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# TOP DOWN VENTILATION AND COOLING

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*This paper examines the problems inherent in passively ventilating and cooling low and medium rise urban buildings. We focus on overcoming numerous key issues, such as those of pollutant ingress associated with locating low-level intake openings in passive displacement ventilation systems. A solution is suggested. The concept that is examined is to take ventilation air into the building from the top and to draw it down into the spaces below using the stack effect associated with the difference in temperature between the internal and external environments. Stale air and excess heat from the spaces are discharged via outlet openings into the same external air pressure zone as the inlet. Results of laboratory experiments using the salt-bath technique are reported which substantiate this concept, and two wind-driven devices which may be used to assist the top-down process are described. This paper also discusses methods of occasionally actively cooling the vertical intake ducts of passively ventilated buildings, adopting the top-down system both to boost airflows and to improve internal environmental quality on occasions when solely passively driven ventilation may prove inadequate.*

## INTRODUCTION

This is a joint paper linking research at the University of Cambridge, U.K., with research at The Bartlett, U.K. The work at Cambridge by Hunt and Linden is part of an ongoing project in which laboratory modeling and theoretical analysis are used to study airflows and thermal stratification within naturally ventilated buildings. The aim of this research is to develop an understanding of the physics of natural ventilation in order to provide designers with "rules of thumb" and an intuition of how air moves through buildings.

The work at The Bartlett arises from more direct architectural concerns. Gage is a practicing architect who has worked extensively on primary health care buildings while teaching at the AA School, London, and now at The Bartlett, University College, London. Many of these buildings exploit the possibilities of natural light, passive ventilation, and passive cooling. They are all in central London.

Some years ago Gage entered a competition to design a passively ventilated and cooled building in Athens. The competition entry, undertaken jointly with Jonathan Surgison, was predicated on the idea that no one in downtown Athens would open a window and expose themselves to the dust, dirt, noise, and air pollution that the city experiences during the summer. To a greater or lesser extent, all cities have this problem. The competition entry was not successful. The idea behind this entry was to cool the thermal mass of the building at night by passing air through vertical ducts in the structure using displacement ventilation.

This idea is only partially workable because, in a continuous duct, the upper levels remain warm and only at lower levels is the fabric cooled. It has, however, suggested a further idea which is explored in this paper.

The use of competitions to inspire architects to think about problems and possibilities in buildings is often questioned. It is probably the case that no competition can, at the time, produce a relevant and well worked out concept. However, a problem can be brought into focus which will, in the future, generate a new idea.

## PRINCIPLES OF PASSIVE VENTILATION AND COOLING

The principles of passive ventilation linked to cooling are well established, and have been used in vernacular building for many centuries. Buildings are constructed from materials which have high levels of thermal capacity — where heat from the air passes into and out of the structure with relative ease. Such materials include stone, dense plaster, concrete, and steel. These buildings are designed so that large volumes of cool night air can pass through them. Ten air changes per hour are not uncommon. This air cools the fabric of the building. During the day these buildings are closed and glazed openings are externally shaded in an attempt to minimize solar gains. Ventilation rates are low. As the internal air is heated through occupancy gains, solar gains, and ventilation gains, heat is absorbed from the air by the fabric of the building and the resultant internal air and fabric temperatures are maintained at an acceptable level.

Ventilation openings are placed and sized to encourage large air movements at night and limited, controllable ventilation during the day. Air moves through the building as a result of wind pressure differences between inlet and outlet openings, and stack pressure differences which result from differences in temperature. In the case of cross ventilation (Figure 1), wind pressure differences drive the air through the building from one side to the other — the inlet opening experiencing positive wind pressure and the outlet opening negative wind pressure.

Stack ventilation utilizes the temperature difference between the internal and external environments to drive a flow of air through a space. Numerous and wide ranging studies, both experimental and empirical, have examined stack-driven ventilation. These flows may be broadly grouped into two categories: mixing ventilation and displacement ventilation. In mixing ventilation, air is introduced so as to mix throughout the space (e.g., as in the case of a warm room with a single high-level opening). In displacement ventilation, warm air collects in an upper zone and escapes through openings at high levels, and cool air for ventilation and cooling is introduced through openings at low levels. Displacement ventilation is the mode of ventilation we shall focus on in this paper.

FIGURE 1. Cross ventilation by differential wind pressure. A zone Z of positive air pressure and a zone Y of negative air pressure is created by the wind passing over the building. Ventilation air is drawn into the space from Z passing out to Y.

Previous studies on displacement ventilation have provided insight into the parameters which control the rate of air exchange and the temperature stratification. In addition, the efficiency of displacement ventilation systems compared with mixing ventilation systems has been examined, as has quantifying the systems' potentials for cooling and how this cooling may be enhanced by harnessing the wind. We make reference to only a fraction of these studies, primarily with a view to describe what we shall refer to as "traditional" displacement ventilation (i.e., the displacement flows which are common practice in naturally ventilated buildings today). In no way do we attempt to provide an exhaustive review of the extensive literature. A comprehensive account of the literature concerning both the theoretical aspects and measurement of displacement ventilation flows may be found in Etheridge and Sandberg (1996). Further discussion of displacement ventilation is given by Nielsen (1993).

FIGURE 2. Stack (displacement) ventilation. Heat gains result in the formation of a warm layer of air at the ceiling which gradually increases in depth until a steady flow is reached (see Figure 4). A thermal boundary is formed at level E. The pressure driving the flow increases as the depth and temperature of the warm layer increases.

In "traditional" displacement ventilation, as shown in Figure 2, cool (and thus, relatively dense) air is introduced through openings at low levels, and warm air, which collects in the upper regions of the space, drains passively through openings located at high levels. The locations of the inlet openings are chosen so that the cool incoming air does not vigorously mix with the warmer air inside the space but rather "slides" beneath this warm body of air and thereby displaces it through the upper openings. In this way the interior becomes thermally stratified and an interface forms separating the warm upper and cool lower air layers in the space. Design requirements place this interface above head height.

In contrast to mixing ventilation, in which the warm interior is gradually diluted by the cool incoming air, displacement ventilation provides an efficient means of removing excess heat and flushing the lower regions of a space with ambient air; in practice, the rate of flushing may be enhanced by increasing the area of the openings, the depth of the warm upper layer, and its temperature above ambient. Linden, *et al*. (1990) deduce these results for traditional displacement ventilation in a single space through the development of a simple theoretical model. Their model is simplified in the sense that it does not provide detailed predictions of air speeds throughout the space. However, its strength lies in predicting "bulk" quantities of the steady air flow, namely, the air exchange rate, the temperature stratification, and the air speeds through the inlet and outlet openings. These quantities, which are of fundamental interest to designers and ventilation engineers, are deduced in terms of the geometry of the enclosure (i.e., vent areas and room height) and the strength of the heat gains. By assuming heat gains can be represented as localized sources of heat on the floor and that heat losses through the fabric are negligibly small, Linden, *et al*. (1990) demonstrate that the height $h$ of the thermal interface above the floor as a fraction of the total height $H$ of the space is governed by the relationship:

is an "effective" opening area which is a combination of the areas of the bottom $a_b$ and top $a_t$ openings. $C_b$ and $C_t$ are coefficients associated with the losses in energy resulting from the flow into and out of the ventilation openings (Ward-Smith, 1980). The constant $c$ (≈0.142) quantifies the rate of entrainment into the thermal plumes rising from the $n$ equal strength heat sources. The theoretical model (1) has been validated by comparison with laboratory experiments which simulate natural ventilation flows at small scale in water tanks (salt bath modeling), and its predictions also compare favorably with measurements made in modern well-insulated spaces (Lane-Serff, *et al*., 1991; Edwards, *et al*., 1994). The theory described has been extended by Cooper and Linden (1996) to account for heat sources of different strengths and by Hunt and Linden (1997a) to account for the additional driving and cooling produced by the wind. More recently, Hunt and Holford (1998) have further extended the theory to describe displacement ventilation flows in multi-storey buildings.

The traditional displacement ventilation approach to passively ventilate and cool a space is discussed further below. In both cases air is taken into the space from the side at a relatively low level or from the bottom.

## PROBLEMS IN THE URBAN CONTEXT

Although "traditional" displacement ventilation has the potential to provide an energy efficient exchange of air with the exterior ambient, there are a number of practical difficulties in the urban environment which may dissuade the architect or ventilation engineer from choosing such a passive system. Research towards improving passive ventilation designs started from considerations of urban pollution. The air in cities is polluted with unwanted gases, particulates, and noise. Studies indicate that the amount of this pollution is substantial at street level and decreases to a general ambient level above the roof (Laxen and Noordally, 1987). Roads have been described as "pollution gutters." The pressure differences which drive passive stack ventilation systems are slight, and for this reason filtration of pollutants is often impossible. There is a security problem in urban areas in finding a safe place at low levels to place the large ventilation inlet openings that are required in passive systems. These must be left open at night if the space is to be night cooled, and there is a real risk of burglary (Kukadia, 1997). Furthermore, if these openings are not carefully located, there may be a problem of heat gain. Cities are constructed from materials which absorb and hold heat. These materials include road asphalt, pavings, and external walling. West facing areas retain heat into the evening and many parts of a city are not effective sources of cool air.

All these problems associated with the low-level intake vents are such that a conscientious architect might feel that passive cooling systems should be limited to green field sites unless an alternative strategy is available.

## TAKING AIR IN FROM THE TOP

The solution to the problems outlined above might lie in taking air into urban buildings from the top (QUARG, 1993). Although there is evidence that pollution concentrations can form above average roof height, most authorities believe that pollution falls to a background level at this height. Therefore, if air can be drawn into the space from the roof, the interior air quality should be improved over that realized with openings at street level. Air entry at roof level minimizes the security risks and reduces road noise to a minimum in most conditions. With regard to passive air intake this so-called "top-down" stack ventilation approach poses a number of questions; the first of which is whether the principle fundamentally defies the laws of physics. Our proposal for the design of a fundamental "top down" passive ventilation system is shown in Figure 3. The design shown has two "chimney-like" structures. The first structure (labeled duct 1 in Figure 3) acts as the air outlet and is designed to fill with warm air resulting from internal heat gains and to channel this warm air up and out of the space. The additional height of the chimney over and above the room height serves to enhance the stack pressures which drive the ventilating flow. The second structure (labeled duct 2) may be thought of as an inverted chimney and is designed to lead cool air from roof level (location C) down the chimney (to location D) where it is then released at low level into the space. The essence of the "top-down" design, therefore, is to replace low-level intake openings with an inverted chimney designed to draw air from roof level down into the bowels of the space. We hypothesize that providing the external temperature T(ext) is lower than the internal upper layer temperature T(int) and duct 1 is at internal temperature while duct 2 is at external temperature, then the stack pressure will drive a flow through the space as indicated in Figure 3 (providing duct friction is low and the outlet opening is not too constrictive).

FIGURE 3. Proposal for top down ventilation. Providing duct 1 is at T(int) and duct 2 is at T(ext) and T(ext) is lower than T<none>(int), then the space will ventilate. (Letters A, B, C, and D relate to Figure 4.)

This top-down displacement flow has been modeled in the fluid dynamics laboratory at the University of Cambridge in the Department of Applied Mathematics and Theoretical Physics, as described below.

## LABORATORY MODELING OF "TOP DOWN" NATURAL VENTILATION FLOWS

Laboratory experiments were performed in order to test whether a traditional passive displacement mode of ventilation may be replaced by a passive top-down displacement ventilation. The experimental technique is described below.

The experiments, designed to simulate airflow patterns and temperature stratification in naturally ventilated spaces, were conducted using a technique commonly referred to as the "salt bath" technique. A transparent plexiglass box, with internal dimensions 0.295 m length by 0.25 m height by 0.2 m width, was suspended in a large environmental tank filled with fresh water. The box was used to represent a generic room or single-spaced building, and the large volume of water contained in the environmental tank represented the external environment. A number of circular holes made in the "roof" of the box were used to represent ventilation openings. Vertical cylindrical tubes, which extended internally from the roof to close to the bottom of the box, were connected to one or more of the roof openings. These transparent plexiglass tubes were designed to act as internal ducts (i.e., analogous to duct 2, the inverted chimney, in Figure 3). The total area of the "ducted" (Figure 3, duct 2) and "non-ducted," or standard roof openings (Figure 3, duct 1) could be varied by removing plastic plugs from the holes.

FIGURE 4. A shadowgraph image of a typical experiment based on Figure 3. If the external ambient temperature at C is maintained at the bottom of the duct D, then the temperature difference between the outlet A and the duct inlet B will cause the air to rise. A thermal boundary forms at E.

In building ventilation, the stack effect arises due to density differences resulting primarily from temperature differences in air. In the experiments, the stack effect was simulated using brine and fresh water to create density differences. Brine is denser than fresh water, and hence, the buoyancy forces act downwards; for this reason the box was inverted and viewed through an inverted video camera, so the flow appears to be driven by a heat source. In order to simulate a localized source of heat on the floor of the space, salt solution was added continuously and at a constant rate through a source in the top of the box. This fluid descended as a turbulent plume and is the analogue of a thermal plume rising from a source of heat. The strength of the source in the experiments could be varied by increasing the salinity and volume flow rate of the salt solution injected into the box. The plexiglass walls of the box are impervious to salt and, hence, the experiments simulate the idealized case of a perfectly insulating building fabric.

Flows were visualized by adding a dye to the brine injected into the box and using a shadowgraph. The dye colors only the salty fluid so that the regions of dense fluid (colored) and regions of fluid at ambient density (uncolored) can be clearly distinguished. The shadowgraph enhances the contrast between regions of different density and allows fine-scale structures in the flow to be seen. The laboratory modeling of stack-driven flows is described in greater detail by Baker and Linden (1991), who demonstrate that stack-driven flows developed using the aforementioned technique are dynamically similar to those in real buildings. As dynamical similarity is achieved, this modeling technique provides a useful tool for visualizing and predicting airflows at full scale. By measuring, for example, the height of the interface and the density difference between the ambient fluid and the salty layer of fluid within the box, quantitative predictions of ventilation rates and equivalent temperature differences for airflows in naturally ventilated buildings can be deduced. Recently, this laboratory technique has been extended to include natural ventilation flows driven by the combined forces of wind and buoyancy (Hunt and Linden, 1997b).

The experiment was started by removing circular plugs from the "ducted" and "non-ducted" roof openings and supplying salt solution to the plume. After some time, a steady-state flow was established.

## RESULTS

An inverted shadowgraph image of the flow in the box model during a typical experiment is shown in

Figure 4. In order to avoid confusion, the results of the experiments are described assuming the direction of motion in the plume is upwards, as it is for the case of a thermal plume rising from a heat source. In Figure 4 the plume can be seen rising from the floor at the center of the model. The internal and external ends of the ducted opening (i.e., of the inverted chimney) are labeled "D" and "C" respectively, and the non-ducted roof opening is labeled "A."

As the plume rose it entrained the denser ambient air and, consequently, the temperature in the plume decreased with height and the volume of fluid it carried upwards increased (note the increase in the width of the plume with increasing vertical distance from the source). When the plume first reached the ceiling of the enclosure, it spread out horizontally to form a warm layer of air. As a result, the hydrostatic pressure difference inside the enclosure between the roof A and the floor B was less than that between the same heights (i.e., points C and D) inside the inverted chimney (assuming a small internal resistance for the inverted chimney). It is this stack pressure difference which then drives the flow. An inflow of air was observed through the ducted opening as indicated by the arrows in Figure 4. This ambient air was drawn down the inverted chimney and entered the space below at low level. Outflow of warm air from the space was through the non-ducted roof opening. There was little mixing between the incoming air and the air inside the space, and a displacement flow and two-layer stratification was established. The two-layer stratification can be clearly seen in Figure 4. A patch of neutrally buoyant dye released outside the model at roof level (at location C) was observed to be drawn down the inverted chimney and was discharged into the interior of the box at low level.

The warm upper layer of air gradually increased in depth and temperature until, after some time, a steady-state flow was reached. The steady flow was established when the air flow rate and heat flux through the upper opening A were equal to the flow rate and heat flux in the plume at the level of the interface. The temperature of the upper layer was then uniform and identical to the temperature in the plume at the level of the interface.

The smooth plexiglass inverted chimney (which had a diameter to length aspect ratio of approximately 1:4.5) did not significantly alter the ventilation flow rate through the space. In fact, the steady interface heights established with i) a top-down chimney (as in Figure 4), and with ii) "traditional" displacement ventilation (i.e., with the top-down chimney replaced by an opening of identical area at floor level) were very similar. This implies that the ventilation flow rates in cases i and ii are also similar and that frictional losses in the top-down chimney were of the same order of magnitude as those for the standard intake opening of the same diameter at floor level. The theoretical model of "traditional" displacement ventilation (1) by Linden, *et al.* (1990) therefore provides a good first-order estimate of the thermal stratification and airflow rates for top-down passive displacement ventilation when duct friction is low.

The experiments clearly demonstrate that it is possible to use stack forces to draw ambient air down into a space from roof level via an inverted chimney using a displacement mode of passive ventilation.

## INLET AND OUTLET AIR POSITIONS

Both Figure 3 and Hunt and Linden’s model, Figure 4, show air both entering and leaving from the top of the chamber.

Buildings are exposed to varying wind conditions which are exacerbated in urban areas by the proximity of other buildings. Regions of positive and negative wind pressures on a typical building on an exposed site are shown in Figure 5. It can be seen that air pressure on the windward side of the building is positive; at the roof it becomes negative and remains so on the leeward side. In built up areas, air movements are far more complex and thus the pressure distribution may be very different to that shown in Figure 5. Differences in pressure generated by the wind frequently exceed those in stack ventilation systems and, hence, if air is entering a building from a position of possible negative pressure, it is vital that the outlet is located in an area with a similar pressure regime.

FIGURE 5. Wind induced pressure zones around a building. Positive pressure Z is induced on the windward side of the building. Negative pressures Y are induced on the leeward facade, the side facades, and the roof.

In principle, it is possible to consider a common intake duct at external air temperature which can serve a number of floors below roof level. To be effective, this duct must carry air at external air temperature when this is cooler than the internal temperature. It is important, therefore, that the air in this duct does not heat up. This affects the intake configuration, which must be insulated and shaded. Sources of heat in the duct must be avoided, and the duct must be insulated from the surrounding building. These characteristics are not those of a glazed atrium. It is possible to speculate that buildings might contain tall dark shafts of minimal lighting and sparse occupancy which are architectural features; the design aspects of such a space would provide a research project in their own right, and in the first instance it is appropriate to look at devices which combine intake and extract ducts into a common rooftop element.

## RESEARCH AT THE BARTLETT

Work at The Bartlett has concentrated on investigating ways of "kick starting" and maintaining the ventilation and cooling strategy described above. This has two inherent problems.

Hunt and Linden’s laboratory experiments which start with the intake duct at external temperature have demonstrated that, if this is the case, top-down ventilation works; in practice, however, this cannot be assured even if the duct is well insulated and practical methods of cooling the duct, either to initialize or as a means of maintaining the flow, must be examined. A rather more difficult problem occurs when the external shade air temperature exceeds the building air temperature. This will occur during the day if the passive cooling design is successful. In this connection, the intake duct cannot be used for passive ventilation without other measures being taken.

Research is directed at examining wind-driven systems and intake duct cooling systems. This work involved making experimental installations and testing them. The work we have conducted is "full size." Full size in this context refers to prototype rooftop elements where no airways are less than 200 mm in diameter. At this scale air moves relatively freely, and absolute results can be given.

For ventilation purposes, average wind speeds for the U.K. are usually taken to be 4 m/s. The roughness of the urban terrain reduces this wind speed, and measurements at The Bartlett indicate that typical duct velocities rarely exceed 2 m/s. These relatively low duct velocities imply that large vent areas are required to provide the necessary air change rates. In turn, for economic reasons, the large duct sizes required limit the number of storeys that a top-down passive ventilation system can serve (e.g., in commercial buildings the more space used by ducts the less the usable space). If the maximum acceptable duct area to floor area ratio is x% then the maximum number of storeys $n_{storey}$ is given by:

where $H$ is the floor to ceiling height, $v$ is the duct velocity, and $ACH$ is the number of air changes per hour. In the case of a building with a floor to ceiling height of 3.5 m, ventilated at a rate of 10 air changes per hour with a duct velocity of 2 m/s, and with a duct area of 4% of the floor area, only 4 storeys can be served.

## WIND-DRIVEN EXPERIMENTS

An obvious model for a wind-driven intake stack is the traditional static Middle Eastern and Indian wind catcher (Figure 6). This design is simple to build, but has the disadvantage that it will fail to work as an intake for a broad range of wind directions. An earlier paper (Gage, 1997) describes our initial work on combined wind-driven intake and extract devices. An initial experiment was reported which suggested that these could achieve between 60% and 70% air speed efficiency (air speed in duct divided by wind speed) when considered as a complete ventilation system. Differences between inlet and outlet vent pressures of up to 10 pascals (Pa) were noted with a wind speed of 3.6 m/s. The significance of these results is that they confirm the dominance of typical wind-induced driving pressures compared to those induced by thermal effects.

FIGURE 6. Traditional windcatchers in Hyderabad Sind, India. Traditional windcatchers only work in conditions where there is a prevailing wind condition.

One of the difficulties in designing a passive stack ventilation system has already been described, namely, the ventilation can be significantly enhanced or hindered by wind pressure differences (Hunt and Linden, 1996). Even small wind speeds induce pressure effects which are comparable to typical stack ventilation effects, often in the order of 1 to 2 Pa. Most commercial passive ventilation devices work on the principle that an object placed in an airflow will induce a positive pressure on its windward side and a negative on its leeward side. A device of this nature will provide ventilation, but the direction of the airflow in the ducts below the device is dependent on wind direction. We now report on two devices which have been constructed for testing in field conditions. These devices, namely a rotating device and a static device, have been designed to ensure that the ducts below a wind catcher operate in a constant manner, irrespective of wind direction.

Both devices adopt similar principles with regard to air entry. An intake funnel is provided with an area 250% larger than the duct area below it. This enlarged area serves to reduce air velocity and resistance at two critical points. The first of these is at the point of entry where an insect mesh must be fitted.

A typical mesh has an opening of 1.4 mm x 1.4 mm and a wire diameter of 0.28 mm giving pressure drops in the order of 0.2 Pa at 0.5 m/s and 0.5 Pa at 1 m/s (Graham, 1998). The latter pressure drop is significant in magnitude given that stack ventilation pressures are typically only in the order of 1 to 2 Pa. Thus, by reducing the air speed incident with the mesh through the use of an enlarged air intake funnel, the loss in stack pressure may also be reduced. Pressure measurements made during wind tunnel tests showed that there was a negligible loss in pressure as a result of the addition of an insect mesh to an air intake funnel with a cross-sectional area three times that of the duct (Gage, 1998).

The second critical point is the location of wind-driven rainwater protection. This is usually achieved using double louvers in front of the insect screen. Typical manufacturers' literature gives resistances for this type of louver of the order of 2 Pa at 0.5 m/s air velocity and 9 to 10 Pa at 1.0 m/s. Resistances of this nature are excessive in any top-down passive displacement system. The resistance problem can be overcome by removing the louvers and placing a rain shield in an enlarged intake duct plenum below the intake hood. The low intake velocity means that the air intake must be shaded and insulated in order to prevent the incoming air from heating up.

If we consider a worst case scenario, namely, a matte black intake located in full sunlight (where heat gains are of the order of q=1000 W/m$^2$) and assume an airflow velocity v=0.5 m/s, then the temperature rise $\Theta$ of the air is given:

where $m$ is the mass flow of air per second through unit area of the intake. In this case the rise in temperature is approximately 1.7° C (taking the specific heat of air $c_p$=1000 j/kg and the density $p$=1.2 kg/m$^3$). Stack temperature differences are typically of the order of 5 to 10° C and, hence, allowing the intake temperature to rise through solar gains may result in a significant reduction in temperature difference and thus in driving pressure.

FIGURE 7. A rotating device.

## A ROTATING DEVICE

This device is shown in Figure 7 and consists of a fixed base section containing drain offs and a rain shield. On top of the base is a turntable, which contains air seals, and on top of this is a glass reinforced plastic (fiberglass) fabrication consisting of an intake hood and a duct leading vertically to a horizontal air outlet. The top fabrication is rotated by a wind-driven servo, or fan wheel, driving through a worm reduction gear to a friction wheel which bears onto the turntable. Fan wheels were used in the U.K. to turn windmills in the 19th century (Reynolds, 1970). This device is similar to those proposed by Michael Hopkins and Partners together with Ove Arup and Partners under the Joule 2 Program (Dunster and Pringle, 1997). The principle behind the operation of the device is in the aerodynamic profile of the vertical duct which causes the device to turn in a wind so that it always aligns itself with its leading edge into the oncoming wind (this natural tendency to rotate and face the wind is aided by a servo motor). In aligning itself in this fashion, the vents (labeled Y) at the top of the device face away from the wind (and are thus in a region of relatively negative wind pressure) and act as outlets, and those near the base of the device face into the wind (and are thus in a region of relatively positive wind pressure) and act as inlets.

Our experience with the device, which is currently under test, is that it has the following advantages and drawbacks:

The airflow below the device is predictable in direction. It is possible, therefore, to consider treating the air on intake by cooling duct walls or assisting its flow by incorporating low energy fans to drive the air down into the space below. A single servo will ensure that the device turns in accordance with wind direction, and it is possible to vertically separate intake and outlet air streams. These are considerable advantages. The device does, however, have intrinsic disadvantages. Some of these relate to fabrication difficulties; probably the most significant of these is the introduction of large ring seals which must be air tight without inducing undue friction.

A more fundamental problem relates to the complex air movements that take place in an urban context, where gusting and vortex formation with consequent rapid changes in wind direction are common. Because the servo takes time to accommodate to wind direction change, it is possible that this type of device will not rotate fast enough to avoid pressure inversions. A further problem relates to the "start-up" wind speed (i.e., the minimum wind speed required to rotate the device). This is an engineering issue and depends on the inertia of the moving cowl and friction in gears and in seals. The average U.K. summer wind speed is of the order of 4 m/s and significant duct pressures are possible at wind speeds which are half this or less. The large rotating cowl is a potentially expensive fabrication, and wear on the mechanical parts needs careful consideration.

FIGURE 8. A static device. The intelligent windvane X infers duct pressure Z and Y from the prevailing wind direction. Dampers W and V are opened while dampers U and T remain shut. Air enters the room through W and exits through V.

FIGURE 9. A static device. When the wind direction changes, the intelligent windvane infers the changed location of duct pressures Z and Y. Dampers U and T are opened. Air enters the room from U and exits from T.

**THE STATIC DEVICE**

The static device is similar to a modern or traditional split-duct "wind catcher" and could be fabricated in an identical manner. The static device we consider consists of a four way split duct with vents orientated to form quadrants (Figure 8). Vents which are pointing towards the wind will be placed under positive pressure, while vents which are pointing away from the wind are under negative pressure. The ducts below the device have similar pressure characteristics to those generated at the vents.

In contrast to the rotating device in which each of the two ducts was permanently assigned to act either as an inlet or an outlet, individual ducts of the static device act as inlets only while the wind pressure on them is positive. Through a system of dampers (which open and close off the ducts in appropriate ways), these "inlet" ducts become outlets if the wind pressure is negative. An "intelligent wind vane" has been developed which contains a microprocessor and drives inlet and outlet dampers in the split duct. The wind vane infers the duct pressure from the wind direction and can switch the dampers open or closed so that intake is always at the bottom of the space served and extract is always at the top (Figure 9).

FIGURE 10. Cooling by a roof garden. The concept shown is to use the roof garden to take in ambient air from F and cool it down by evapotranspiration so that the temperature at B, C, and D is cooler than the temperature at A. The concept only works in the morning and the evening (see Figure 11).

The advantages and disadvantages of the static device are the mirror image of those of the rotating device. It has a fast response, and both seal and wear problems are reduced. It is also considerably simpler to construct. The device is variable in the sense that the microprocessor can be programmed to differentiate between summer and winter conditions.

The Hopkins/Arup research (Dunster and Pringle, 1997) suggests that the static device is, however, substantially less efficient than the rotating device. Negative and positive wind pressures at the openings of the static device are not as extreme as for the rotating device and, hence, the driving pressures and consequently its efficiency are reduced compared to the rotating device. Our intention is to verify, at low wind speeds, the findings of Dunster and Pringle (1997) where there are complex criteria for desired performance.

## COOLING THE INTAKE DUCT

When the external air temperature is higher than the internal air temperature, the intake duct will cease to work as a gravity siphon and a purely passive top-down mode of ventilation will not be possible. Under these conditions the duct can only deliver daytime ventilation if air is forced down by a fan, or wind pressure, or if the air in the duct is actively cooled.

There are considerable advantages to cooling the incoming air. If cooling is not employed, warm air entering a space (by forced means) at low levels will rise through and mix with the cooler surroundings thereby disturbing the stable stratification pattern in the space. This will not occur if the air is cooled to below room air temperature. Cool air entering the space will also give a thermal advantage by taking up some daytime gains.

Most methods of air cooling rely on fans which drive air through heating exchangers which have a relatively high level of resistance to air movement. Clearly, this is not appropriate to a passive intake stack. We must therefore look at simple devices which cool the air without impeding the airflow.

## EVAPORATIVE COOLING

Intake air can either be cooled by using phase change in water (latent heat of evaporation) or by refrigeration. We have examined various evaporative cooling techniques. The cooling power of water evaporation has been known for many years; desert coolers included devices for cooling intake air using unglazed earthenware and wet cloth. More recently, work by Cook, *et al.* (1997) has explored the use of falling water droplets in downdraught evaporative coolers. These are potentially successful; they do, however, introduce a legionnaire risk and potential water damage into a building.

## ROOF GARDENS

Evapotranspiration from plants has been suggested as a way of reducing temperatures in and around buildings, and as a method of cooling ventilation air (Barroso-Krause, 1993). Experiments which suggest that shaded roof gardens have a limited role in this application have been reported elsewhere (Gage, 1997). The idea that a roof garden could be a source of tempered air is very attractive because it combines internal and external amenity for building uses (Figure 10).

No evidence has been presented to disprove Long, *et al*. (1964) (as reported in Oke, 1978), who found that planting appears to extend the period of available night-time cooling. The presence of plant life is to create a microclimate in which temperatures at plant level fall below shade temperatures above the plants in the early evening and remain lower until early morning. During this period of the day and night, strategically located plant life (Figure 10) may thereby enhance any passive cooling. Around midday, however, the presence of plant life offers no advantages through evapotranspiration as air temperatures in planted areas are somewhat higher than external shade air temperatures (Figure 11).

FIGURE 11. Wind speed, temperature, and vapor pressure in a barley field by Long, *et al*. (1964), reported in Oke (1978). Temperatures in the stand of vegetation are lower at night, in the morning, and in the evening, but are hotter at midday, in comparison to shade temperatures above the field.

## REFRIGERATION

Refrigeration as a mode of "top-up" cooling to passively ventilated buildings is often thought of as a separate system to the passive ventilation system itself, and usually as a system of cooled pipes and panels.

Taking air into the building from the top offers significant advantages. In a system of top-down ventilation it is possible to use gravity chillers of the type used in cold stores to directly cool the incoming

FIGURE 12. Proposed heat pump-assisted top down ventilation. A heat pump 1 powered by a photovoltaic panel K takes heat out of the air at the top of duct 2 via a chiller panel H and dumps it into the top of duct 1 via a heater panel G. Temperatures in duct 2 will be lower than the ambient external shade temperature.

air. Refrigeration can be provided by conventional equipment, which can be driven by photovoltaic panels without the use of batteries (Figure 12).

We propose, in the next stage of our work, to construct equipment to test the efficiency of this approach. Our proposed test equipment will exploit techniques developed in the static wind- driven device shown in Figure 9 in order to avoid wind-induced pressure inversions in cooling ducts. This work will appear as the subject of a separate paper.

## CONCLUSION

Research to date suggests that it is possible to passively ventilate and cool urban buildings, taking air into these buildings from the top. In a displacement ventilation system this involves incorporating an "inverted chimney" into the design. The inverted chimney extends from roof level to near floor level in the room in which the ventilation is sought. Our hypothesis has been confirmed for the case of a well-insulated naturally ventilated building with low internal duct resistances through laboratory experiments in water tanks.

This approach, referred to as "top-down" ventilation, requires large vertical supply and extract ducts in order to minimize pressure losses through duct friction and is, in consequence, only appropriate for low and medium rise buildings. In taller spaces, the large duct diameters required to give suitably low internal duct resistance may prove impractical.

It is probable that a very simple active cooling strategy can be adopted to induce ventilation in the afternoons on hot days. This will also serve to enhance internal conditions during the period when diurnal passive cooling is most likely to fail.

This type of top-down ventilation and cooling system can be wind assisted and both rotating cowl and fixed cowl devices are a possible means of achieving this, the latter being significantly easier to construct. Harnessing the wind to assist the stack-driven flow could allow reduced duct dimensions and thereby extend the range of applicability of the top-down technique to include taller spaces.

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