Airflow distribution in complex building drainage networks: An electrical analogy to aid understanding.

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Abstract
Airflow distribution in complex building networks plays an important part in the equalization of pressure fluctuations, the protection of water trap seals and ultimately the protection of habitable spaces from the ingress of foul sewer gases.

The mechanisms governing airflow in building drainage systems are well understood and have lent themselves to numerical models based on method of characteristics and the solution of the St.Venant equations of momentum and continuity, the basis for the computer prediction program AIRNET.

AIRNET can accurately predict the ingress of air entering the system through open terminations and air admittance devices such as air admittance valves (AAV) and waterless traps, subject to a restriction placed on the airflow by the type of termination. It is possible to show that the restriction placed on the airflow by these configurations follows the same laws governing electrical current flow and electrical resistance.

The methodology employed is to use data obtained from the validated program AIRNET to verify that airflow though a range of terminations and pipe configurations follows the laws of electrical circuit theory. The results show that venting arrangements can be appraised by inspection, and that the introduction of the electrical resistance analogy aids understanding of airflow distribution in complex networks, particularly where additional venting is required to overcome existing problems.

Keywords
Air pressure, drainage design, electrical analogy.

1. Introduction

The application of electrical circuit analysis methods to fluid systems is not without precedence. One of the seminal works on waterhammer analysis by graphical means was shown to be equally as valid for surge waves in electrical circuits as pressure surges in pipelines [1]. Closer to the field of building drainage systems is the work carried out by the National Bureau of Standards in the U.S.A. in the 1980s, which applied Hardy-Cross network analysis to a study of a Veterans Administration Hospital in the Bronx, New York [2].The method used a loop circuit approach, applying rules equivalent to Kirchoff's laws in electrical d.c. circuit theory, and was used to predict optimum vent sizes for the building drainage system.

The purpose of describing the electrical analogy proposed in this paper is help to demystify the operation of drainage networks. There are many misconceptions about the effectiveness of venting configurations, which inevitably lead to either an over estimation or under estimation of requirements or no difference at all.

It might be considered that an electrical d.c. analogy would not be representative of the processes involved in building drainage systems. The processes in a building drainage system are inherently dynamic, requiring predictions of the propagation of transient pressure waves and unsteady fluid flows. The d.c. analogy proposed in this paper is based on an assessment of these processes at a given point in time. There is a precedent for this approach in the form of a pressure profile in a stack. Consider the pressure profile in Figure 1. This graph represents the profile in a stack at a given point in time, it does not represent transient behaviour and is not a permanent pressure profile. It is used as an aid to understanding some of the important processes in a drainage system, and has been very successful at doing so. It is hoped that the electrical analogy can also aid understanding, using a snapshot approach also.

It is important to note that this paper does not describe a model for predicting airflows or pressure regimes, that is best left to numerical models such as AIRNET, it is simply intended act as an aid to understanding, using methods adopted by the author to quickly assess venting arrangements in a wide range of simulations carried out in recent research. The approach is to assess different configurations, and to predict, using equivalent electrical circuit analysis, whether one configuration is more effective than the other.

2. The AIRNET simulation tool

The computer program AIRNET has been used extensively in this research. The program's strength lies in the extensive loss coefficients and boundary conditions developed in ongoing research at Heriot-Watt University to accurately represent real drainage system boundaries and appliances.

The program simulates the propagation of low amplitude air pressure transients using the fundamental St. Venant equations of motion and continuity and by the numerical solution of these equations, via the method of characteristics. The method is used to yield air pressure and velocity within a duct system subjected to air pressure transient propagation. [3],[4]. As the air pressure and density are linked, the defining finite difference equations have to be recast in terms of air velocity and wave speed.

2.1. Entrained airflow analysis

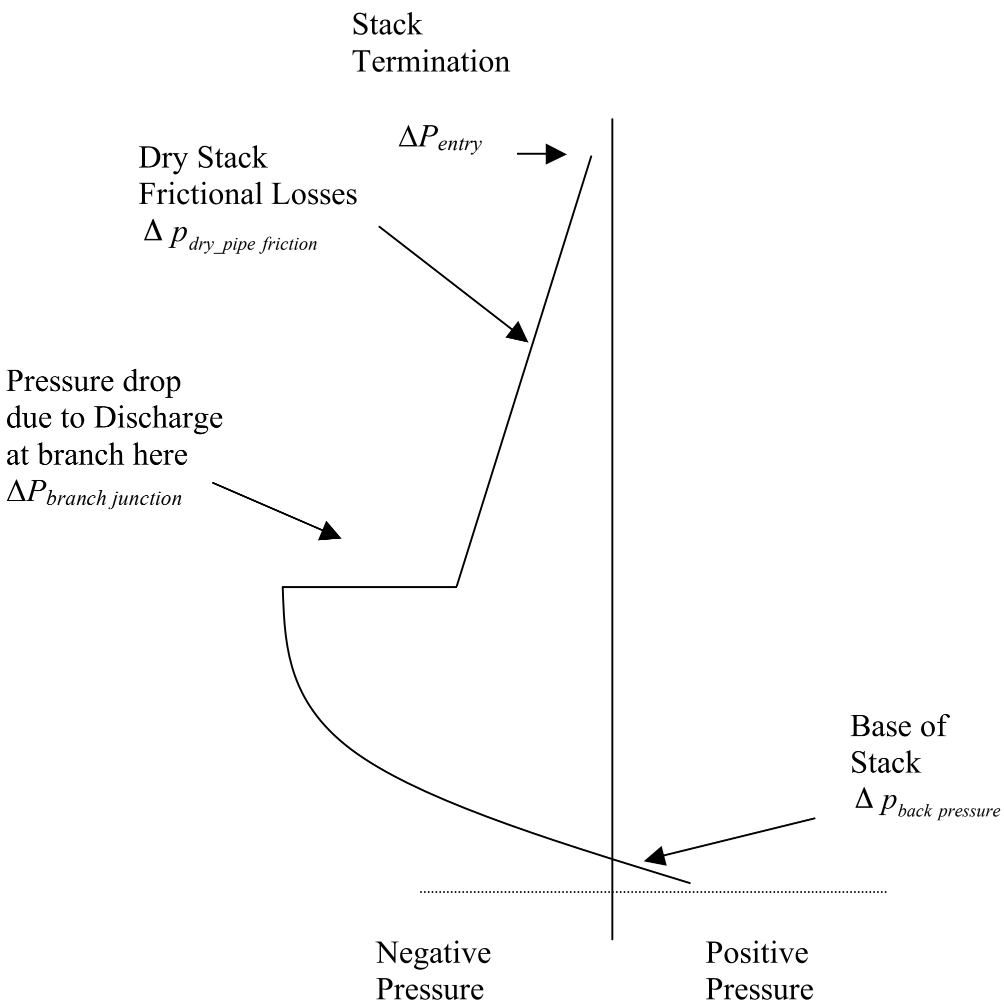
The basic principles governing the model's operation can be seen by looking at the example of an entrained airflow analysis as illustrated in Figure 1. As water enters the stack from a branch, an airflow is entrained into the network and leads to a suction pressure in the vertical stack. Pressure drops are experienced at the termination at the top of the stack due to separation losses associated with the method of termination the airflow passes through (AAV or open end). Frictional losses in the dry stack lead to a further pressure drop and can be calculated from an application of D'arcy's equation. A further pressure drop is evident as the water from the branch forces its way through the air core.

Figure 1 also shows the positive pressure at the base of the stack as the airflow is forced through the water curtain formed at the bend at the base of the stack.

These pressure losses in the stack may be combined as

$$\Delta p_{total} = \Delta p_{entry} + \Delta p_{dry\_pipe\ friction} + \Delta p_{branch\ junction} + \Delta p_{back\ pressure} \qquad 1$$

The 'motive force' to entrain this airflow and compensate for these `pressure losses' is derived from the shear force between the annular terminal velocity water layer and the air in the wet portion of the stack. This can be considered as a `negative' friction factor that generates an equal pressure rise to that determined from equation 1 - the equivalent to a fan characteristic drawing air through the stack. Ongoing research has identified the format and relationships governing this shear force representation, and allows the prediction of the transient response of the stack network to variations in applied water downflows [5]



$$\Delta\, p_{total} = \Delta\, p_{entry} + \Delta\, p_{dry\_pipe\ friction} + \Delta\, p_{branch\ junction} + \Delta\, p_{back\ pressure}$$

Figure 1 - Entrained Airflow Analysis for AIRNET Model

3. Airflow and system pressure analogy

The entrained airflow analysis example outlined above can be thought of as a network of pressure losses that are induced by the motive force of the work down on the air by the water. This is analogous to the relationship between applied voltage, circuit resistance and current flow in a simple d.c. electrical circuit.

The basis for the analogy can be explained with the use of a few very simple electrical circuits and their drainage equivalents. Firstly, it is necessary to define the analogous terms used in this paper.

Electrical Property		**Air flow property**
Voltage	→	Pressure
Current	→	Airflow
Resistance	→	Friction

3.1 Simple rules about Voltage and current and their application to drainage

Voltage

Voltage is also known as potential difference or electro-motive force (EMF) and is essentially the cost in energy (work done) required to move a unit of positive charge from the more negative point (lower potential) to the more positive point (higher potential). Equivilantly, it is the energy released when a unit of charge moves 'downhill' from the higher potential to the lower. A joule of work is needed to move a coloumb of charge through a potential difference of one volt. The coloumb is the unit of electric charge and it equals the charge of 6 x 10^8 electrons, approximately [6].

The analogue of voltage in a drainage system is Pressure. Pressure or more accurately pressure difference is usually measured between two points, or at a single point if it is referenced to a known pressure, e.g. atmospheric pressure. A pressure difference can induce an airflow, or the pressure difference can occur as a result of an airflow induced by other means, as in the case where an airflow is induced by water falling down a stack.

Current

Current is the rate of flow of electric charge past a point. It is quantified in amperes (amp). where 1 amp = flow of one culoumb per second. By convention, current moves from a positive to negative point in a circuit, even though the actual electron flow is negative to positive.

In a building drainage system the analogue of current is airflow rate, measured in m^3/s or more usually l/s. The quantity of air moved through a system is related to the pressure difference across the system and the friction of its component parts. A significant difference between the two being that $\Delta p \propto Q_a^2$ in a drainage context, where $V \propto I$ in an electrical circuit.

OHMS Law

Ohms law states that the voltage, V, current, I, and Resistance R, in an electrical circuit are related, such;

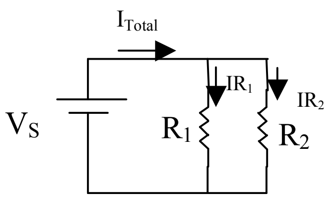
$V = IR$ which leads to an expression for power; $P=VI$

This is a fundamental relationship for all electrical circuitry.

In a drainage system this would relate pressure difference, airflow rate and system friction such that there is a balance between the three. For example, for a given system with a constant driving force (Q_w) if the friction is increased (decrease in pipe diameter) then to maintain the same airflow rate there would need to be an increase is pressure difference.

<u>Kirchoffs current law</u>

States that he sum of currents into a node equals the sum of all the currents out of the node, conservation of charge (conservation of energy). For a series circuit the current is the same everywhere. This law also applies to drainage networks as will be shown in section 5.2 of this paper.



$I_{Total} = IR_1 + IR_2$

$I_{Total} = V_S/R_{Total}$
$R_{Total} = (R1.R2)/(R1+R2)$
$VR_1 = VR_2 = V_S$

Figure 2 - Kirchoff and Ohms Laws applied to a simple

<u>Kirchoffs voltage law</u>

For parallel circuits the voltage is the same across all branches and the sum of the voltage drops around the circuit is zero. This is also true for pressure drops in a system.

<u>Thévenin's theorem</u>

This theorem states that any complex circuit (Figure 3(a)) can be represented by a single voltage source V_{TH} and an equivalent circuit resistance R_{TH} as shown in Figure 3(b).

<u>Norton's theorem</u>

Norton's theorem is closely related to Thévenin's theorem as it states that any complex circuit can be represented by a current source in parallel with the Norton equivalent resistance of the circuit as illustrated in Figure 3(c)

The main use of Kirchoff's laws and the Thévenin and Norton theorems are that when applied to a drainage system they suggest that it is the entire system that determines the air and pressure regimes, not just a path between the motive force of the water and atmosphere. This is a powerful conclusion since it means that drainage designs must be assessed in their entirety. Equivalent circuits for building drainage systems are shown in section 5.

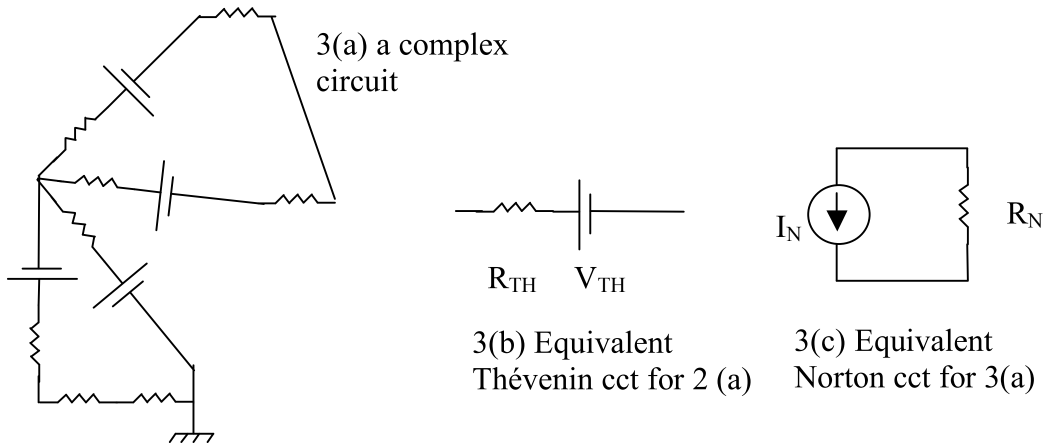


Figure 3 - Thévenin and Norton equivalent circuits

3.2 Resistance to airflow

Frictional resistance to airflow in a drainage system is analogous to resistance in electrical circuits in that they both impede the flow of current (electrical or air) and both cause a drop in potential (voltage or pressure) in their respective networks. It is informative to assess the resistive properties of different components found in drainage systems in order to apply the analogy to real designs.

Various drainage components display a resistance to flow which can give an indication of their effectiveness. Air admittance valves will display an infinite resistance to flow until its opening pressure is reached, after which this resistance to flow will vary with applied suction pressure as shown by Figure 4 which shows the general form of the loss coefficient against applied suction pressure curve for an AAV.

An air pressure attenuator poses an interesting situation. Under negative pressures it will present an infinite resistance to air flow. Under a positive pressure however, it will open and act as a reservoir, analogous to a smoothing capacitor in the electrical model. The purpose of a smoothing capacitor is to intercept and attenuate surges in d.c. circuits.

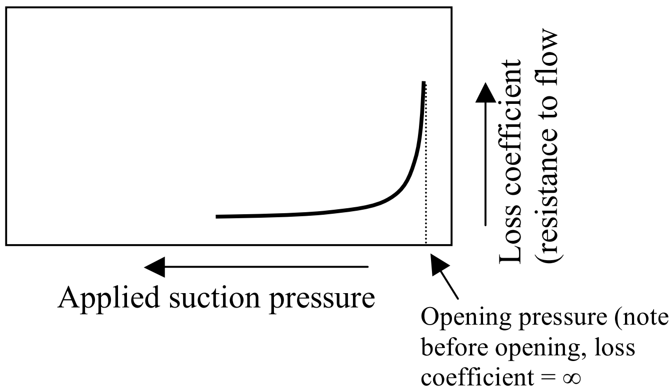


Figure 4 - General form of loss Coefficient for AAV

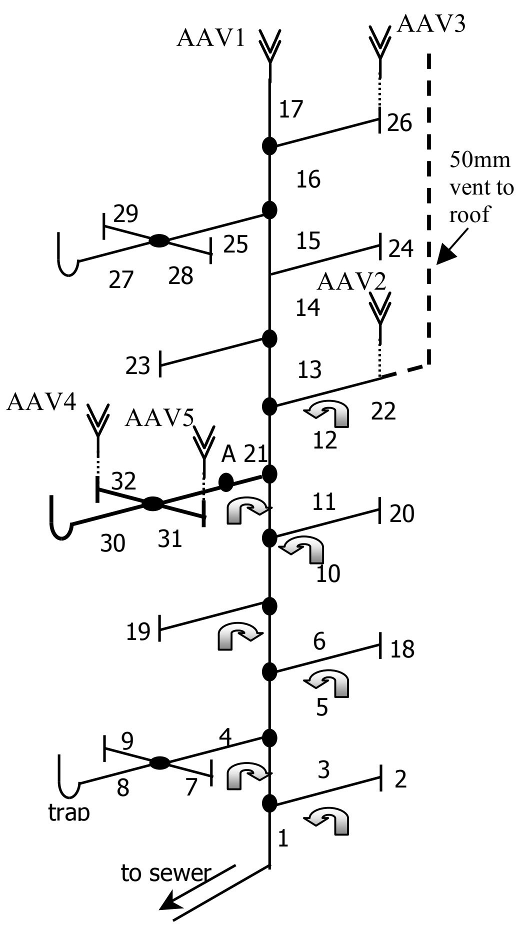
4. Assessing designs: comparing output AIRNET with analogous electrical circuits

The application of the electrical analogy highlights a few important points and will be discussed below. The scenarios chosen are as follows;

1. Airflow in a stack
2. Additional venting on branches.

4.1 Airflow in a stack

The design under consideration is shown in Figure 5. This single stack system has been singled out for analysis. The system includes provision for secondary venting on branches containing fixtures, connected to the main stack. The fixtures are represented in this example as a single water trap seal on the end of the branch, however this could be a group of fixtures connected to the branch, or connected to the main stack individually.



Key

= Discharging branch

= Air Admittance Valve (AAV)

= 50mmWater trap seal

Pipes 1,2,5,6,11,12,13,14,15,16,17 are 3m long 100mm diameter

Pipes 4,21,25 are 2m long 100mm diameter

Pipes 2,7,8,9,18,19,20,22,23,24,26,27, 28,29,30,31,32 are 0.25m long and 100mm diameter

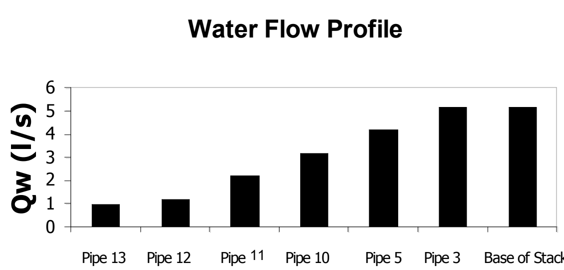


Figure 6 - Water flow profile for simulation

Figure 5 - A single stack system

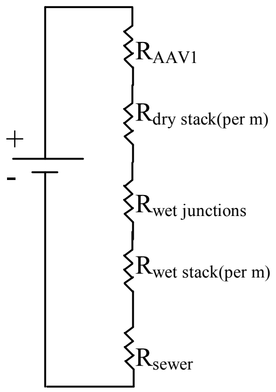


Figure 7 (a) Equivalent circuit for Stack with

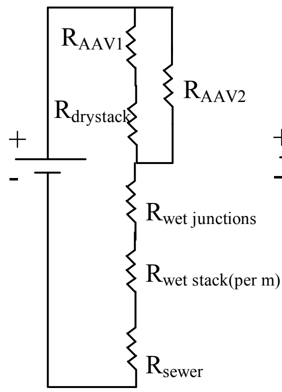


Figure 7 (b) Equivalent circuit for Stack with AAV1 and AAV2

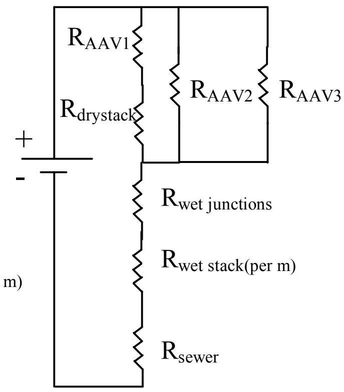


Figure 7 (c) Equivalent circuit for Stack With AAV1,2&3

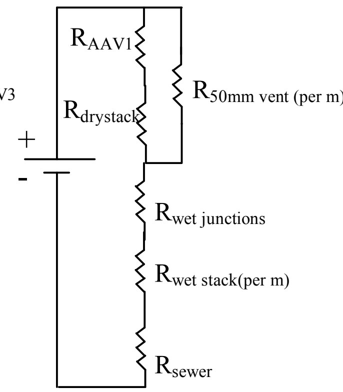


Figure 7 (d) Equivalent circuit for Stack 50mm vent pipe

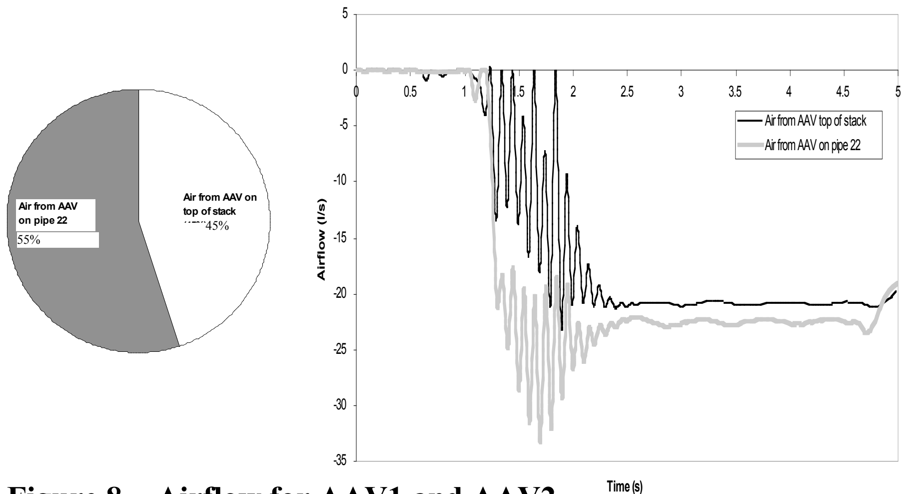


Figure 8 - Airflow for AAV1 and AAV2

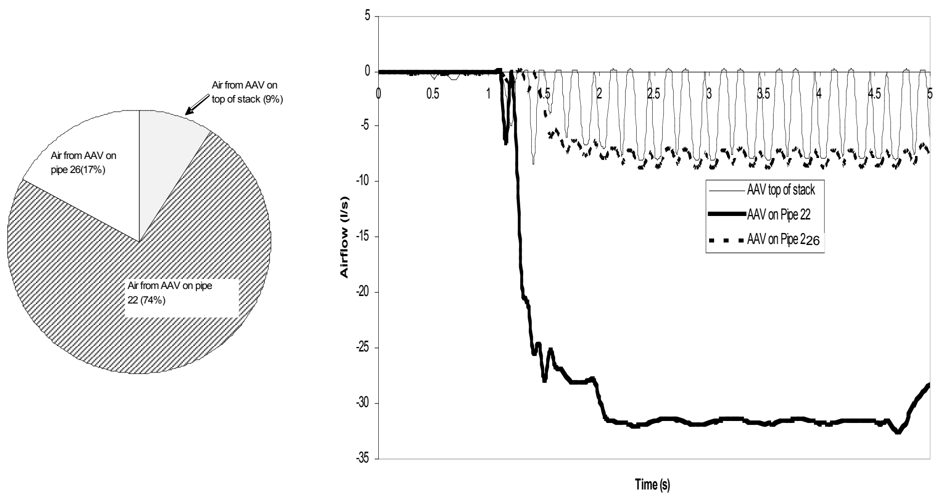


Figure 9 - Airflow for AAV1, AAV2 and AAV3

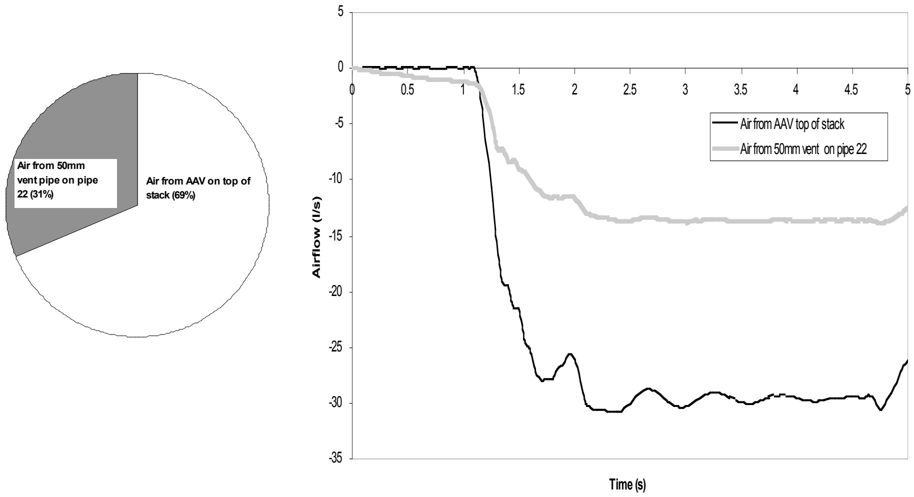


Figure 10 - Airflow data for 50mm vent pipe

Figure 5 shows a single stack system which is subjected to the maximum design flow permitted for this size of system according to EN12056-2 [7]. The water profile used together with the distribution of water inlet is shown in Figure 6. The equivalent electrical circuit for this configuration is shown in Figure 7(a). It can be seen that the main resistance to airflow are seen as series resistances due to entry losses from AAV1, the dry stack and wet stack friction and an interesting additional resistive source from the main sewer. It is possible to represent the interface as a 'bulked' resistance to flow since the sewer may not be at atmospheric pressure. There may even be an airflow source from the sewer which may reduce the airflow in through the top of the system. In this system all of the air will enter through AAV1, and the pressure drops along the system will be such as to maintain this airflow. In reality the wet stack friction can be thought of as the internal resistance of the motive force (the water flow in the stack or the battery in the analogy) and is included here for completeness as it will contribute to the overall resistance of the circuit.

Figure 5 shows the same system with an additional AAV2 on a branch (pipe 22) just above the highest branch with a water flow, pipe 14. Because the additional AAV is connected to the stack via a branch and that the space outside the AAV is at atmospheric pressure an equivalent circuit as shown in Figure 7(b) can be postulated. This is effectively a parallel circuit. Assuming both AAV have the same loss coefficient (effective resistance) then there will be a slightly higher resistance in the stack leg of the parallel circuit which would lead to a prediction that more air will enter the system via the AAV2 on pipe 22 than through the AAV1 on top of the stack. There is another reason why the this is the path of least resistance; when both AAV are closed they both present a dead end, in effect an infinite resistance, when the pressure drops the AAV will open, thus reducing its resistance, the first AAV to open will present the path of least resistance to airflow, which will be maintained during the event.

The airflows from both AAV are shown in Figure 8. It can be seen that most of the air does enter the system via the AAV2 (55% against 45%). It can also be seen that the AAV2 opens first.

To expand this analysis a little further an additional AAV3 was located on pipe 26 as shown in Figure 5 and a simulation run. The equivalent circuit for this configuration is shown in Figure 7(c). As AAV1 and AAV3 are in parallel with AAV2 it would be expected that some air will enter via AAV3 but still not as much as enters through AAV2. Again, this is due to the higher resistance of the AAV1 and AAV3 route due to AAV2 opening first. Airflows for this scenario are shown in Figure 9.

Finally the AAV were removed from the circuit and a 50mm vent pipe run from pipe 22 to the roof (15m). An equivalent circuit for this is shown in Figure 7(d). The amount of air contributed to the system by the 50mm vent pipe will depend on the pipe friction, which for a small bore pipe is considerable. The results of the simulation are shown in Figure 10. It can be seen that less air enters the system via the 15m long 50mm diameter pipe than the AAV on pipe 22. This highlights the high friction of small diameter vent pipework, rendering it ineffective if 'atmosphere' is a long way away.

4.2 Additional venting on a branch

A popular misconception in the mind of many designers is that more venting can be provided for a system by the addition of more venting to a branch. The electrical analogy is useful in assessing if this is indeed the case. Consider the branch arrangement shown by the highlighted branch in Figure 5, pipes 21, 30, 31 and 32. The trap shown is protected from pressure fluctuations by the venting arrangements, which theoretically could be AAV4 or AAV5 or both.

In the first scenario (a) a single AAV4 is used. The equivalent electrical circuit is shown in Figure 11 and the airflow at point A is shown in Figure 13. If a different scenario (b) is tested with the inclusion of an additional AAV5, then a new electrical equivalent circuit can be postulated, as shown in Figure 12. This time both AAV are in parallel and are subject to an analysis due to Kirchoff's voltage law. The current in both legs of the circuit will be the same, and must necessarily be half of the total current.

The output from AIRNET shows clearly that the airflow from both AAV are the same and no greater than had there been only one AAV in the circuit.

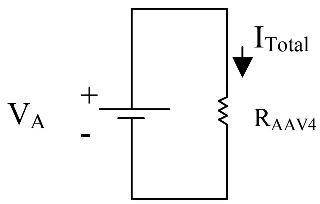


Figure 11 Equivalent Circuit for ranch with AAV4(a)

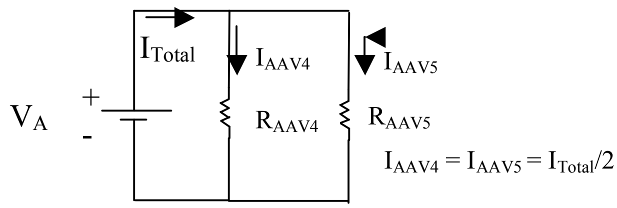


Figure 12 Equivalent Circuit for branch with AAV4 and AAV5 (b)

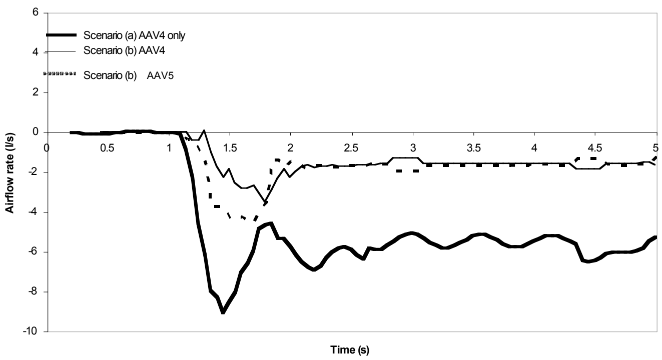


Figure 13 - Airflow for scenario (a) and Scenario (b)

Note that the Airflow contribution from AAV4 is halved when AAV5 is added.

5. Conclusions

This paper has shown that the properties of building drainage networks can be viewed as an analogous electrical circuit. The advantage of using an electrical analogy is that it is much more usual to assess current flow in complex circuits by knowing a few important facts about the components. The tendency in building drainage design has been to stick rigidly to preconceived ideas without the intuition associated with assessment of current flow and voltage across electrical components. While this is method is not a numerical predictive method it has been shown to aid understanding and assess the relative merits of different venting arrangements quickly.

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