OPTIMUM VENTILATION AND AIR FLOW
CONTROL IN BUILDINGS

17th AIVC Conference, Gothenburg, Sweden,
17-20 September, 1996

NOVEL METHODS OF INDUCING AIR FLOWS WITHIN BUILDINGS

D P Campbell, R S Webb

Department of Building Engineering & Surveying,
Heriot-Watt University, Edinburgh, EH14 4AS, UK

Novel methods of inducing air flows within buildings

by: Dr. D. P. Campbell
R.S. Webb,
Dept of Building Engineering & Surveying,
Heriot-Watt University,
Edinburgh, EH14 4AS, U.K.

submitted to: 17th AIVC Conference,
Gothenburg, Sweden, September 17-20 1996.

Synopsis

Water use is distributed throughout building structures. Energy used to pump the water to higher levels in the building is not currently recovered, and is dissipated by performing work on air in the ventilation system which is vented to the atmosphere, when the water is discharged into the drainage stack. This energy can be utilised productively, however, by strategically placing the air inlet for the drainage stack inside the building, thereby utilising the potential energy stored in the water to draw air through the building. Airflow induction by falling water films is a well known problem in the drainage industry, and airflow rates of 10-20 times the water flow rate are common. Basic analysis of the ventilation requirements for typical large buildings suggest that this may contribute between 1 and 7.5% of the total ventilation requirement. Air admittance valves would be effective at isolating the habitable space from the waste water.

1 Introduction

The increasing cost of energy and raw materials, and the desire to maximise investment value, are exacting an increasing demand on services engineers to produce energy efficient buildings. In addition to this, the increased public awareness of energy management and so-called 'green issues' are generating the driving forces for designers and engineers alike to produce new or alternative solutions to traditional servicing problems. These forces are also encouraging the development of new technologies or the utilisation of existing technologies and techniques which, up until now, have been ignored, unseen or simply considered uneconomical, and to use them in new ways.

This paper considers the application of existing technology in a new way to assist in the movement of air for ventilation in large buildings. The technique itself relies on the potential energy of water raised to the top of large buildings. When the water is discharged into the drainage stack after use, the potential energy is presently dissipated unproductively by allowing it to induce an air flow within the stack. Drainage systems are designed to optimize the resulting air flows generated, but it is possible to isolate certain attributes of drainage systems which can be exploited to maximise air flow induction rather than optimize it. If properly integrated within a building, such a system may be able to generate sufficient air flow within certain building designs, and with certain usage patterns, that it becomes significant in terms of the contribution made to passive ventilation.

2 Theoretical Background

The prevention of excessive air flow induction by water flowing within building drainage systems has been successfully achieved following intensive research over many decades. The mechanisms governing the induction process are well understood and predictable within the scope of standard drainage fittings. The mechanisms of air movement will be examined within this context, and then applied to the role of ventilation by natural air movement in buildings.

2.1 Water flows in drainage systems

Within a drainage network the ability to induce air flows belongs to the applied water flow, and the efficiency of air movement is heavily influenced by the water film thickness and velocity. In a circular pipe, water quickly forms an annulus as illustrated in Figure 1. Other workers have investigated the development of the annular flow pattern (Pink, 1973[1,2]) and the velocity and thickness of the annulus has been accurately measured (Wise, 1986)(Swaffield and Thancanamootoo, 1989). When the free surface flow in the branch reaches the stack junction, the horizontal velocity component enables the flow to reach the opposite wall of the stack quickly, where the flow separates and flows round the vertical stack with a high degree of swirl. Annular flow is quickly established (typically within 1 metre) but, until the flow becomes annular, elliptical air spaces will intermittently form on either side of and below the branch jet. These constitute a curving path, joining the air in the stack above the branch to the central air core below the branch, the area of which is influenced by the geometry of the junction. The area of the elliptical spaces available for air transport is obviously also dependant on discharge rate, which in turn is dependant on the nature of the appliance(s) discharging and the

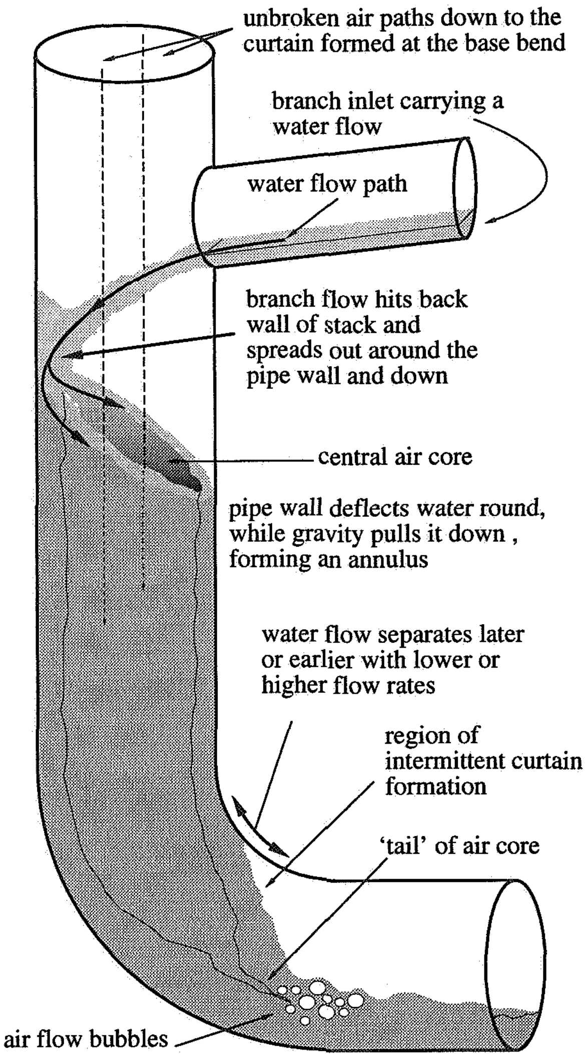

Figure 1 Formation of annular water flow with an entrained air flow at the core, when a branch discharges into a vertical stack

diameter ratio of the branch to the stack. Narrow, fast flows with high slopes give rise to larger spaces than wide, slow and horizontal discharges. In any event, the flow quickly forms as a descending annulus around a central air core, with the motive force that the water film exerts on the air core being applied along the wetted perimeter of the water/air interface.

As the water in the stack moves down, the velocity changes under the influence of gravity and friction with the stack walls. Eventually the friction force equals the gravity force and the water velocity becomes constant. Figure 2 illustrates this condition for uniform and steady conditions, in which it is assumed that the initial lateral swirl velocity components have decayed to zero. From Figure 2, in which the shear stress between the water and the air is neglected, and from Newtons Second Law of Motion,

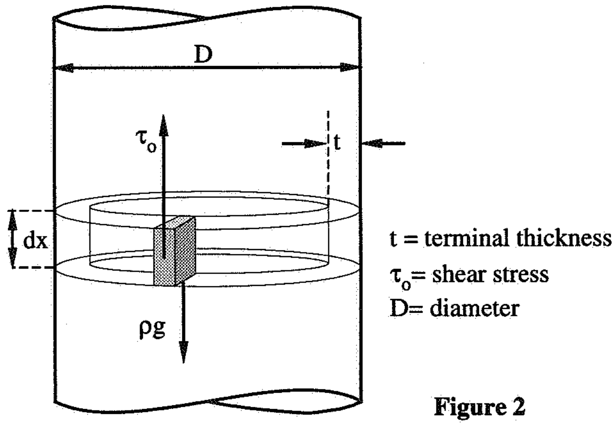

Figure 2
Forces acting on a toroidal flow element in a developed annular stack water flow. Shear stress acts at the pipe/water interface and negates the gravity force when terminal velocity is reached. Forces shown acting on a segment of the torrus for clarity.

$$\rho g(\pi \,D\, t\, dx) - \tau_0 \pi \,D\, dx = \rho\, \pi\, D\, t\, dx \frac{dv_w}{dt} \tag{1}$$

dividing through by $\pi D dx$ gives

$$\rho\, g\, t - \tau_0 = \rho\, t \frac{dv_w}{dt}.$$

At the terminal velocity of the water flow, the acceleration term becomes zero, thus

$$\tau_o = \rho g t \tag{2}$$

The shear stress of the water on the wall is given by

$$\tau_o = \tfrac{1}{2} \rho f v_w^2 \tag{3}$$

where *f* is an appropriate friction factor. Substituting equation (3) into equation (2) and rearranging for *t* gives:

$$t = \frac{f}{2g} v_w^2 \tag{4}$$

Rearranging equation (2.4) again, this time for v_w gives

$$\mathrm{v_w} = \sqrt{\frac{2\mathrm{gt}}{f}} \tag{5}$$

Equations (4) and (5) demonstrate that a relationship exists between water film terminal thickness and the terminal water flow velocity. This relationship can be developed to yield an expression relating terminal water velocity to stack diameter and volumetric water flow rate (Swaffield and Galowin, 1992):

$$\mathrm{v}_t = \left(\frac{Q_w}{D}\right)^{0.4} \tag{6}$$

which in turn demonstrates that the terminal water velocity and film thickness are related to both stack diameter and water flow rate. Figure 3 shows the variation in water film thickness (at the terminal water velocity) for flow rates up to 4 l/s for 75, 100 and 150mm diameter smooth stacks (Swaffield & Galowin, 1992). Figure 4 shows the percentage change in central air core wetted perimeter, i.e. after the thicknesses of the respective annular water films have been subtracted, for the three pipes. Figure 5 shows the variation in terminal water velocity for the three pipes under the same conditions, and Figure 6 shows the percentage change in the water velocities. From Figures 4 and 6, the variation in air core wetted perimeter is very small for water flow rates of between 1 and 4.5 l/s, whereas the variation in water velocity is very large over the same range of flow rates.

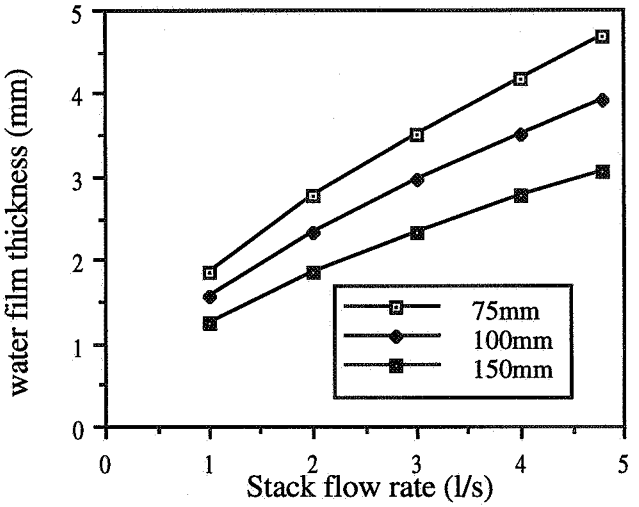

Figure 3. Water film thickness and flow rate

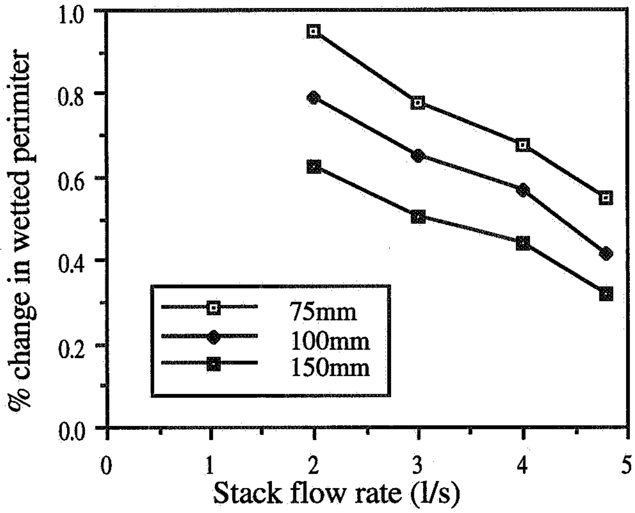

Figure 4. % change in wetted perimiter

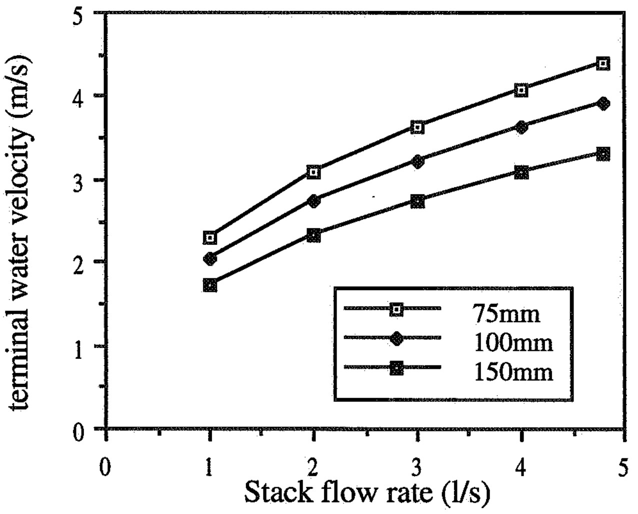

Figure 5. Terminal water velocity and flow rates

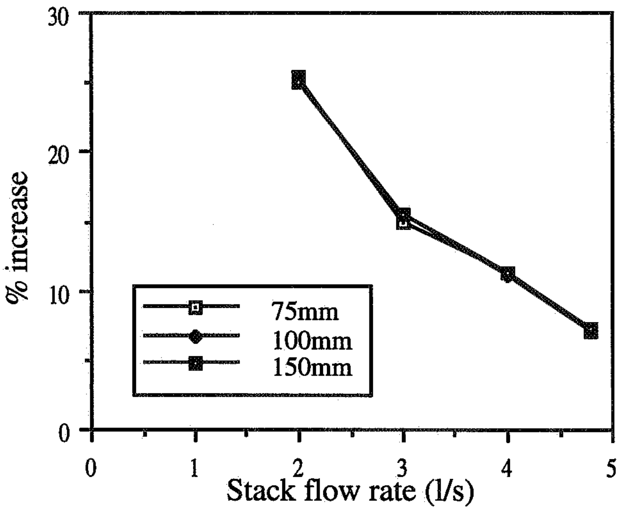

Figure 6. % change in water velocity with air flow

For typical smooth drainage pipes, such as UPVC plastic or glass, stack limiting flows are defined so that the water film thickness of an annular flow which has attained its terminal velocity is never greater than $\frac{1}{16}$D, i.e. $\frac{1}{4}$ of the stack area. The vertical distance *H* required for the water film to reach 99% of the terminal velocity v_t is $H = 0.159v_t^2$ (Swaffield & Gallowin, 1992). For vertical stack water flow velocities of about 4 m/s (about 4.5 l/s), this suggests that v_t occurs at about 2.5m from branch entry. It should be noted that the equations in this Section for determining water velocity are based on flow rate and pipe area and, in the absence of any correction factors, will give mean velocities for the water film. In fact, a gradient across a section of the water film will exist, from zero at the water/pipe interface, to the mean velocity somewhere inside the flow element, through to some higher value at the inside (air column) surface of the water annulus. Although the inside surface of the water annulus is not smooth, very little water, in the form of spray or droplets, appears in the central air column (Pink, 1973[1]). It is to be expected that air velocities will be higher than those calculated based on mean water film velocities as the applied shear, based on the air/water interface velocity, is underestimated.

This Section has illustrated the relationship between water film thickness and water velocity in the stack, and the dependance of those flow parameters on stack diameter. Clearly, the objective of this study will be to determine the best geometry of duct or pipe for a given water flow rate for achieving maximum air flow rates.

2.2 Cause of air movement in the stack

In the 'wet' stack length, air movement is induced by interface shear between the inside surface of the descending water annulus and the air core. This force can only be exerted along the wetted perimeter of the air core and is therefore proportional to its length as well as the velocity of the water surface (not the water mean velocity). At the air/water interface, the velocity of air and water are equal. In the 'dry' upper stack, above any active discharging branches, air is drawn in from outside to sustain the air movement and a pressure drop will develop as the air encounters entry and frictional losses.

It has been pointed out that a velocity profile existed across a water flow element, and that calculated velocities were mean values. Assuming that the velocity profile is linear, the velocity of the water at the air/water interface will be double the calculated mean velocity. The velocity profile is unlikely to be linear, however. The motive force applied to the air by the water may be expressed as:

$$F = \tau_i P_{AC} \Delta L \text{ (Swaffield and Galowin, 1992)}$$

where the wetted perimeter of the central air core P_{AC} is $\pi(D-2t)$ and τ_i is the shear force, which is dependant on the square of the air velocity. From Figures 4 and 6, the shear force *F* is influenced by two parameters:

(a) wetted perimeter of the air core, whose rate of decrease in length is decreasing by fractions of % as flow rate increases, Figure 4.

(b) water velocity, whose rate of increase is decreasing by tens of % as water flow rate increases, Figure 6

Thus the contribution of the water velocity is easily the dominant term in determining the motive force that the air core experiences for any given diameter of stack.

The overall effect on air transport in the stack is that as the flow increases towards conditions that promote full bore flow, the rate of air transport will begin to decrease and this is supported by experimental observations. This can be explained by appreciating that an increase in water flow rates will bring about a reduction in the area of the central air core, as the water film thickens. This will tend to reduce the air carrying capacity of the central air column, and cause the motive force due to the increasing water flow rate to peak and then decrease. Maximum air flow rates currently obtained with circular cross section pipes are of the order of 10-15 times the water flow rate (Campbell, 1993).

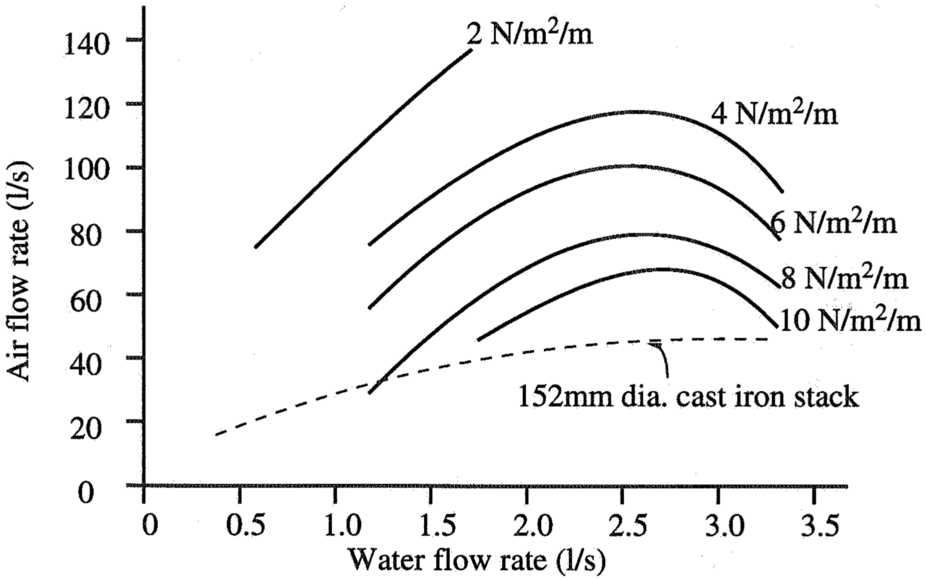

Figure 7 Form of the relationship and typical values for entrained air flow rate variation with water flowrate and pressure gradient in the 'wet' stack length,

3 Analysis

3.1 Water usage in Buildings

Water usage rates for large buildings are easily measured by water meters. Predictions of water consumption rates are more problematic and depend on statistical methods for estimating water demand based on probability and the discharge unit method, in which appliances are assigned arbitrary discharge unit values. Standardised d.u./Q curves allow engineers to convert from estimated demand units back to a normalised, steady state flow rate, which approximates to the averaged long-term demands of the system. These demand estimations are gross over-simplifications because they provide only steady-state estimates of what the continuous flow rate would be, when averaged over a suitably long period. As a guide, CIBSE (1986) guidelines on sizing new installations suggest that water demand will lie somewhere between 45 (office) and 140 (hotel) litres per person per day (l.p.d.), although many usage patterns can be higher. Assuming a flow rate of 100 l.p.d., and a population of 500 people, occupying the building during office hours, gives 500x100/7/60/60 = $2ls^{-1}$.

It has been shown that water velocity is the most important factor in determining the volume of air transported. Maximum water velocities achievable under gravity for a flow of 2l/s are in the region of 2.2 m/s and, under these maximum velocity conditions, Equation 4 predicts the water film thickness to be around 2mm. At 2.5 m/s and 2l/s, a water film of 2mm thickness would have a length of 0.002/(2.5*0.002) = 40cm. In order to maximise the water velocity, friction with the pipe or duct wall must be minimised, suggesting a circular cross section. A circular cross section would also maximise the volume of the air core, further increasing air movement efficiency. The fact that the wetted area of the air core is minimised by this design is not important as the lengths involved will maintain an adequate frictional driving force on the air. From Figure 3, the airflow expected from these conditions will be around 30 l/s.

3.2 Ventilation Requirements

Ventilation requirements vary according to building occupancy and usage profiles. Typical estimates from CIBSE guides give 5l/s per person or 0.8l/s per square meter of floor area. Using these values, and assuming a floor area of 500 square meters, suggests that 30l/s from waste water sources would provide somewhere between 1 and 7.5% of the total ventilation requirement for the hypothetical building, depending on usage patterns.

3.3 Design & Performance of Waste Water System

The data used in this analysis have included water from all sources, i.e. both grey and black. Clearly, there will be a requirement to isolate the habitable space from the effect of this waste and the current state of the drainage industry will set a more than adequate standard. The use of air admittance valves as a means of allowing air into a drainage system, and not out, has been accepted throughout Europe (with the exception of the U.K.) and the U.S.. The simple provision of one of these devices at the head of the stack, strategically placed or vented to a suitable space, would therefore be expected to draw 30 l/s of air out of the space and down the stack, while preventing the possibility of odour or pathogen escape. Air admittance valves have been found to present little extra entry loss to air movement, and are silent and dependable in operation.

If incorporated into the design of a new build, there will be very little extra cost incurred, if any. Diverting the stack head to a suitable location in existing buildings will cost very little, even if a wall has to be drilled.

Conclusions

Airflow induction caused by water falling in circular pipes can be understood and predicted by the application of basic fluid mechanics principles. The rate of airflow induction depends principally on the water velocity but also on the pipe diameter. The optimum shape for maximum airflow induction is circular. It may be possible to supplement the ventilation in large buildings by utilising the airflows set up within building drainage ventilation networks.

Typical large building forms, with either 500 occupants or 500 square meters of floor area, produce airflow rates in the drainage ventilation networks which amount to 1 and 7.5% of the recommended ventilation requirements, respectively. A usage pattern study is recommended to find the optimum building plan for use in this way.

References

Campbell, 1993 Mathematical modelling of air pressure transients in building drainage ventilation systems", PhD Thesis, Heriot-Watt University, Edinburgh.

Pink, 1973^1 'A study of water flow in vertical stacks by means of a probe', BRE current paper, 36/73

Pink, 1973^2 'A study of stack length on the air flow in drainage stacks', BRE current paper, 38/73

Swaffield and Galowin, 1992, 'The engineered design of building drainage systems', Ashgate-Gower, England

Swaffield and Thancanamootoo, 1991, 'Modelling unsteady annular downflow in vertical building drainage stacks', Building and Environment, vol 26, no. 2, pp99-110

Wise, 1986, 'Water, sanitary and waste services for buildings', 2nd edition, Mitchel, London