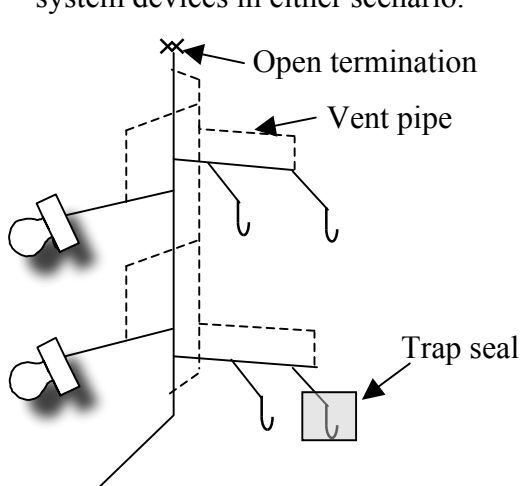


Figure 3 Fully vented system with open top and parallel vent pipe

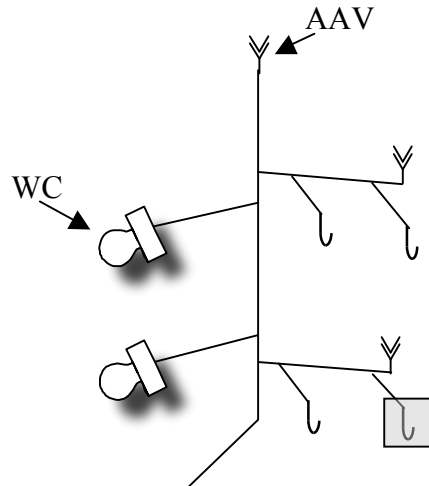


Figure 4 Two story house with AAVs on branches and an AAV termination at the top of the stack

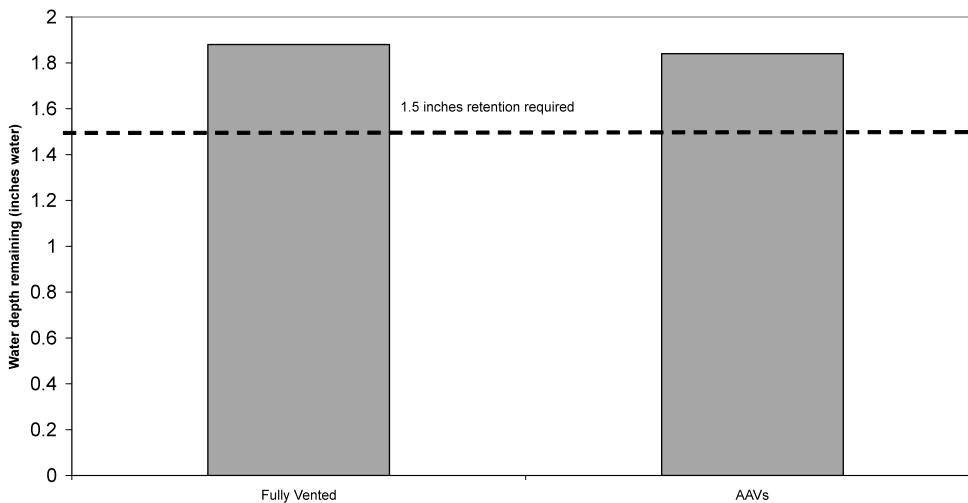


Figure 5 Comparison of water retained in the ground floor trap indicated (shaded on schematic)

4.3 10 Story Building

The 10 story building scenario is shown in Figure 6 below. There are basically three installation types being simulated here; the fully vented system Figure 6(a) and a one pipe system with distributed venting and an AAV on the top of the stack, Figure 6 (b). This system also includes a relief vent. Figure 6 (c) is the one pipe system with distributed AAVs and PAPAs subjected to a positive air pressure transient simulated to replicate the occurrence of a surcharge in the sewer. In each of the scenarios a representative water trap is shown on three floors up the building

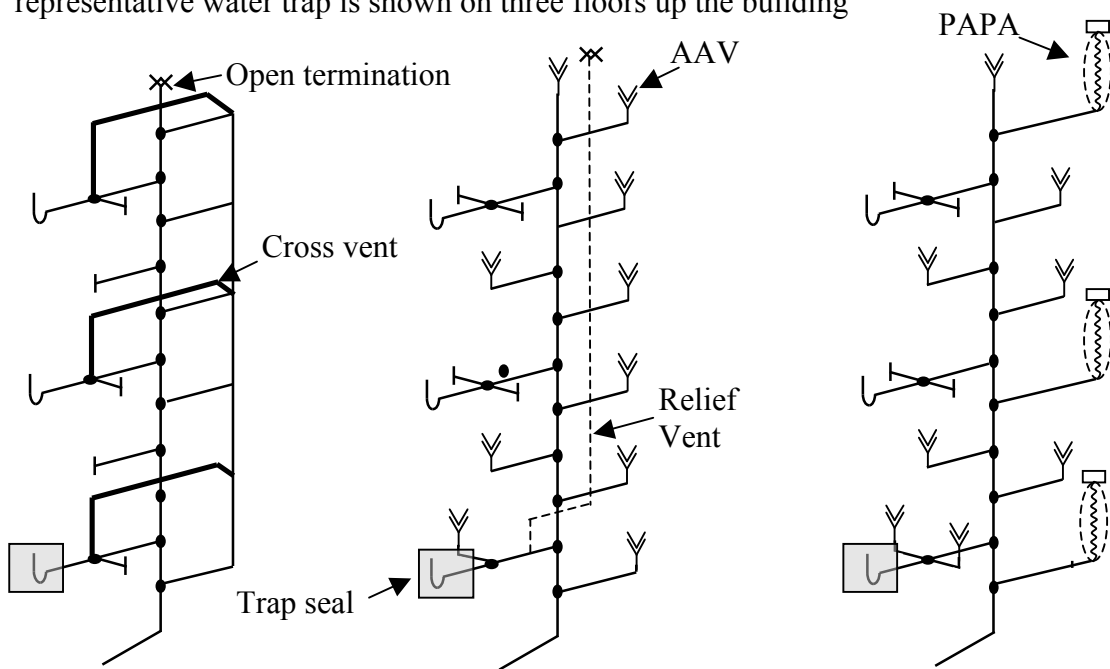


Figure 6 (a)

Figure 6 (b)

Figure 6 (c)

Discussion

The flow rate used in this simulation represents a maximum for the 4" vertical stack in question (80 USgpm). This flow rate is unlikely to be observed in practice as the simultaneous discharges required are a probabilistic impossibility (Hunter 1940). The flow rate is therefore indicative of a 'worst case scenario' in order to push the drainage vent system to its limits, and therefore show comparisons between the options investigated. The discharges making up the flow rate are distributed evenly along the stack to simulate a number of simultaneous discharges (approximated 16 USgpm from 5 different floors).

The bar graph shown in Figure 7 illustrates the water depth retained in the shaded water trap in Figure 6 following this event. It can be seen that under these conditions

the system with AAVs installed (Figure 6b) has retained the most water. Why is this? Well, the main reason is that the flow in the vertical stack induces a negative pressure transient as it calls for more air. This negative transient propagates to all parts of the system ‘looking for air’. The negative transient represents a suction force which will try to draw water out of the trap seal. If the negative transient is too great it will suck water out of the trap. To stop this happening, air must be provided from somewhere else. The methods shown in Figure 6(a) and Figure 6(b) show two different methods. In Figure 6(a) the air must travel from the top of the stack, approximately 100ft away (but only after the negative transient has propagated to the top of the stack first so the round trip is approximately 200ft). Alternatively, air can be provided locally by the provision of an AAV (Figure 6(b)). In this case the round trip to is only a matter of 10 ft. This means that the air can be provided quicker than the fully vented system.

The bar graph also shows the influence of cross vent diameter on vent performance. The smaller vent pipe is less effective than the larger vent pipe due to increased friction. This is identical to the point made by Waring in 1895 (see Introduction above).

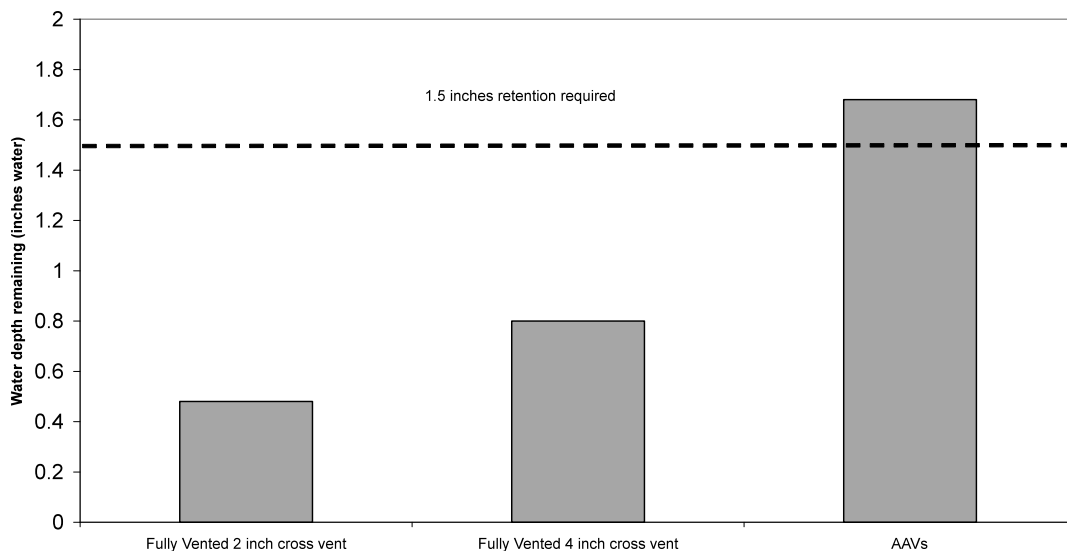


Figure 7 Comparison of water retained in the lowest water trap (shaded on schematic) conditions based on negative transient

Figure 8 shows the trap retention on the same trap as the result of a positive pressure transient in the system. The positive transient was generated by simulating a surcharge in the sewer, causing the airflow through the stack to be stopped. Again two methods of dealing with this scenario; the fully vented system shown in Figure 6(a) and the ‘active control’ option utilizing AAVs and PAPAs as shown in Figure 6(c). The bar graph of trap retention clearly shows that the active control system protects against this sort of event, and that the AAV system with a relief vent provides better protection than the fully vented system. The reasons for active control being better are two- fold; firstly, the distribution of the air inlets reduces the maximum positive pressure possible in the first place and secondly, the PAPA presents a volume which can consume the positive pressure wave, attenuate it and destroy it, rendering it harmless. This is borne out by the amount of water displaced by the positive pressure wave.

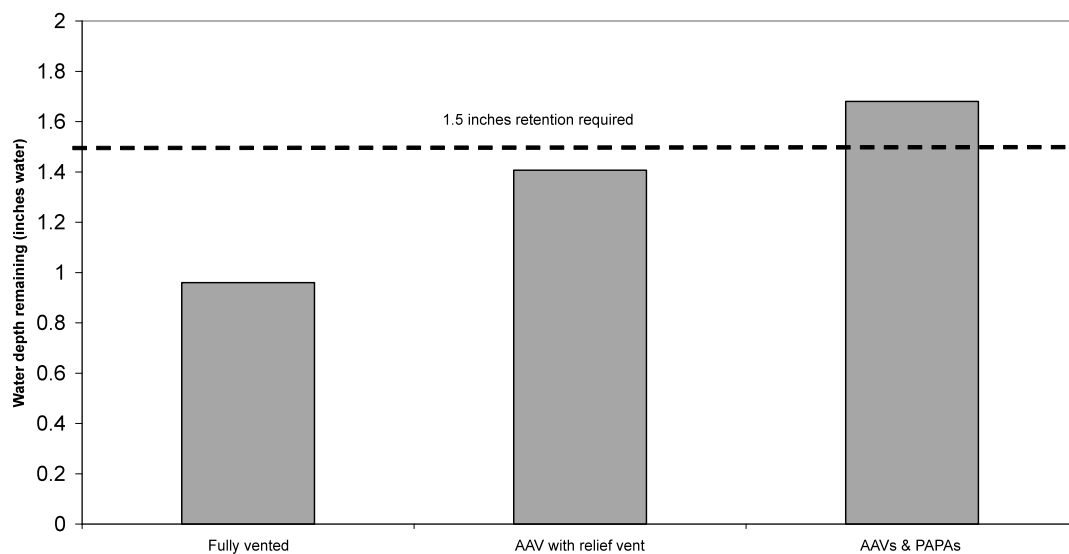


Figure 8 Comparison of water retained in the ground floor trap indicated (shaded on schematic) Conditions based on positive transient

5. Conclusions

This report has considered the implications for venting in building drainage systems. The discussion has concentrated on the fundamental fluid mechanics which so readily describe the unsteady flows resulting from plumbing fixture discharges. The description of the workings of a drainage and vent system in these terms is not new,

many early innovators were well aware of this, however, many codes and regulations worldwide seem to avoid the engineering imperative of a description based on fluid mechanics in favor of a prescriptive legalistic approach based on the evolution of the industry rather than the science.

The fundamentals of system friction and pressure transient generation and propagation are central to understanding why venting is required in the first place. Possible solutions for alleviating pressure transients were discussed, including the well respected view that in certain circumstances systems operate perfectly well without venting.

The advent of fast digital computers has resulted in the ability to model and simulate unsteady air and water flows in building drainage and vent systems; providing the capability of solving the well understood governing wave equations first described in the 18th Century. The computer simulation program AIRNET has been under development for over 20 years and has been validated in many laboratory and site investigations. This report shows results from simulations of two building types; a two storey building and a ten storey building. The output from the program confirms the validity of distributed venting utilizing AAVs and the effectiveness of the positive air pressure attenuator (PAPA) at dealing with positive pressure transients.

It is hoped that this paper has gone some way in de-mystifying the workings of the building drainage and vent system 'lurking' beneath the sink and floorboards. It is also hoped that the work of those attempting to create a safe, hygienic environment for people, for the first time, such as Waring, Putnam, Reynolds and Wise should be remembered in a favorable light, not least because of their commitment (Waring died as a result of investigations into a possible link between sanitation and yellow fever), but because their observations were based on the sound engineering and scientific methods often absent from deliberations today.

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