EDG 80 RA • August 2014 (Edited 23.08.2018)
environmentdesignguide.com.au
*Reviewed and approved for currency in August 2018*

ISSN 1442-5017

# Natural Ventilation in Passive Design

**Richard Aynsley**

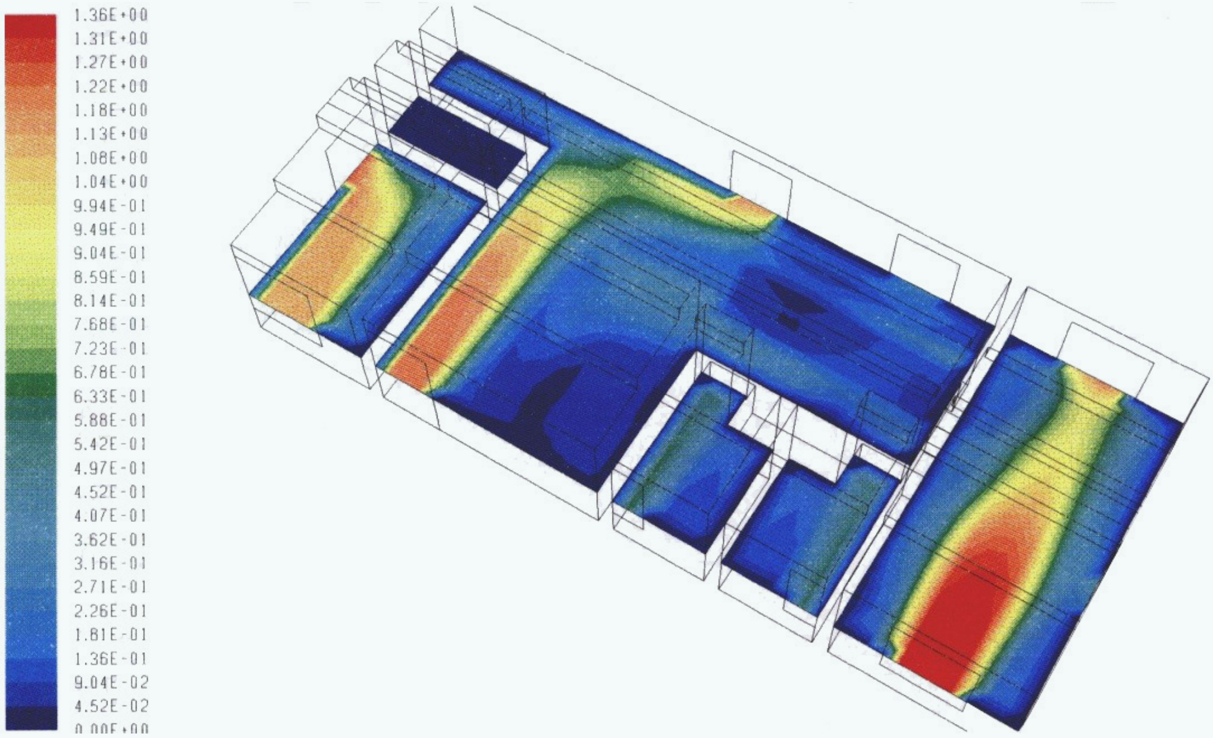



Figure A: A 3D CFD study of internal cross ventilation of a house. Colours indicate air velocity 1m above floor level (Australian Institute of Tropical Architecture, JCU 1998)

## ABSTRACT

This Note provides a background 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. This Note was originally published in May 1996 and was updated by Richard Aynsley in May 2001, in May 2007 and August 2014. The EDG code for this Design Note was previously TEC 2.

# Introduction

Natural ventilation is a valuable tool for sustainable development as it relies only on natural air movement, and can save significant amounts of 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 fossil fuel based energy generation. 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 to provide personal thermal comfort.

Since the 1950s the use of mechanical ventilation and air conditioning has been adopted as a means of compensating for excess heat gains experienced in many modern lightweight, 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, rather than user-based control systems.

The need to reduce our energy consumption 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 (3D) phenomenon. At present the tools available to design for good natural ventilation are either inexact rules of thumb appropriate for early design, or complicated wind tunnel or computational modelling techniques.

## THE ROLES OF NATURAL VENTILATION IN BUILDINGS

Natural ventilation provides multiple services in buildings (Brown 2004), which include:

1. Providing air for breathing
2. Moving air on human skin enhancing both convective and evaporative cooling
3. Replacing warm air with cooler air, and thus lowering indoor air temperatures
4. Removing heat accumulation from a building mass or structure
5. Building enclosure drying and structural integrity

### Breathing

Breathing is a biological requirement and a minor form of bodily cooling. While the amount of air needed for breathing is much less than that for cooling (Brown 2004), outside air has other amenities. Unlike recirculated indoor air, outdoor air is diluted, dynamic in speed and can carry sounds and smells (Hildebrand 2011). Outside air is reflective of microclimate, topography, geography and other conditions around the given site (Arens 1985).

### Occupant cooling

Air movement cools an occupant's skin directly. Air movement works to cool the human body in a number of ways, including: the evaporation of sweat from the skin, by convectively replacing the warmer air near the skin with cooler air, and by replacing warm exhaled air with cooler inhaled air.

### Space cooling

Occupied spaces accumulate heat from lighting, people, equipment, solar and envelope loads, which increases the ambient air temperature over time. Space cooling refers to the replacement of warmer indoor air with cooler outside air; as such, it requires that outside air temperatures be lower than indoor temperatures.

### Mass or structural cooling

Structural or mass cooling refers to the removal of accumulated heat within the building mass at times when outdoor temperatures are below the comfort zone; it is directly related to the thermal storage capacity of the building's thermal mass and its exposure to airflow. Cool air passes across the surface of building materials, removing heat in the process. Mass cooling tends to be used at night to offset the cooling need during the heat of the following day (Cheung et al. 2004). While air cooling savings have been achieved, in humid conditions, mass cooling is less effective in reducing latent heat and thus daytime relative humidity..

### Building enclosure drying and structural integrity

Besides cooling occupants, spaces and structures, wind-driven ventilation drying is also an effective means of removing moisture from drained, vented (external) cavity walls to avoid occurrence of condensation and mould (Bassett & McNeil 2005).

## THE USE OF NATURAL VENTILATION IN BUILDINGS

In practice, 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. For deep plan buildings, natural ventilation is unsuitable because the air tends to become contaminated long before it is exhausted to the outside.

Passive solar and energy efficient buildings are often reliant on effective natural ventilation as one of their main strategies for the maintenance of human thermal comfort. Natural ventilation has been used for tall buildings in temperate and cold climates (BTP 2001) and has been frequently utilised for tall residential buildings in warm humid tropical climates, where average wind speedts are lower than in temperate latitudes (such as shown in Table 4) and stack effects are small (Ai et al. 2013).

## CLIMATIC APPLICABILITY OF NATURAL VENTILATION

The climate applicability of natural ventilation should be considered alongside the site's physical features.

### Temperate winters 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). In winter the problem for temperate and cold climates is to avoid excessive wind through ventilation openings and leaks in the building envelope. The challenge in cold conditions is to restrict incoming air such as to achieve the minimum amount of fresh air required for breathing without causing cold draughts, increased humidity, or excessive heat loss.

### Temperate summers and warm, humid climates

In temperate climates during summer and in warm, humid climates, natural ventilation using wind pressure and/or stack effect is applicable for achieving airflow for indoor thermal comfort (Arens et al. 1984). In warm, humid climates particularly, natural ventilation is utilised to enhance indoor thermal comfort by evaporative cooling for the occupant and by reducing the effects of occupant-generated humidity within the space. Under this condition it is necessary to have sufficient external wind pressure to create air movement within the building, particularly through the occupied zones.

### 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 lower the incoming air temperature and raise its relative humidity (Koenigsberger et al. 1974). Under hot, dry summer conditions, when the outside air is well above the tolerable indoor temperature, it may be necessary to shut out the external air altogether until the temperature drops to more acceptable levels. In pre-WWII 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.

# Impacts to natural ventilation

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

- the site and local landscape features, including building spacing
- the building form and building envelope design
- the internal planning and room design

Each of these is described in the following sections.

## SITE INFLUENCES

While wind speeds at 500m above ground level are fairly constant, wind speeds below this level are slowed to varying degrees by the terrain roughness and other physical site conditions. Rougher terrain such as urban centres have more reduced wind speeds.

It is important to check 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 during all but extreme conditions) and for night time cooling of the building.

Local wind speeds can be estimated from Bureau of Meteorology (BOM) wind data, which is typically recorded 10m above ground at local airports (see category 2 terrain roughness in Table 3); this wind data is used as the reference wind speed. These figures must be moderated to local factors (i.e. shelter belts and large buildings). The effects of shelter on wind speed can also be estimated using Australian Standard (AS) 1170.2 - Wind Loads.

Performing an hourly wind frequency analysis can help determine if there is a reasonable probability of sufficient wind speed from appropriate directions for acceptable indoor thermal conditions. Circulating fans can usually provide indoor air movement for periods when natural ventilation is less likely (Aynsley 1996, 2009a, 2009b).

## HOW TO PERFORM A WIND FREQUENCY ANALYSIS

The Bureau of Meteorology (BOM) records hourly wind speed and direction at a limited number of sites. Hourly wind data for each month is sorted by wind speed interval and (eight) wind directions, as shown the table below. This tabulated data can be more meaningful when the speed data is expressed as a percentage of time, as shown in italics.

If this process is repeated for each of the hours for a month, these data can be combined with other hourly climate data (i.e. air temperature and humidity) to assess likely thermal comfort throughout the year. Climate analysis software tools (i.e. Climate Consultant and Ecotect) can help designers visualise wind data alongside other climate data, as shown in Figure 1. This visualisation can help determine the probability of sufficient wind speed from appropriate directions for acceptable indoor thermal conditions.

| | | Speed (m/s) | | | | | | | | | | | | observations by direction | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Calms < 0.5 | | 0.5-2 | | 2-4 | | 4-6 | | 6-8 | | > 8 | | | |
| Direction | N | 0 | *0%* | 1 | *1%* | 8 | *6%* | 16 | *11%* | 9 | *6%* | 1 | *1%* | 35 | *25%* |
| | NE | 0 | *0%* | 3 | *2%* | 9 | *6%* | 35 | *25%* | 25 | *18%* | 0 | *0%* | 72 | *51%* |
| | E | 0 | *0%* | 0 | *0%* | 2 | *1%* | 5 | *4%* | 12 | *9%* | 3 | *2%* | 22 | *16%* |
| | SE | 0 | *0%* | 0 | *0%* | 1 | *1%* | 1 | *1%* | 0 | *0%* | 2 | *1%* | 4 | *3%* |
| | SE | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* |
| | SW | 0 | *0%* | 0 | *0%* | 1 | *1%* | 1 | *1%* | 0 | *0%* | 0 | *0%* | 2 | *1%* |
| | W | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* |
| | NW | 0 | *0%* | 0 | *0%* | 2 | *1%* | 2 | *1%* | 1 | *1%* | 0 | *0%* | 5 | *4%* |
| | Calms | 1 | *1%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 0 | *0%* | 1 | *1%* |
| observations by speed | | 1 | *1%* | 4 | *3%* | 23 | *16%* | 60 | *43%* | 47 | *33%* | 6 | *4%* | 141 | *100%* |

Table 1. Numbers and percentages of occurrences by wind direction and wind speed intervals during the month of January at 3pm for Townsville, Qld.

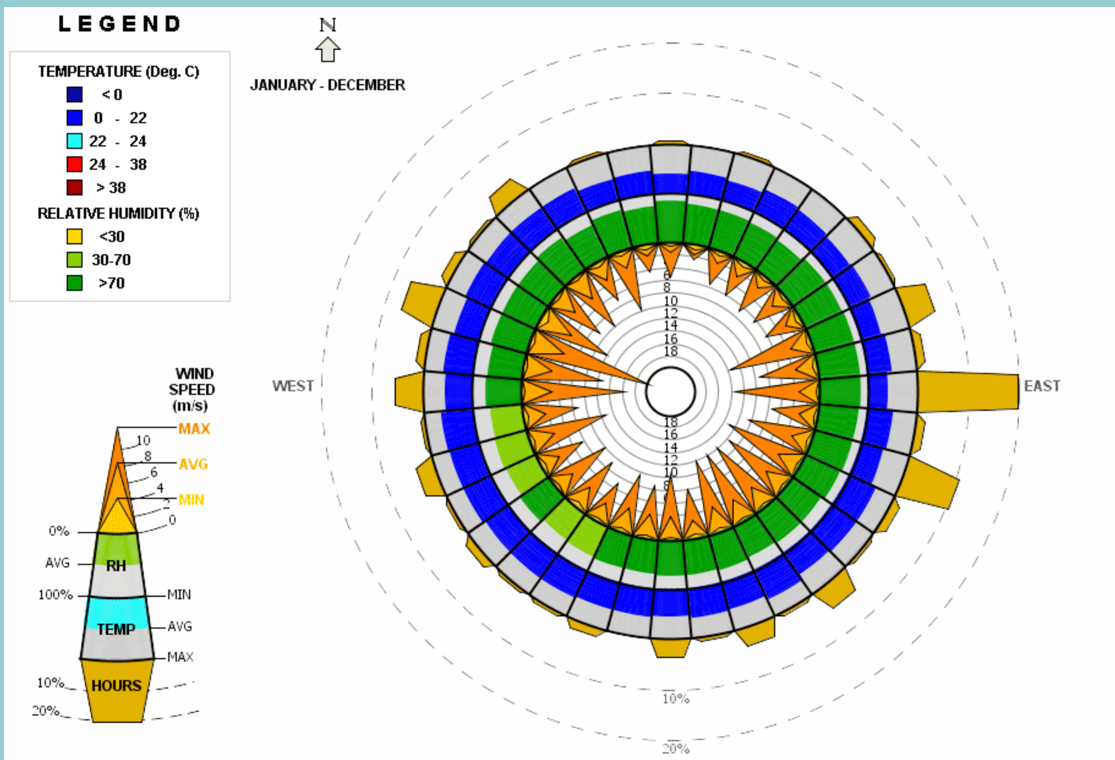



Figure 1. Example wind frequency shown graphically as a 'wind wheel'. (Image: screenshot from Climate Consultant 5 software)

## Terrain, hills and valleys

In areas without significant hills and valleys, using the wind speed at a nearby airport, one can estimate the wind speed at various heights in terrains of different roughness from Table 3. When there are substantial hills, corrections can be made to the estimated mean wind speed by multiplying wind speeds by the appropriate factor from Table 2. 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).

In hilly terrain, wind directions at a building site need to be checked against those from the reference location, and changes in direction at the site noted for each reference wind direction.

The influence of relative height and spacing of buildings on air flow in urban environments has been tested via numerous boundary layer wind tunnel (BLWT) studies conducted around the world (ASCE 2011). Such studies provide design data for quantifying potential natural ventilation from wind pressure differences on building surfaces and air speeds through openings. Street-level environmental conditions for pedestrians are also tested in these types of studies.

| | Lower third | Middle third | Top third | Over top |
|---|---|---|---|---|
| ≥1:10 <1:5 | 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 |
| ≥1:5 | 1.0 | 1.25 | 1.55 | 1.25 |

Table 2. Multipliers for wind speed over hills and escarpments (from Australian Standard AS 1170.2 Wind Loads)

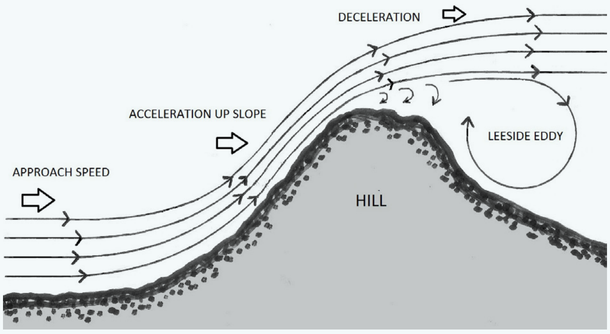



Figure 2. Wind streams over a hill. Reduced spacing of streamlines indicated accelerating airflow. Increased spacing of streamlines indicated decelerating airflow. (Image courtesy of author)

| Height above ground (metres) | 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% | 103% | 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 terrain roughness. (Aynsley 2005)

### Vegetation Impacts

Vegetation can be used to modify the outdoor wind direction so as to enhance ventilation and 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 adjacent to buildings can also be used to direct the wind as required for natural ventilation.

While tree density reduces local air temperatures by shielding the ground from solar radiation, cools air by evapotranspiration and potentially reduces 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 2m above ground level at a nearby airport. In flat suburban terrain without trees, mean wind speeds 2m above ground level are approximately 78% of 2m airport wind speeds. Flat suburban terrain with typical tree density has mean 2m wind speeds approximately 70% of those at a nearby airport.

### Water features

A water feature within or nearby a building can engender a sense of coolness. In medium to low humidity conditions, this psychological effect can be enhanced if water that is significantly cooler than indoor air is used as a thin film cascade or fine fountain spray to maximise its surface 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. With hot and dry ambient air, 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 increases with wind speed over a given moist surface.

## BUILDING FORM AND WINDOW OPENINGS

Naturally ventilated buildings should be oriented to maximise their exposure to the required (summer) wind direction, and designed with a relatively narrow plan to minimise resistance to air flow through the building (for cross ventilation). Rooms elevated above ground level will catch stronger winds (though this may be counterproductive if openings are shielded by a tree canopy).

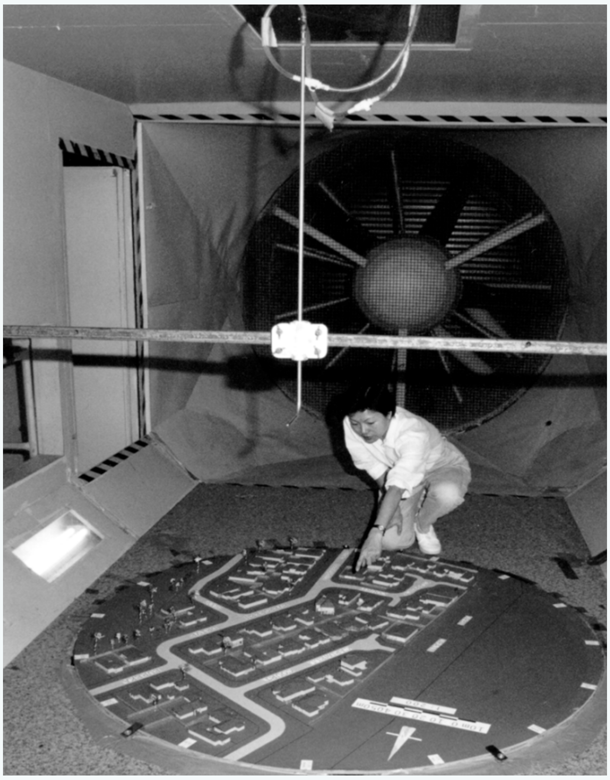


Figure 3. Townsville subdivision modelled in a boundary layer wind tunnel at James Cook University, Queensland. Note the close spacing of houses and the inclusion of surrounding buildings, which strongly influence ventilation. (Image courtesy of author.)

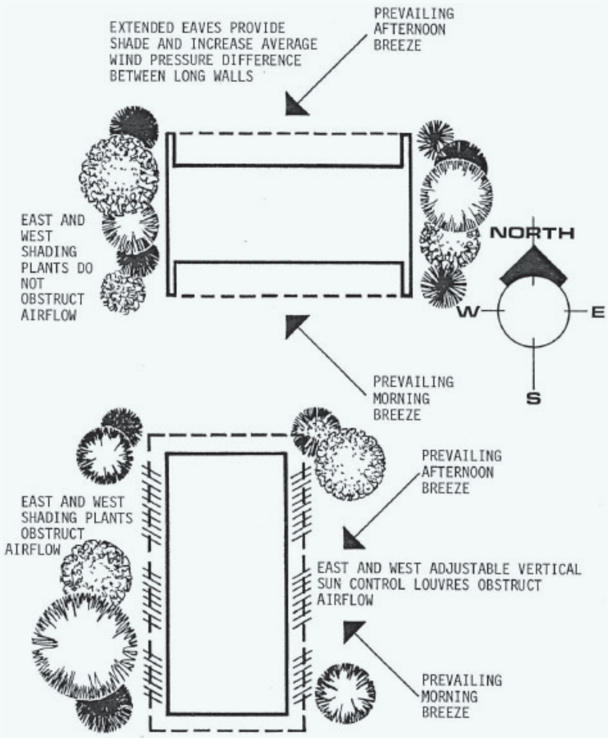



Figure 4. Orientation of long walls to minimise obstruction of openings by shading devices. (Aynsley 1979)

To ensure a broad distribution of natural ventilation within a space, wall openings need to have a high porosity, or a high percentage of openings on both windward and leeward walls. Solar heated buildings require particular attention in order to optimise both the solar and ventilation requirements. Ideally, solar orientation and breeze paths should 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 is specified by 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% open; realistically the air inlets should be designed for personal comfort, and take 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. Horizontal openings near floor level are more effective than vertical openings for ventilation purposes. Horizontal or wider openings can capture wind from a wider array of angles. 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, the total air outlet area should be larger than the air inlet area.

If it is only possible to ventilate a room on one façade, windows or ventilation openings should be located 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. Wing walls, eaves and similar façade elements near openings can also assist in creating a pressure differential to induce some single-sided airflow; this will be elaborated upon further below.

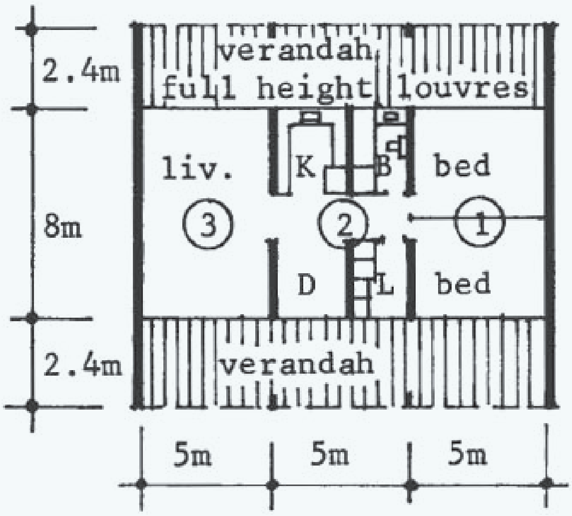



Figure 5. Reference plan for the flow visualisation study shown in Figures 6 and 7. (Aynsley 1992)

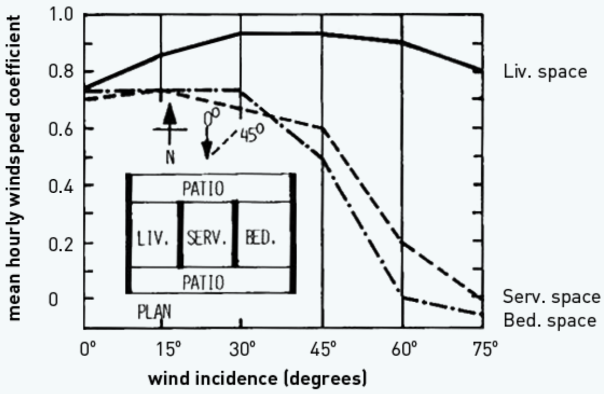



Figure 6. Mean hourly wind speed coefficients by wind incidence for a house on ground level, referenced to mean freestream windspeed at 10m. (Aynsley 1992)

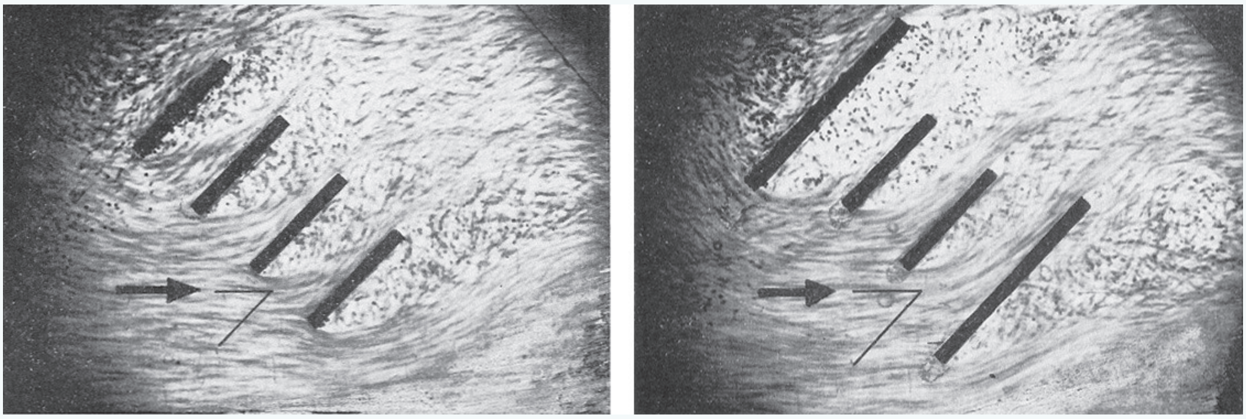


Figure 7. Flow visualisation using styrene beads created in a water tunnel at the former Department of Architectural Science at the University of Sydney. The left image shows three equal cross ventilated compartments, while the right shows how compartments with extended end walls impact flow. Note how the wing wall in the downstream compartment enhances the air flow in the living area where daytime activities occur, while the wing wall on the windward bedrooms reduces air flow. If air flow was predominantly from this direction the wing wall projection on the windward compartment should be removed. (Aynsley 1977)

### Window types and other building façade components

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 (or sideways) air flow parallel to the window wall (IJV 2005).

Sliding windows can be problematic in that only half of the window can be opened, and they cannot be adjusted according to the wind direction (Aynsley 1977). That said wing walls or window jambs (for inset windows) may redirect airflow to capture breezes from angles. Additionally, sliding windows are more compatible with exterior shades, i.e. exterior venetian blinds or perforated panels.

Louvre or jalousie windows offer up to almost 100% opening area. Where prevailing wind directions are very consistent, wing walls to the downwind side of louvre windows can increase air flow through the windows at times when the approaching prevailing wind is not perpendicular to the window wall. Extending eaves and taking cross walls (or wing walls) out to the eave line, like wing walls, will tend to trap and channel cross ventilation through the building (Aynsley et al. 1977).

### Insect Screens

Insect screens are desirable in many locations, particularly in the tropics where insects spread serious illnesses like malaria and dengue fever. Insect screens positioned over large areas at the outer edge of verandas to form a lanai, rather than over smaller window and door openings, can maximise the clear opening area. This approach also creates a useful, insect-free outdoor space. Screens close to or within openings may be difficult to operate with certain types of window sashes; easily removed, magnetically held screens are also available.

Airflow resistance to rounded wire meshes are higher at low wind speeds. See Table 4 for the effect of various types of screens on airflow.

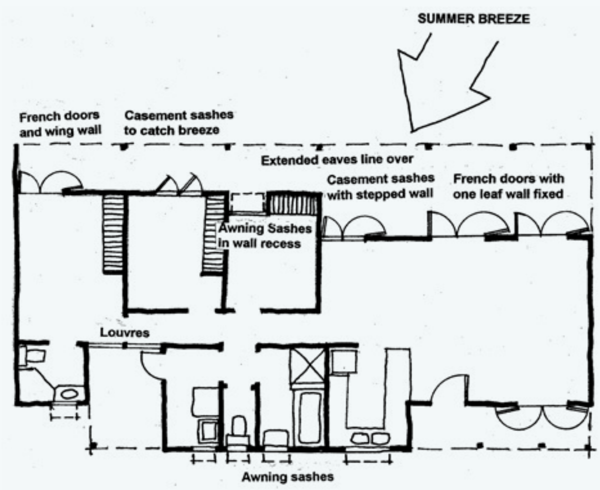



Figure 8. Typical window applications for natural ventilation. (Image courtesy of author)

| Wind speed through clear opening | Wind Speed Reduction (percentage) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | through bronze wire screen 5.5 wires/cm 80% porosity | | | | through plastic coated fibreglass 7 threads/cm 66% porosity | | | |
| | 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 (clean and dusty) insect screens on air speeds through openings. The percentage loss in wind speed is relative to the wind speed through a similar opening without a screen. (Aynsley et al. 1977)

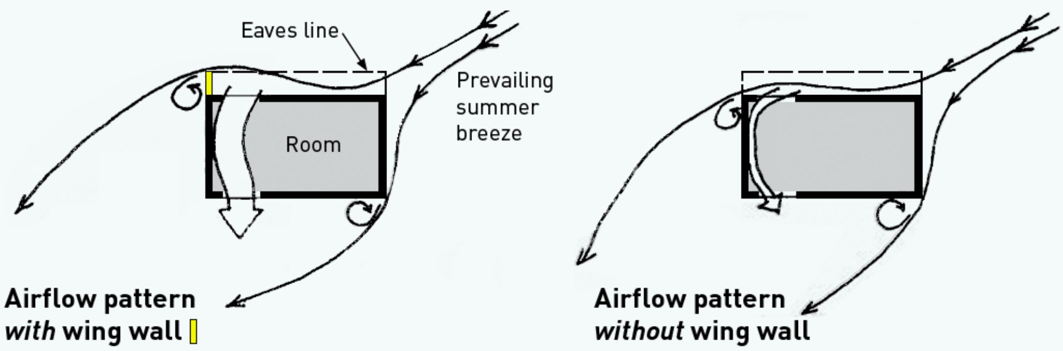



Figure 9. The airflow benefits of a wing wall (left image) when breeze is inclined to the house. (Aynsley 1999)

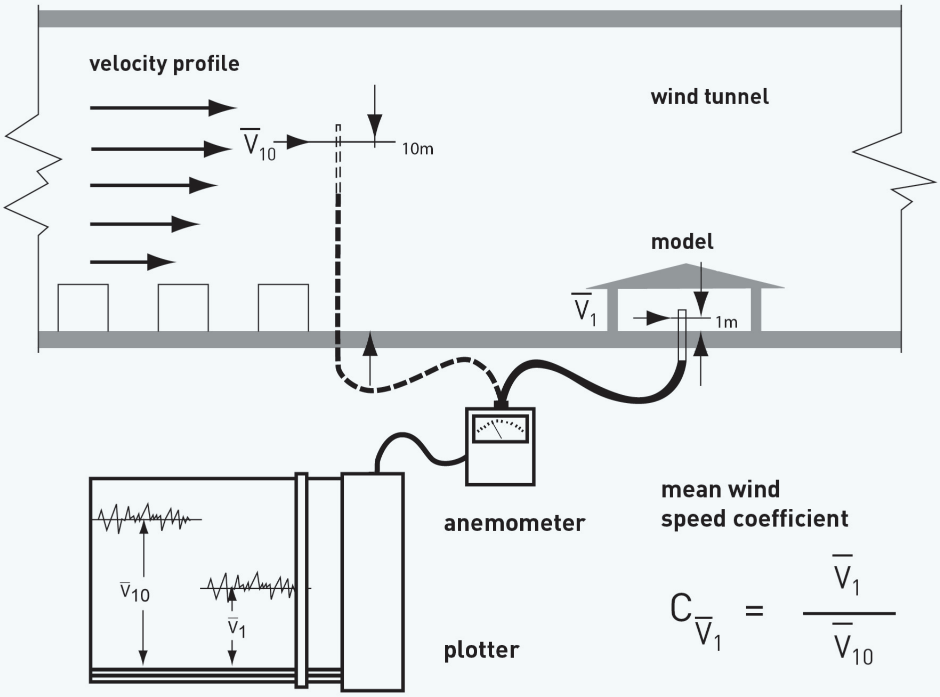



Figure 10. Indoor wind speed coefficient measurement in a boundary layer wind tunnel. (Adapted from Aynsley 1992)

## Internal planning and room layout

To facilitate the natural ventilation of rooms, the resistance to airflow through the building should 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 direct occupant cooling, the airflow path must pass through the zones frequented by the building occupants, usually within 2m of floor level and particularly near head level. Airflow above the heads of occupants is of little value for occupant cooling in summer, but can be useful in winter for achieving minimum ventilation needs while avoiding draughts.

Wall openings adjacent to a cross wall encourage the jet of airflow through the opening to cling to the cross wall; thus 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 at the extremities of an incoming air stream from windward openings are less effective for indoor comfort cooling.

3D wind tunnel or computer flow visualisation studies of breeze paths can be used to optimise furniture placement for thermal comfort. It is advisable to model furniture to account for the impact of its presence on the prevailing wind directions (noting the relative frequency and speed from reference locations) as the placement of openings may need adjustment to achieve optimum performance.

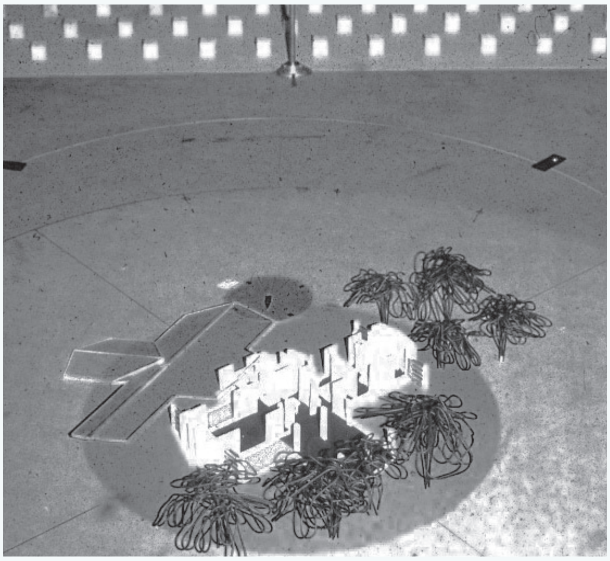


Figure 11. Hollow house model, with roof removed and surrounding trees inserted, used for measuring indoor wind speed coefficients in the BLWT. (Image courtesy of author.)

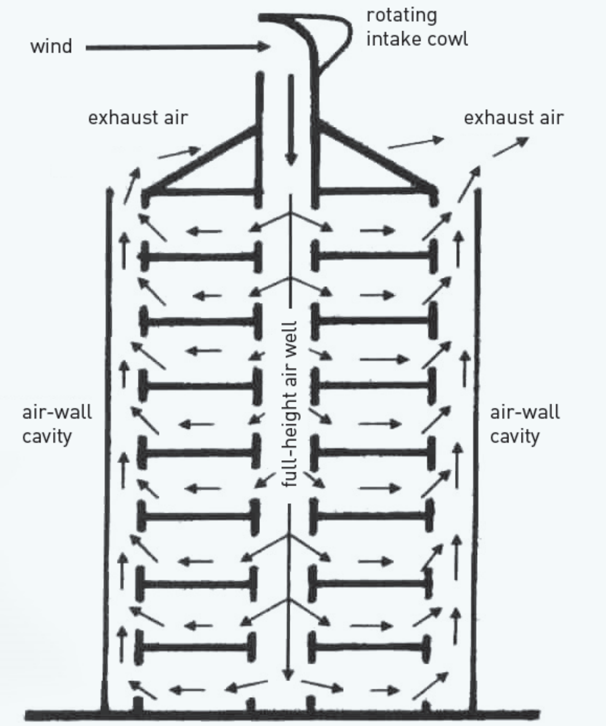



Figure 12. An air-well to air-wall ventilation scheme for a tall building (ASCE 2011)

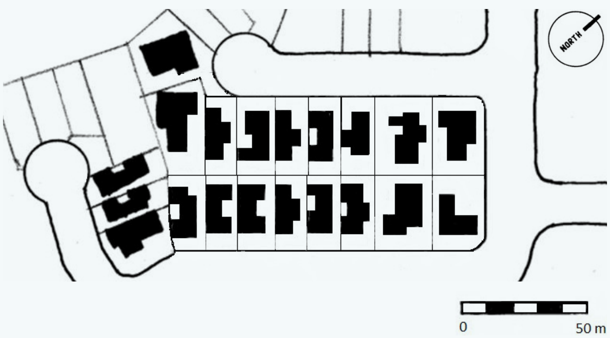



Figure 13. Small house subdivisions increase suburban densities to minimise road and drainage costs. Such subdivisions limit opportunities for natural ventilation. Houses would benefit from having their long walls facing north and south to optimise solar exposure and allow for low airflow resistant summer shading of wall openings. (Image courtesy of author)

# Pressure and airflow

Natural ventilation is induced by differences in air pressure across the building. These differences in air pressure may be due to wind forces or temperature differences, resulting in wind-driven ventilation or stack ventilation respectively.

## WIND-DRIVEN VENTILATION

Wind-driven ventilation results from pressure differences caused when building walls obstruct airflow. The pressure differences tends to be positive on windward walls and negative on leeward walls. At any given time, the differences in wind pressure between various points on the building surface fluctuate with wind speed, wind direction and building shape.

When air is stationary, it exerts a pressure equally in all directions; such pressures are referred to as static pressure. Moving air has mass, so it can exert a dynamic pressure on an object in the direction of its motion. Air entering a building opening exerts a total pressure that is equal to the sum of the static and dynamic pressures.

In the case of wind-driven cross ventilation, air enters through an opening on the windward side of a building, passes through an internal space and exits through an opening on the leeward side. The pressure difference that drives air through a building is the difference between the total pressure (from the air entering the windward opening) and the external static pressure around the leeward opening. The dynamic pressure in the air stream leaving the leeward opening is dissipated in turbulence downstream.

Using static pressures measured on solid models in wind tunnels to estimate wind-driven ventilation through a building will usually result in an underestimation of the ventilation. (This is because surface pressure data from solid models ignores the dynamic pressure and static pressure from airflow through an opening.) The total pressure at windward openings can only be determined using 3D computational fluid dynamics (CFD) simulation or wind tunnel studies using hollow models with all openings and internal walls.

The effective total 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 wind speed at eaves height. (Note that the convention is to reference all pressure coefficients on low rise houses to the dynamic pressure of the approaching wind at eaves height above ground level in the local terrain roughness.) 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.

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) and tend to be used for determining wind loads on buildings. 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, or the ratio of the opening area to wall area.

The common practice of using the static pressure data for estimating airflow through windward openings in 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 (especially through large openings) is to seek assistance from experienced consultants who use calibrated CFD software with large eddy simulation capability (ASHRAE Handbook 2009), or from consultants familiar with boundary layer wind tunnel (BLWT) modelling. It is important that relevant openings and surrounding obstructions are carefully incorporated into such a model and that interior wind speeds can be measured.

## STACK VENTILATION

Stack effect is brought about when warm air rises up through high level outlets, drawing in colder, heavier air from outside. The stack effect is derived from differences in air density, usually due to 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. Even under calm winter conditions the difference in temperature between the indoor and outdoor air will usually create sufficient stack effect to draw in fresh air. Open fire places are an extreme form of this with air being exhausted up the flue.

The efficiency of stacks can be improved by:

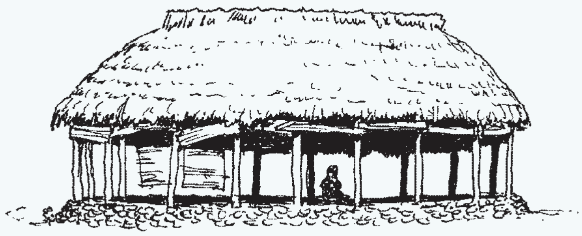
- Increasing the stack height
- Increasing the temperature difference between the bottom and top of the stack
- Minimising the airflow resistance through the stack by minimising the number of bends, and ensuring they have a generous radius

Note that ventilation stacks relying on temperature differences are more efficient as exhaust stacks. This is because the buoyancy force of warm air assists the 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 in some instances. Stack ventilation systems are more complex than what most architects imagine and the use of specialist consultants is advised.

## COMBINED STACK AND WIND PRESSURE

Where both wind pressure 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 may be less than many designers expect; the airflow is proportional to the square root of the total pressure difference (ASHRAE Fundamentals). That is, the difference between the total pressure at the inlet of a stack (static pressure + dynamic pressure) and the static pressure at the outlet. (Dynamic pressure at the stack inlet is usually unknown and dynamic pressure at the outlet of the stack does not contribute to airflow through the stack as it is dissipated in turbulence downstream from the stack. This can be shown by applying the Bernoulli equation to such airflow.)



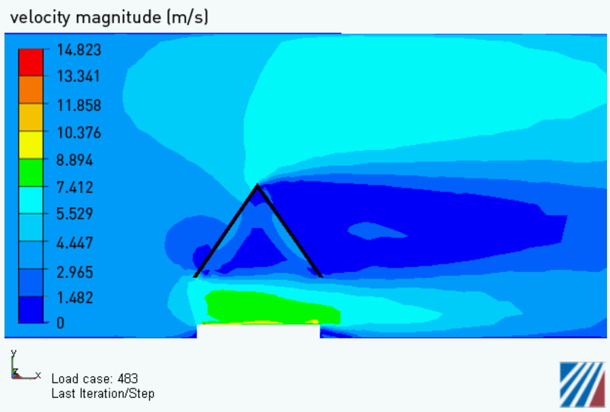



Figure 14. The CFD image (lower) shows mean relative velocities (from which wind speed coefficients are calculated) over and through a Samoan fale (illustrated above) close to the sea using CFD software. (Source: Aynsley 2007, using CFdesign)

### MULTIPLE INLET AND OUTLET OPENINGS

Where a space has multiple inlet and outlet openings, direct calculation of the airflow rate is not possible due to the lack of dynamic pressure data at inlet openings, and so it is necessary to obtain expert assistance from consultants using boundary layer wind tunnel tests or computational fluid dynamics computer programs. Use of CFD software requires expert knowledge to achieve reliable results (ASHRAE Handbook 2009).

### INDOOR WIND SPEED COEFFICIENTS

In the event that there is a lack of dynamic pressure data for inlet openings, a more direct approach to describing natural ventilation through buildings is through the use of indoor wind speed coefficients (Aynsley 2006). An indoor wind speed coefficient is the ratio of the average indoor wind speed at a (crucial occupied) location, to the average 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 for compatibility with local weather data.

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. That is, indoor air speed = 0.24 x local airport wind speed in flat terrain at 10m. 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).

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. These geometries pose severe wind load problems in regions frequented by tropical cyclones. The 2D CFD analysis indicates that air speed 1m above floor level is approximately twice that of the approaching breeze (at 10m above ground level), with an indoor wind speed coefficient of 2.2. This value is likely to be exaggerated because the 2D airflow does not account for 3D airflow into the wake around the ends of the roof.

## Thermal comfort criteria for natural ventilation

Designers need to be aware that occupants in air conditioned environments have different thermal expectations to occupants in free running, naturally ventilated buildings. The choice of a thermal comfort index or model is critical when thermal conditions are different to a standard air conditioned space (where air and radiant temperatures are between 22°C and 25°C, relative humidity is less than 55% and air speed of less than 0.2 m/s). The Predictive Mean Vote (PMV) and PMV and ET (Effective Temperature) comfort models are not appropriate for assessing thermal comfort in warm climatic conditions (where the operative, or the average of air and radiant, temperature is above 28°C and relative humidity greater than 55%). In warm humid climates, thermal neutrality (the temperature at which a person feels thermally neutral) predicted for occupants of naturally ventilated buildings using the Adaptive Comfort Model is up to 3°C warmer than that for occupants of air conditioned buildings using PMV (Fanger 1972).

ASHRAE Standard 55 states that the adaptive comfort model is exclusively for naturally ventilated buildings, as there were insufficient numbers of mixed-mode buildings (or those which rely on a combination of natural and mechanical conditioning) that existed in the database from which the model was derived.

Below are a list of key thermal comfort models and their suitability to different climatic and building conditions:

### THE OCCUPANT COOLING EFFECT OF AIR MOVEMENT

As mentioned earlier, air movement has a cooling impact on thermal comfort. The cooling effect of air movement can be found using Standard Effective Temperature (SET), based on the combined influence of the six thermal comfort variables:

1. Metabolic rate, expressed in Mets (or $W/m^2$)
2. Clothing insulation value, expressed in clo (or $m^2 \bullet °C/W$)
3. Air temperature, expressed in °C
4. Radiant temperature, expressed in °C
5. Air speed, expressed in m/s
6. Relative humidity, expressed as a petrcentage %

| Thermal comfort model | Appropriate thermal conditions | Building conditioning type(s) |
|---|---|---|
| PMV (Predicted Mean Vote) and PMV & ET* (effective temperature) | cool / cold, air and radiant temperatures around 22°C – 25°C, RH < 55% | mechanically conditioned |
| SET (standard effective temperature) adjusted PMV or PMV with Elevated Air Speed | Operative temperature > 28°C non-restricted, warm, humid ok | mechanically conditioned with local air speed > 0.2 m/s |
| Adaptive comfort model | non-restricted (warm, humid ok) | Naturally ventilated or possibly mixed-mode |
| Adaptive comfort + elevated air speeds | non-restricted (warm, humid ok) | Naturally ventilated with local air movement |

Table 5. Key thermal comfort models and their suitability to different climatic and building conditions.

The cooling effect of moving air for a person subjected to the six thermal comfort factors is expressed as a difference in °C. These calculations can be performed using the user-friendly ASHRAE Thermal Comfort Tool computer software (ASHRAE 2013) or the CBE Thermal Comfort Tool, which is freely available online. The ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy (2013) adopts this method for determining the cooling effect of air speed on human thermal comfort.

An air speed of approximately 1.0 m/s is the limit before desktop papers will start to blow around. Some office workers manage with airflows of up to 2.2 m/s with under-desk fans (Bauman et al. 2000).

# Other considerations

## VENTILATION AND THE 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, however, this form of 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 (i.e. masonry walls, or concrete floor slabs) can be used as airflow channels to speed the night cooling process (Fairey et al. 1985).

## 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 and duty of care associated with their successful implementation and operation. High humidity in rock beds or buried cooling tubes can lead to mould and bacteria growth, so good drainage and regular inspection and cleaning of these systems is essential.

# Conclusion

The evaluation of natural ventilation should take into consideration the variability of wind speed, direction and frequency by referring to wind 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 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 obtain the assistance of specialist consultants.

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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 °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.

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