Natural Ventilation in Passive Design

Richard Aynsley

This note, Tec 2, originally published in May 1996, was reviewed by Richard Aynsley in May 2001, and again in May 2007. This summary page includes recent updates to the topic since publication.

Summary of

Actions Towards Sustainable Outcomes

Environmental Issues/Principal Impacts

- Natural ventilation can save significant amounts of fossil fuel based energy by reducing the need for mechanical ventilation and air conditioning.
- Reduced use of air conditioning reduces greenhouse gases released into the atmosphere from electricity generating plant that produces the energy used for cooling buildings.
- Air movement within buildings removes foul air and moisture and provides cooling in summer, for human thermal comfort.

Basic Strategies

In many design situations, boundaries and constraints limit the application of cutting EDGe actions. In these circumstances, designers should at least consider the following:

- Take advantage of light summer winds in the design of the site layout and building form.
- Orient buildings to maximise their exposure to the prevailing summer wind direction.
- Design buildings with a relatively narrow plan form across the prevailing wind direction, to facilitate the passage of air through the building.
- Locate wall openings to facilitate the passage of air through the building.
- Use water features in, or near a building to engender a sense of coolness.
- Use passive evaporative cooling methods in hot dry climates, by passing incoming air over or through wetted surfaces.
- Use vegetation to modify the external wind direction, to enhance ventilation and cool incoming air.
- Utilise ceiling fans where appropriate to minimise the need for refrigerated air conditioning.

Cutting EDGe Strategies

- Horizontal openings near floor level are more effective than vertical openings, for ventilation purposes.
- Elevate rooms above the ground to catch stronger winds.
- Use three dimensional wind tunnel or computer flow visualisation studies of breeze paths to optimise the placement of windows and furniture.
- Use solar chimneys to increase airflow in temperate climate regions.
- Thermal comfort in warm humid environments is best evaluated using new Environmental Temperature technologies, (see all references, below), together with the cooling effect of air movement.

Synergies and References

- Auliciems, A & Szokolay, S, 1997, *Thermal Comfort*, PLEA Note 3, Passive and Low Energy Architecture International in association with the University of Queensland Department of Architecture, Brisbane, p64.
- Awbi, HB, 1995, *Ventilation of buildings*, E & FN Spon, London, pp313.
- *BEDP Environment Design Guide*: Gen 12, Gen 33, Des 12, Des 20.
- Docherty, M & Szokolay, S, 1999, *Climate Analysis*, PLEA Note 5, Passive and Low Energy Architecture International in association with the University of Queensland Department of Architecture, Brisbane, p56.
- Hyde, R, 2000, *Climate Responsive Design: A study of buildings in moderate and hot humid tropics*, E & FN Spon, London, pp244.
- Aynsley, R, 2006, *Indoor wind speed coefficients for estimating summer comfort*, International Journal of Ventilation, Special edition, Vol 5, No 1, June, pp3-12.
- *ARCHIPAK* (Windows 2000 version), by Steve Szokolay is a passive design software program which can be used to estimate thermal comfort zones, including the cooling effect of airflow. The software can be ordered from PO Box 851, Kenmore, Qld, 4069 or by fax + 61 7 3378 1051.

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This Note provides a basic introduction to the lost art of designing for natural ventilation, and discusses some of the more useful rules of thumb. It considers the principal factors affecting air movement, wind pressure and thermal comfort.

1.0 Introduction

Natural ventilation is clearly a valuable tool for sustainable development as it relies only on natural air movement, and can save significant amounts of fossil fuel based energy by reducing the need for mechanical ventilation and air conditioning. Reducing electrical energy used for cooling contributes to the reduction of greenhouse gas emissions from the electrical generating plant providing the energy.

From the earliest times building designers have made use of naturally induced air movement to address two basic needs in buildings: the removal of foul air and moisture, and personal thermal comfort.

Since the 1950s the use of mechanical ventilation and, particularly, air conditioning has been adopted as a means of compensating for excess heat gains experienced in many modern lightweight and highly glazed buildings. This increased use of mechanical services has provided building designers and clients with a great deal of freedom in terms of envelope design and internal flexibility. However, the cost has been much higher energy consumption and the introduction of centralised control systems, rather than user-based controls.

The need to reduce our consumption of energy and to give users more control over their immediate environments, are good reasons for designers now to re-evaluate the role of natural ventilation in buildings and to become familiar with the basic principles involved.

Air movement in and around buildings is a complex, three-dimensional phenomenon. At present the tools available to design for good natural ventilation are either inexact rules of thumb, or complicated wind tunnel or computer based modelling techniques.

1.1 The use of Natural Ventilation

The real test for naturally ventilated buildings is the provision of adequate cooling in summer. Under this condition it is necessary to have sufficient external wind pressure to create air movement within the building and, particularly, through the occupied zones.

Under hot, dry summer conditions, when the outside air temperature is well above the tolerable internal level, it may be necessary to shut off the external air altogether until the temperature drops to more acceptable levels. In pre-second world war buildings such as schools and hospitals, this was allowed for by having very high ceilings to store large volumes of air, and by using ceiling fans to provide personal cooling.

In warm, humid climates, natural ventilation is utilised to enhance indoor thermal comfort by reducing the effects of relative humidity above 60%.

The other testing time for naturally ventilated buildings is in cold winters. The challenge then is to restrict incoming air to achieve the minimum necessary fresh air without causing cold draughts or excessive heat loss. Even under calm winter conditions the difference in temperature between the building interior and outside air will usually create sufficient stack effect to draw in fresh air.

The stack effect is brought about by warm air rising up to be exhausted through high level outlets and so drawing in colder, heavier air from outside. Open fires are an extreme form of this with air being exhausted up the flue.

In practice, the use of natural ventilation in modern buildings is most common in relatively low rise, shallow plan buildings such as housing, schools, health centres and small office units. An air movement of 1.0 m/s is the limit before papers on a desk will start to blow around.

Dry bulb	Met	Clo	Relative humidity %	Air max (m/s)	Air min (m/s)
21	1	0.9	40	0.1	none
21	1	0.9	60	0.1	none
21	1	0.9	80	0.1	none
24	1	0.9	40	0.1	0.1
24	1	0.9	60	0.1	0.1
24	1	0.9	80	0.1	0.1
27	1	0.5	30	0.95	0.6
27	1	0.5	50	1.35	0.6
27	1	0.5	75	2.05	0.6

Where: Met is the metabolic rate. For a sedentary person 1 met = 58.1 W/m²
Clo is the unit of thermal insulation of clothing, 1 Clo = 0.155 m².k/W

Table 1. Recommended Air Velocity Rates for Interiors (when occupied)
Source: ASHRAE Thermal Comfort Tool (software).

Natural ventilation is often not used for tall buildings in temperate and cold climates, partly because of excess wind speeds at higher levels, but also, due to problems arising from the stack effect. Natural ventilation is frequently utilised for tall residential buildings in warm humid tropical climates, where average wind speeds are lower than those in temperate latitudes, and stack effects are small. For deep plan buildings, natural ventilation is unsuitable because the air tends to become contaminated long before it is exhausted to the outside.

Today's passive solar and energy efficient buildings are reliant on effective natural ventilation as one of their main strategies for the maintenance of thermal comfort.

1.2 Achieving Ventilation

The principal factors affecting natural air movement around and within buildings are:

- the site and local landscaping features
- the building form and building envelope design
- the internal planning and room design.

Each of these is described in the following sections.

2.0 Influence of Site and Landscaping Features

It is important to check on local wind conditions and factors that might influence local conditions when designing for a particular site. Ideally there should be some light winds in summer to provide sufficient internal air movement for thermal comfort during all but extreme conditions, and for night time cooling of the building.

In winter the problem for temperate and cold climates is to avoid excessive wind through ventilation openings and leaks in the building envelope.

Local wind speeds can be estimated from Bureau of Meteorology wind data, which is usually recorded 10 metres above the ground at local airports. This information has to be moderated according to local factors such as shelter belts and large buildings. The effects of shelter on wind speed can be estimated using Australian Standard AS 1170 Pt. 2-Wind Loads.

Wind speeds at 500 metres above ground level are fairly constant. Wind speeds below this level are slowed to varying degrees by the roughness at the ground surface. This slowing in mean wind speed is greater in rougher terrain such as urban centres (Table 3). The reference for these relative wind speeds is the wind speed 10 metres above ground level in category 2 terrain roughness, which represents that at airports. In areas without significant hills and valleys, knowing the mean wind speed at a nearby airport, one can estimate the wind speed at various heights in terrains of different roughness from Table 2. When there are substantial hills, corrections can be made to estimated mean wind speed by multiplying wind speeds by the appropriate factor from Table 3.

Topographic features such as hills, ridges and escarpments can have a marked influence on local wind speeds. Winds can be accelerated by up to 54% on the windward side of a hill. Conversely on the leeward or sheltered side of the hill the wind speeds near the ground are usually reduced and the wind direction changed (and even reversed if a recirculating eddy is formed).

Average Slope	Lower Third	Middle Third	Top Third	Over Top
≥1:10 <1:7.5	1.0	1.0	1.15	1.0
≥ 1:5 <1:7.5	1.0	1.0	1.25	1.0
≥ 1:3 < 1:5	1.0	1.15	1.4	1.15
≥ 1:3	1.0	1.25	1.55	1.25

Table 2. Multipliers for Wind Speed Over Hills and Escarpments

Height (metre) above ground	**Category 1** (Water) Log Law	**Category 2** (Airport) Log Law	**Category 3** (Suburb) Log Law	**Category 4** (Urban) Power Law
500				159%
400			159%	146%
300		159%	152%	132%
200	156%	152%	143%	114%
100	147%	140%	128%	89%
50	138%	128%	113%	69%
30	132%	119%	101%	58%
20	126%	112%	93%	50%
15	123%	107%	86%	45%
10	117%	100% Ref	77%	39%
9	116%	98%	75%	37%
8	115%	96%	72%	36%
7	113%	94%	69%	34%
6	111%	91%	66%	32%
5	109%	88%	62%	30%
4	106%	84%	57%	28%
3	102%	79%	51%	25%
2	97%	72%	42%	
1	88%	60%	27%	
0.5	84%	48%	11%	

Table 3. Reduction in Wind Speed Due to Roughness of Terrain

2.1 Water Features and Vegetation

A water feature in or near a building can engender a sense of coolness. This psychological effect can be enhanced by 'sensible cooling' if, in medium to low humidity conditions, water which is significantly cooler than indoor air is used as a thin film cascade or fine fountain spray to maximise its surface area contact with the indoor air.

Evaporative cooling uses the latent heat of evaporation to cool hot dry air as it passes over or through wetted surfaces. Provided the ambient air is hot and dry, the cooling effect can be significant. This process has been used for thousands of years in traditional buildings in desert regions (Koenigsberger et al, 1974). Similar cooling occurs by evaporation of moisture from the surface of soils and transpiration by plants – the evaporation of water via leaves into the air. The rate of evaporation from soil and transpiration from leaves increases with wind speed over the ground or leaves.

Vegetation can be used to modify the external wind direction so as to enhance ventilation, as well as cool incoming air. As a bonus, fragrant species can be used to perfume the air flowing through buildings.

It is important, however, to keep dense shrubs and tree canopies clear of windows and other air inlets to the building.

Grassed berms can also be used adjacent to buildings to direct the wind as required for natural ventilation.

3.0 Building Form and Building Envelope Design

Naturally ventilated buildings should be oriented to maximise their exposure to the required (summer) wind direction, and designed with a relatively narrow plan form to facilitate the passage of air through the building (cross ventilation). Solar heated buildings require particular attention in order to optimise both the solar and ventilation requirements. Ideally, solar orientation and breeze paths coincide.

Single story deep plan buildings can be naturally ventilated through roof outlets, but ceiling fans are necessary for summer thermal comfort away from the perimeter zone (Aynsley, 2006).

The minimum size of openings for ventilation purposes, are specified by the building regulations but there is no guidance for the maximum size of opening. For warm humid conditions it might be desirable to have virtually 100 % openings but, realistically, the air inlets should be designed for personal comfort, taking into account other requirements such as sun control, security, privacy and potential heat losses in winter.

Windows should be located to receive the prevailing wind for summer conditions and, ideally, be installed on both sides of the occupied spaces to provide cross ventilation.

If appropriate, horizontal openings near floor level are more effective than vertical openings for ventilation purposes.

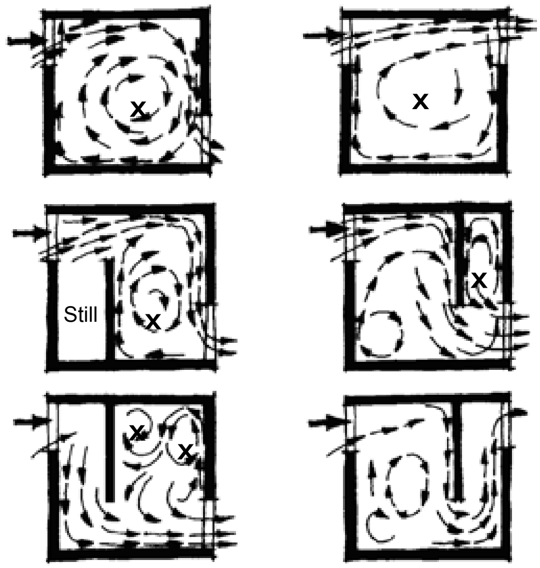

Figure 1. Flow Patterns Through Internal Spaces (Givoni, B. 1981, *Man, Climate and Architecture*, Van Nostrand Reinhold, New York, p 303)

Friction-stayed casement windows on the windward side of the building offer some directional control of indoor airflow into occupied zones. Casement sashes or hinged doors can be up to 60% more efficient than other sashes or sliding doors on windward walls for capturing incidental air flow.

Sliding windows are problematic in that only half of the window can be opened, and they cannot be adjusted according to the wind direction.

Extending eaves and taking cross walls out to the eaves line will tend to trap and channel the wind into the building.

Rooms elevated above ground level will catch stronger winds (this may be counterproductive if the rooms then become shielded by the tree canopy).

Operable windows or air outlets on the leeward side of the building are as important as those on the windward side. Incoming air slows down within the building and so, to maximise the ventilation, the total air outlet area should be larger than the air inlet area.

If it is only possible to ventilate a room on one facade then windows should be located to provide ventilation openings at different heights to induce some local air movement. For example, double hung sash windows can be adjusted to allow fresh air in at the low level and exhaust air out at the top.

4.0 Internal Planning and Room Layout

To facilitate the natural ventilation of rooms, the resistance to airflow through the building has to be minimised. This means having large openings for the passage of air, and reducing the number of rooms through which the air has to pass. A good example of this is a school classroom with verandah access and windows along opposite walls.

Obviously there is a potential conflict between designing for free air movement and other design requirements. For example, large wall openings for natural ventilation, particularly near ground level, can compromise security unless security screens are fitted.

Also, locating ventilation openings in internal walls and partitions may cause excess sound transmission, or have implications for fire safety.

To be effective for personal thermal comfort, the air path through the building must pass through the zones frequented by the building occupants, that is, within 2 metres of floor level. Airflow above the heads of occupants is of little value in summer, but can be useful in winter for achieving minimum ventilation needs while avoiding draughts. For indoor cooling, arrange seating and beds so they are in the main airstream.

Wall openings adjacent to a cross wall encourage the jet of airflow through the opening to cling to the cross wall and so, for particularly warm conditions, seating or beds located against the cross wall would benefit from this airflow.

Airflow through openings in the centre portion of windward walls tends to maintain the same direction as the approaching wind. Therefore, seating or beds should be placed close to such openings.

Slow moving eddies form on the extremities of the incoming air stream from windward openings and are less effective for indoor comfort cooling.

Three-dimensional wind tunnel or computer flow visualisation studies of breeze paths can be used to optimise placement of furniture for indoor thermal comfort. It is advisable to model furniture in the flow to account for the full impact of its presence on the breeze path. It is necessary to study breeze path patterns for all prevailing wind directions (noting their relative frequency and wind speed from nearby airport wind records) as the location of openings may need to be adjusted to achieve optimum performance. In hilly terrain, wind directions at a building site need to be checked against those recorded at the airport, and changes in direction at the site noted for each wind direction at the airport.

5.0 Principles of Thermal Comfort

5.1 Physical Thermal Comfort

In the past there have been a number of studies to determine the effects upon subjects of various combinations of air temperature, radiant temperature, relative humidity and air movement, for determining human responses to thermal conditions. These have shown that there is a range of conditions in which subjects judge themselves to be thermally comfortable in naturally ventilated buildings. Outside this range subjects become uncomfortably hot or cold, depending primarily on the air temperature.

The thermal comfort range to satisfy 80% of people extends approximately 3.5K above and below this neutral temperature (with K designating the temperature difference on the Celsius scale).

In warm humid climates, thermal neutrality of occupants of naturally ventilated buildings using this equation is up to 3K warmer than the thermal neutrality predicted for occupants of air conditioned buildings using the results of Fanger (1972).

$$Tn = 18.9 + 0.255\ ET^*$$

One useful model predicts a temperature for thermal neutrality (Tn), which is the central comfort point, based on the mean monthly outdoor effective temperature (ET*). This is found on a psychrometric chart at the intersection of the average of maximum and minimum monthly air temperatures, and the average monthly relative humidity from RHam and RHpm data, and reading off the ET* on the psychrometric chart for that condition.

Equation 1. To Calculate a Temperature for Thermal Neutrality
(Auliciems & Szokolay)

5.2 Adjustments to Thermal Comfort Range

The following adjustments have been suggested by Macfarlane (1958) for comfort zones in naturally ventilated buildings.

- Thermal comfort zone temperatures are likely to be lowered by 0.8K for each 10% increase in relative humidity when relative humidity exceeds 60%.
- Thermal comfort zone temperatures are likely to be lowered by 0.55K for each 2.8K increase in internal surface (radiant) temperatures above 38°C.
- Thermal comfort zone temperatures are likely to be raised by 0.55K for each 0.15 m/s of airflow past exposed skin, up to air temperatures of 33°C.

These adjustments indicate the adverse influences of high humidity and radiant heat gain, and the beneficial effects of airflow in critical conditions such as warm humid climates. Although airflow above 1.0 m/s may disturb loose papers, some office workers manage with airflows of up to 2.2 m/s. In humid tropical climates, airflow with wet bulb air temperatures above 36°C (core body temperature) no longer enhances thermal comfort (Wyndham and Strydom, 1965).

Using survey data by Khedari et al (2000) in Thailand, the writer constructed a graph: Figure 2, relating the cooling effect of air movement to ambient relative humidity. These data relate to subjects in normal summer clothing engaged in sedentary activity.

5.3 Bioclimatic Charts

Comfort zones are often shown graphically on a bioclimatic version of a psychometric chart. For example the mean monthly outdoor dry bulb temperature for Townsville during January is 27.6°C with a relative humidity (RH) of 62% (Szokolay, 1987).

This still air comfort zone, indicated in section 5.1, can be extended into higher dry bulb air temperatures by providing natural ventilation. Select the airflow provided by natural ventilation or fans along the bottom of Figure 2, and extend a line vertically until it intersects the appropriate RH line.

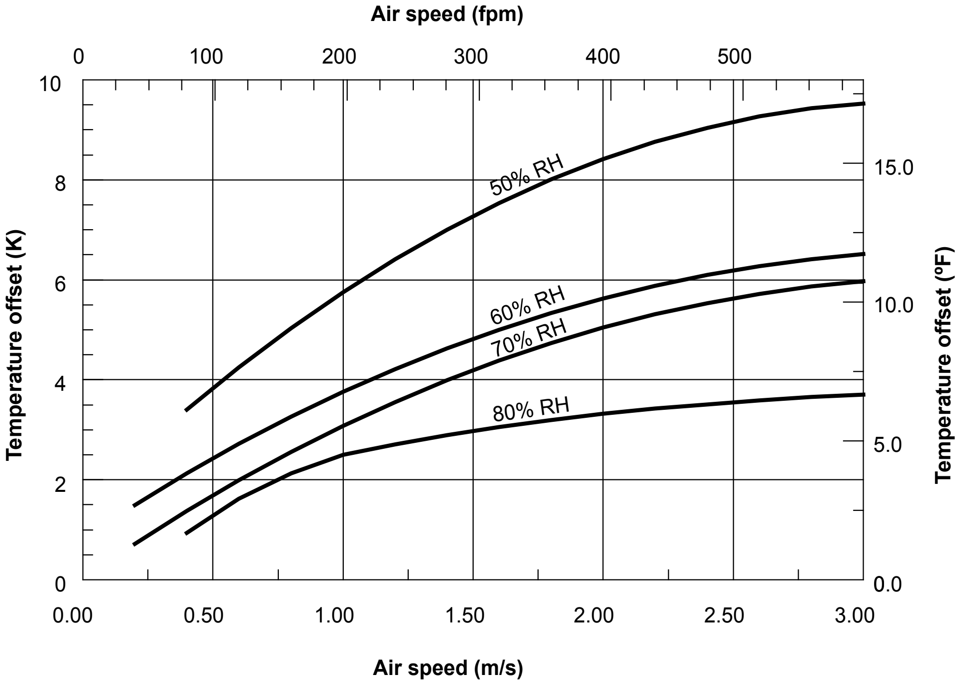

Figure 2. Cooling Effect of Air Movement after Khedari et al (2000)

From that point extend a horizontal line to the left and read off the cooling effect on building occupants. This cooling effect is due to enhanced convective and evaporative heat transfer from the occupants' skin. There is no reduction in the air temperature in the space.

6.0 Pressure Sources for Air Flow

6.1 Wind Pressures

Natural ventilation is induced by differences in air pressure across the building. The essential principle is that building walls obstruct airflow and so create wind pressure differences between windward and leeward walls. The effective pressure difference tends to be greatest (about 1.4 times the dynamic pressure at eaves level for typical rectangular buildings), when wall openings are about 15% to 20% of wall area (Aynsley et al, 1977). This means that average wind speeds through wall openings have the potential to be 18% higher than the local wind speed.

Without any openings the wind pressure difference is about 1.1 times the dynamic pressure at eaves level. With a 60% wall opening or more, the wind pressure difference between windward and leeward surfaces remains constant around 1.0 times the dynamic pressure at eaves level.

At any given time the differences in wind pressure between various points on the surface of buildings vary with wind speed, wind direction and building shape.

The wind pressure at a particular point on the external surface of a building can be calculated using the equation:

$$P_1 = C_{P1} \times 0.6V^2$$

Where:

P_1 = Wind pressure on a solid building surface at a point 1, in Pascals

C_{P1} = Wind pressure coefficient for that area of the surface for a particular wind direction, dimensionless

V = Wind velocity approaching the building in metres per second at a height equal to eaves height, in metres per second.

Equation 2. To Calculate the wind pressure on an a building exterior

While wind pressure distribution data over simple building shapes are available in many publications, these pressures on solid shapes represent the static pressure over building surfaces (Sawachi et al, 2006). The wind pressure on windward surfaces of buildings that drives natural ventilation through openings is the sum of both static pressure and dynamic pressure. The dynamic pressure at windward openings in cross-ventilated buildings increases with the porosity of the building (ratio of area of wall openings to area of walls). Indoor pressure coefficients influence the discharge through wall openings (Equation 3). For cross-ventilated spaces the normal wind indoor pressure coefficients are around 0.6, but at inclined incidence, or breeze paths through the space and exiting via the side walls the coefficient can fall to around 0.2.

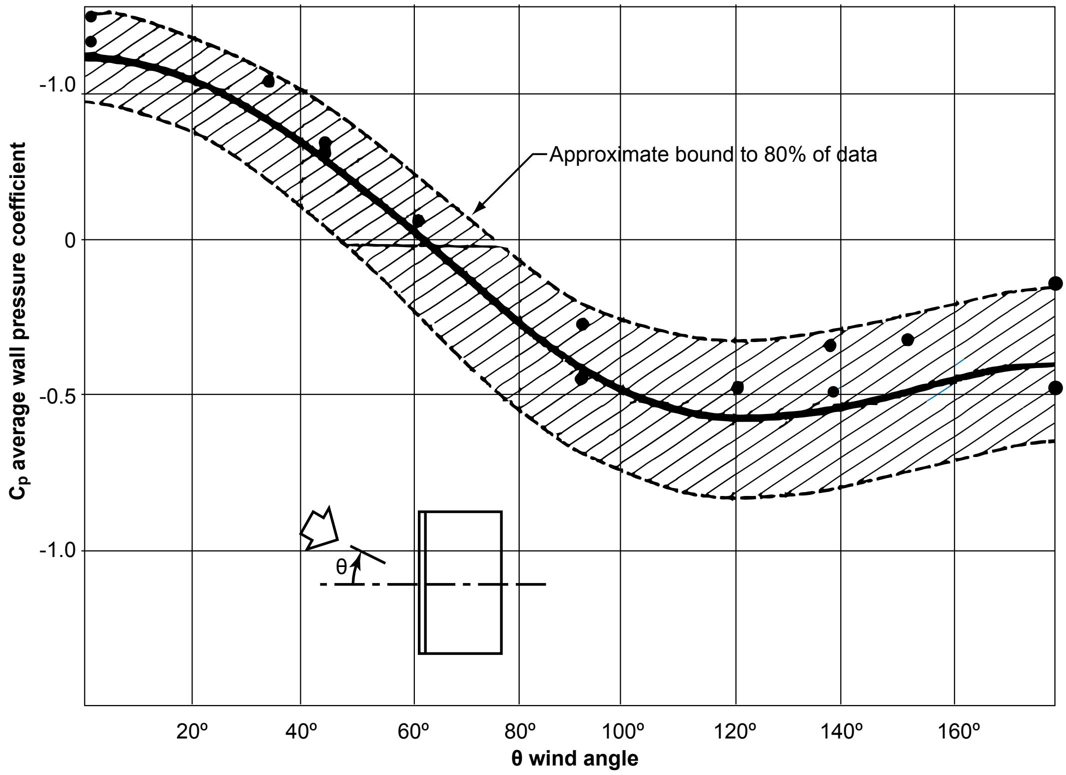

Figure 3. Typical Wall-averaged Wind pressure Coefficients for Low-rise Buildings
(Swami & Chandra, 1987)

$$Q = C_d A (2(p_t - p_s)/\bullet)^{1/2}$$

Where:

Q	is the discharge through an orifice
Cd	is the discharge coefficient for the orifice (opening)
A	is the area of the orifice
pt	is the total pressure across the opening
ps	is the static pressure in the space downstream of the orifice, and
•	is the mass density of the air, all in consistent units

Equation 3. To Calculate the Flow Rate through a Wall Opening

The discharge of air through an orifice is a function of the discharge coefficient (efficiency) of the orifice (opening), and the pressure difference between the total pressure (dynamic plus static) across the orifice, and the static pressure (often measured on the ceiling) of the downstream space. For airflow into and out of a building space, the ratio of the outlet opening area to the inlet opening area, as well as the straightness of the breeze path, will influence the static pressure in the space (Karava et al, 2006; Heiselberg and Sandberg, 2006; Vickery & Karakatsanis, 1989).

Data on the dynamic pressure near openings in windward surfaces is not readily available except from detailed Computational Fluid Dynamics (CFD) modelling (Kurabuchi et al, 2006). In technical publications where discharge coefficients for building openings are greater than 1.0, i.e. 100% efficient, this indicates that the reference pressure difference used is static pressure difference and the dynamic pressure on the windward side of the opening has been ignored.

The common practice of using the static pressure data for estimating airflow through windward openings in well-designed buildings, together with a discharge coefficient of around 0.6, can result in underestimation of airflow by up to 50% or more, particularly if openings have casement sashes (Heiselberg & Sandberg, 2006). On the other hand, estimates of ventilation using this method can over estimate natural ventilation by up to 66% in buildings that are poorly designed for natural ventilation.

Current best practice for estimating natural ventilation through large openings is to seek assistance from experienced consultants who use calibrated computational fluid dynamics software with large eddy simulation capability, or measurement of indoor wind speed coefficients inside hollow models with relevant openings and surrounding obstructions in a boundary layer wind tunnel.

6.2 Stack Effect

The stack effect is derived from differences in air density, which usually develop as a result of the differences in temperature between building interiors and outside air. These produce differences in air pressure that can be used to induce air movement through buildings.

The efficiency of stacks can be improved by:

- Increasing the stack height.
- Increasing the temperature difference between the bottom and top of the stack.
- Minimising the airflow resistance through the stack by minimising the number of bends, and ensuring they have a generous radius.

Note that ventilation stacks relying on temperature differences are more efficient as exhaust stacks. This is because the buoyancy force of warm air assists suction force from wind at the top of stacks. Stack outlets with rotating cowls are insensitive to wind direction.

When openings at the top of stacks are used as air intakes or air scoops, orientation of the intake opening to the wind becomes very important with respect to the airflow efficiency of the opening. For this reason, rotating cowls that automatically align the intake opening into the wind should be considered. Stack ventilation systems are more complex than most architects imagine and use of specialist consultants is advised.

6.3 Solar Chimneys

Solar chimneys are stacks incorporating flat plate or trombe wall solar collectors, which heat the contained air when exposed to sunlight. The heated air expands, decreasing its density, and begins to rise by gravity toward the chimney outlet, pulling cooler interior air up into the collector to be heated and continue the airflow.

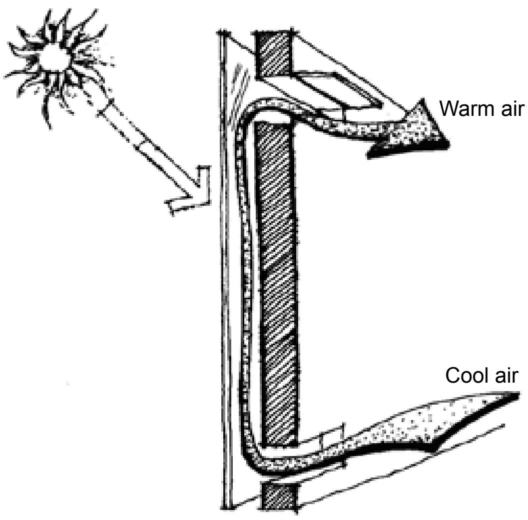

Figure 4. The Solar Chimney Effect

The efficiency of solar chimneys can be improved by:

- Increasing the stack height.
- Increasing the temperature difference between collector and ambient air.
- Minimising the airflow resistance through the chimney by minimising bends.
- Reducing airflow resistance through the chimney with generous radius to bends.
- Designing inlet openings as wind tower scoops facing the prevailing wind.

Care should be taken to provide sufficient insulation to the interior side of solar collectors to prevent unwanted indoor heat gain from solar collectors.

Ventilation from the combined effects of a solar chimney and wind towers can be estimated using equations developed by Bansal et al (1994).

6.4 Pressure Differentials and Airflow

Where a space has multiple inlet and outlet openings, direct calculation of the airflow rate is not possible, and so it is necessary to obtain expert assistance from consultants using boundary layer wind tunnel tests or computational fluid dynamics computer programs.

6.5 Combined Stack and Wind Pressure

Where both wind pressure difference and stack effect are acting, they are added to give the total pressure differential. The airflow resulting from the combined effects of wind and stack effect is less than many designers expect, because the airflow is proportional to the square root of the total pressure difference (ASHRAE Fundamentals).

6.6 Indoor Wind Speed Coefficients

Given the difficulties in determining airflow through windward wall openings, a more direct approach to describing natural ventilation through buildings is the use of indoor wind speed coefficients (Aynsley, 2006). An indoor wind speed coefficient is the ratio of average indoor wind speed, to the unobstructed outdoor wind speed. The outdoor reference wind speed is often chosen as the wind speed measured 10m above ground level at a nearby airport, to allow estimates of probability of effective natural ventilation during particular months of the year at that location. Contemporary residential subdivisions, with up to 50% ground cover by houses, severely restrict opportunities for natural ventilation.

Contemporary Australian houses in small lot subdivisions have indoor wind speed coefficients around 0.24 (ranging between 0.05 and 0.65) when referenced to local 10m airport wind speeds. Cross-ventilated houses specifically designed by architects to optimise natural ventilation achieve indoor wind speed coefficients around 0.6 (ranging between 0.5 and 1.1). Before architects get too excited regarding their skill at natural ventilation, it should be noted that the indoor wind speed coefficient in a traditional Samoan fale is around 2.0 due to the high steep-pitched roof and their wind-exposed location along the shoreline.

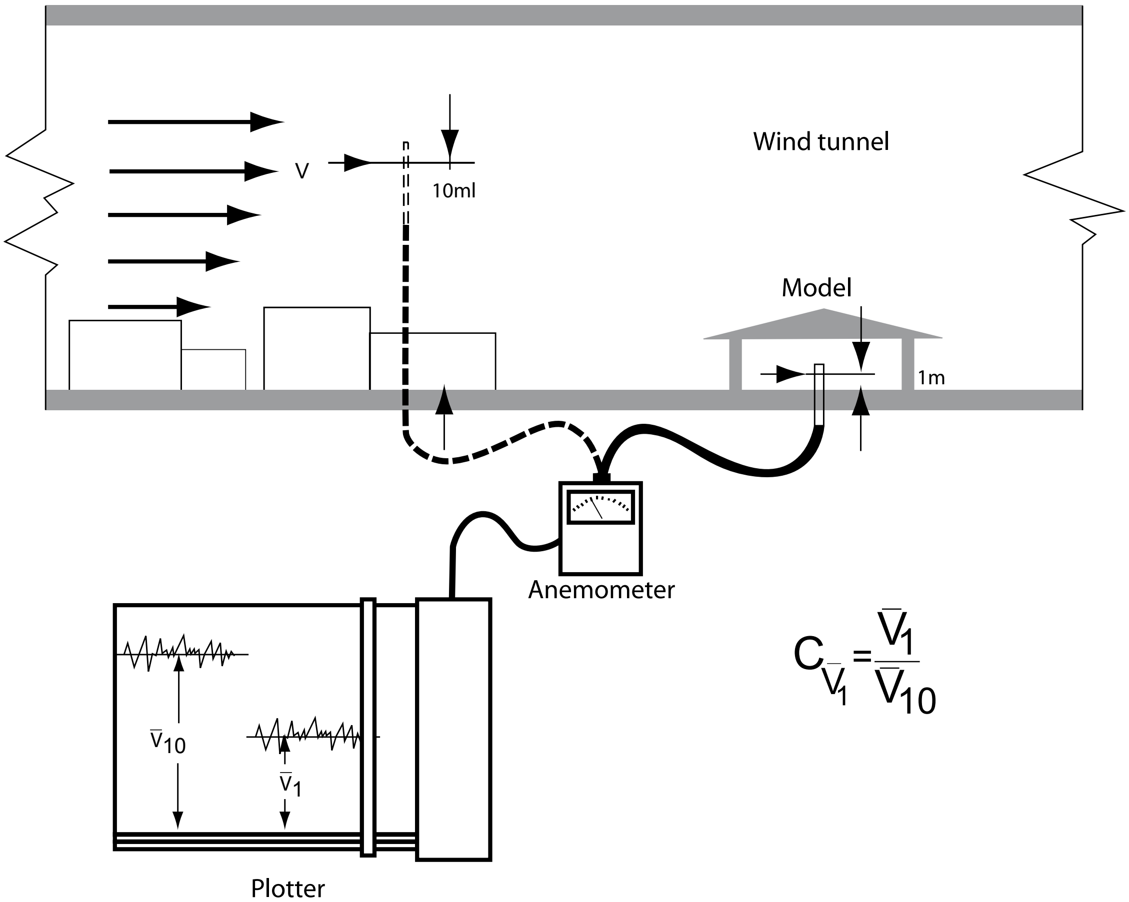

Figure 5. Indoor wind speed coefficient measurement in a boundary layer wind tunnel

6.7 Climatic applicability of natural ventilation

Temperate and Cold Climates

In temperate climates during winter and in cold climates, it is necessary to ensure adequate exchange of indoor air to maintain indoor air quality. This can be achieved by natural ventilation using wind pressure and/or stack effect through small openings (Aynsley et al, 1977).

Temperate and Warm Humid Climates

In temperate climates during summer and in warm, humid climates, natural ventilation using wind pressure and/or stack effect are applicable for achieving airflow for indoor thermal comfort (Arens et al, 1984).

Hot Arid Climates

Buildings in hot, arid, desert climates can benefit from natural ventilation via the stack effect, to draw air through evaporative cooling systems or by wind pressure at night, to enhance night cooling of the building. Natural ventilation during daytime should be avoided unless it is through an evaporative cooling system, to ensure the temperature of incoming air is lowered and its relative humidity is raised (Koenigsberger et al, 1974).

6.8 Interrelationships of Ventilation with Passive Solar use of Thermal Mass

In warmer climates, airflow through a building can be used to enhance the night cooling of internal mass (Li & Xu, 2006). Observations suggest this enhancement can amount to a reduction of up to 15% in the diurnal temperature variation providing lower indoor daytime temperatures (Cook, 1989).

In warm humid climates this additional cooling is marginalised by the adverse effect of humidity on indoor thermal comfort. These climates are the most difficult to moderate using passive solar techniques. Any massive building elements on the exterior of buildings in warm climates need shading from direct sun to avoid unnecessary solar heat gain during the warmest months. Cores through building mass such as masonry walls, or concrete floor slabs, can be used as airflow channels to speed the night cooling process (Fairey et al, 1985).

6.9 Earth Pipes

Earth pipes or cooling tubes take advantage of the relatively constant soil temperature a metre or so beneath ground level. In summer this soil temperature is significantly lower than daytime air temperature, so outdoor air drawn into a building through buried thin-walled plastic tubes is cooled (ASHRAE Fundamentals). The efficiency of earth cooling tubes varies with heat transfer through adjacent soil. This depends on soil type and moisture content and can vary throughout the year. An alternative to plastic tubing is drawing air through a bed of porous rock fill. This technique is referred to as rock bed cooling. Both of these techniques have significant technical challenges associated with their successful implementation.

6.10 Insect Screens

Insect screens are desirable in many locations, particularly in the tropics where a number of serious illnesses such as Malaria and Dengue Fever are spread by insects.

Smooth rounded wires or threads forming the mesh of insect screens have non-linear resistance to airflow. Airflow resistance is higher at low wind speeds. See Table 4 for the effect of various types of screens on airflow.

The figures in brackets are the percentage loss in wind speed relative to the wind speed through a similar opening without a screen.

To maximise the clear area of opening in insect screens, they are often positioned over large areas at the outer edge of verandahs, to form a lanai, rather than over smaller window and door openings. This approach also creates useful insect-free outdoor space. Where screens are placed close to openings there may be difficulty operating certain types of sashes with insect screens in place, but easily removed, magnetically held screens are now available.

6.11 Vegetation Impacts

While the density of trees will reduce local air temperatures by shielding the ground from solar radiation, cool air by evapotranspiration and potentially reduce the dust content in air streams, it can also reduce the potential for natural ventilation of buildings. Shrubs with dense foliage should not be allowed to obstruct wall openings intended to provide natural ventilation.

In flat suburban terrain, large numbers of trees can significantly slow airflow near the ground. Studies (Heisler, 1989) have shown that significant numbers of large trees (77% of ground cover) can reduce mean wind speeds 2 metres above ground level to 24% of the mean wind speeds 2 metres above ground level at a nearby airport. In flat suburban terrain without trees, mean wind speeds 2 metres above ground level are approximately 78% of 2 metre airport wind speeds. Flat suburban terrain with typical tree density has mean 2 metre wind speeds approximately 70% of those at a nearby airport.

7.0 Conclusion

The evaluation of natural ventilation should take into consideration the variability of wind speed and direction, by referring to wind frequency data, adjusted for local terrain, adjacent shelter and topography. By following the guidelines above, natural ventilation can be incorporated into the design of buildings to both replace stale or polluted indoor air in cool and temperate climates, and to provide indoor airflow in temperate and warm humid climates to enhance indoor thermal comfort.

The design of naturally ventilated buildings for tropical and hot arid climates is particularly challenging, and is only touched on here. Designers wishing to study the subject in more depth or to apply the more refined techniques should access the reference texts and/or obtain the assistance of specialist consultants.

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	% Wind Speed Reduction			
	Wind speed through bronze wire screen (m/s) 5.5 wires/cm Porosity 80%		Wind speed through plastic coated fibreglass (m/s) 7 threads/cm Porosity 66%	
Wind speed through clear opening (m/s)	*Clean*	*Dusty*	*Clean*	*Dusty*
0.5	0.25 (50%)	0.18 (64%)	0.10 (80%)	0.08 (84%)
1.0	0.55 (45%)	0.40 (60%)	0.35 (65%)	0.25 (75%)
1.5	1.06 (29%)	0.85 (43%)	0.80 (47%)	0.65 (56%)
2.0	1.50 (25%)	1.30 (35%)	1.15 (43%)	1.00 (50%)
2.5	2.00 (20%)	1.65 (34%)	1.50 (40%)	1.35 (46%)

Table 4. Effect of insect screens (clean and dusty) on natural ventilation wind speeds through openings.

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Glossary

Bioclimatic The effects of climatic conditions on living organisms. Bioclimatic in relation to architecture is building designed and built on the basis of the climate and local resources (energy and materials).

Effective temperature (ET*) A concept of equivalent temperature which considers temperature, humidity and velocity of air movement but not radiation. It is scaled on a psychrometric chart.

Evapotranspiration The loss of water from the Earth's surface as a result of both evaporation from the surface of soil, rocks and bodies of water, and transpiration from plants.

Fale Traditional thatched house of Samoa.

fpm Feet per minute

K Degrees Kelvin, based on absolute zero (-273 deg. C) as zero; the SI unit of thermodynamic temperature, equal in magnitude to 1 degree difference on the Celsius scale.

Lanai Verandah or roofed patio, originating in Hawaii. It may be partly enclosed.

Latent heat Heat required to convert a solid into a liquid or vapour, or a liquid into a vapour without change in temperature.

Psychrometric chart A graphic representation of the thermodynamic properties of moist air for use in the evaluation of thermal comfort criteria and the design of air conditioning, heating and ventilation systems.

RH Relative humidity: the ratio/percentage, of the actual quantity of water vapour present in a given volume of air to that when the air is fully saturated.

Sensible cooling The removal of sensible heat by lowering the temperature in a space.

Sensible heat The portion of heat which, when applied in heating and cooling, changes only the temperature of a substance, The heat gained or lost can be 'sensed' directly by corresponding rise or fall in temperature.

Shelter belts A line of trees, etc planted as protection from the wind

Thermal neutrality (Tn) The condition in which the thermal environment of a homeothermic animal is such that its heat production (metabolism) is not increased either by cold stress or heat stress. The temperature range in which this minimum occurs is called the zone of thermal neutrality. For humans, this zone is 29°–31°C (84°–88°F).

WB The temperature indicated by a mercury-in-glass thermometer wrapped in a damp wick whose far end is immersed in water. This is lower than dry bulb temperature due to the evaporation of water from the wick.

Biography

Richard Aynsley, (BArch [Hons I], MS [Arch Eng], PhD), is Chair of the American Society of Civil Engineers' Aerodynamics Committee, Member ASHRAE SSPC 55 Committee on human thermal comfort, and Director Research & Development at Big Ass Fan Company, Lexington KY, USA. Former UNESCO Professor of Tropical Architecture and Director, The Australian Institute of Tropical Architecture, James Cook University of North Queensland, Richard Aynsley has previously held numerous academic posts in Australia and overseas. Dr. Aynsley has had over thirty years of experience in teaching and research and as a consultant to federal and state government and private clients on airflow through and around buildings, thermal performance of buildings, energy-efficiency of buildings and is the author of numerous publications and other media on various building science topics.