Ventilative Cooling: State of the Art

B. Fleury
ENTPE-LASH - Rue Audin - 69518 Vaulx en Velin Cedex - France

ABSTRACT : Ventilative cooling represents one of the heat dissipation techniques in the building design process. In this paper, we identify the driving forces of natural ventilation and their implications within the building. We focus on the various strategies to enhance the air circulation and exhibit the limits of this cooling technique. Design guidelines for architects based on existing knowledge are suggested. Finally, perspectives in terms of future research actions are exposed.

1. PRINCIPLES

Ventilation provides cooling by using air to carry heat away from the building and/or from the human body itself. Air movement may be created either by natural forces (wind and stack effect) or mechanical power (fan). Air flow patterns are the result of differences in the pressure distribution around and within the building. Air moves from high pressure regions to low pressure ones.

When the outside air temperature is lower than the inside air temperature, building ventilation may exhaust internal heat gains or solar gains during the day and may flush the building with cool air over the night. Indoor air movement also enhances the convective exchange at the skin surface and increases the rate of evaporation of moisture from the skin. Evaporation is a very powerful cooling mechanism which may bring a feeling of comfort to occupants under hot conditions. However, in order to be effective, the surrounding air should not be too humid. Turbulent movement favours both of these mechanisms for heat removal.

To favour occupant and/or building cooling by ventilation, it is necessary to optimise the air circulation within the landscape and the interior spaces by an appropriate architectural design [1,2]. After a review of the elementary physical principles, we present design guidelines to enhance the potential of ventilation as a cooling strategy.

2. DRIVING FORCES OF NATURAL VENTILATION

2.1. Wind effect

When the wind strikes an obstacle such as a building, a positive high pressure zone is created in front of the opposing facade. The air surrounds the building and eddies develop on the side and leeward facade inducing a low pressure region. In the presence of a connecting path (open window, door, shaft) between the high and low pressure zones, cross ventilation will be induced. Pressure difference and air flow resistance determine the mass flow rate and the air velocity within the occupied space. Optimizing air flow represents the objective of natural ventilation.

2.2. Stack effect

Temperature difference induces a density difference and according to physical principles, light air tends to move to a higher position if possible. Air movement is therefore established due to the so-called buoyancy forces. Ventilation through buoyancy requires a significant temperature differential as well as a low building's internal vertical resistance to air movement. Stack effect and wind effect can act separately or together but usually buoyancy forces are dominated by wind if blowing.

3. EFFECTS OF NATURAL VENTILATION

3.1. Building Cooling

If the temperature of the incoming air from the outside is lower than the temperature of air inside the building, ventilation may be an effective cooling strategy. Air from the atmosphere is used as a heat sink.
Heat removal capacity of the ventilation air is calculated by :

$$Q = \rho \ V \ C_p \ (T_{exhaust} - T_{supply})^{+} \qquad \text{(Watt)}$$

where
ρ : air density (kg/m^3)
V : volume flow rate (m^3/s)
C_p : specific heat capacity (J/kg°C)
T_{supply} : Temperature of incoming air (°C)
$T_{exhaust}$: Temperature of exhausting air (°C)

Approximatly, this may be written :

$$Q = 0.35 \ V \ \Delta T \qquad \text{(Watt)} \qquad \text{with } V \text{ in } (m^3/h)$$

Clearly, the key issues are the *volume* of air which can be moved naturally through a building, the temperature of the air *outside*, and that of the air inside the building. It is not easy to predict the rate of natural ventilation, and for a future building it is not easy to predict the internal temperature. Internal and external heat transfer processes interact in a dynamic and complex way. The objective is usually to maximise the volume flow rate in order to exhaust a maximum amount of heat. This flow rate is only limited by the upper limit of the air velocity within the space.

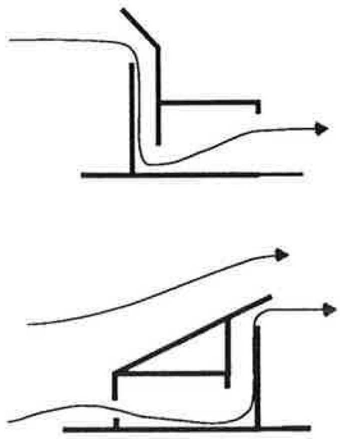
3.2. Occupant cooling

Air velocity is a key variable of the occupant comfort because it impacts on the convective exhange and the rate evaporation of moisture from the skin. As a rule of thumb, an increase of air velocity of 0.15 m/s compensates an increase of 1°C in temperature at moderate humidity level (RH<75%). However, the air speed should be limited to 1m/s in an environment where sheet of paper can blow. Otherwise, this limit can be easily doubled.

4. VENTILATIVE STRATEGIES

Diverse strategies can be adopted to take benefit of the driving forces of the natural ventilation.

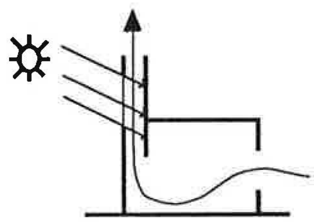
4.1. Wind Tower



Wind towers draw upon the driving forces of the wind to generate air movement within the building [3,4]. There are various systems based on this principle. The wind-scoop inlet of the tower, oriented toward the windward side captures the wind and drives the air down the chimney. The air exits through a leeward opening of the building. The air flow is enhanced by cold night air. Alternatively, the chimney cap is designed to create a low pressure region at the top of the tower, and the suction initiates airflow up the chimney. A windward opening should be associated with the system for air inlet. The anabatic process benefits in this case from buoyancy of the warm inside air.

Both these principles may be combined in a single tower providing both admittance and exhaust of air. A self-contained system is thus created.

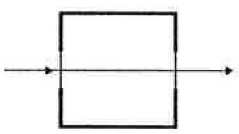
4.2. Solar Chimney



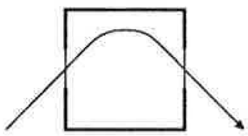
Solar chimneys use the sun to warm-up an internal surface of the chimney. Buoyancy forces due to temperature difference help induce an upward flow along the plate. The chimney width should be closed to the boundary layer width in order to avoid potential backward flow [5]. The chimney may serve as a stairwell and be completely integrated in the building architecture.

4.3. Openings : Distribution and Shape [6,7,8]

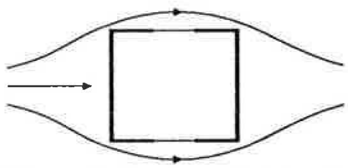
Single sided ventilation is an inefficient strategy; cross-ventilation is prefered.



When inlet and outlet are aligned with the wind, the air flow is shortcircuited and poor secondary flow is generated next to the main stream.

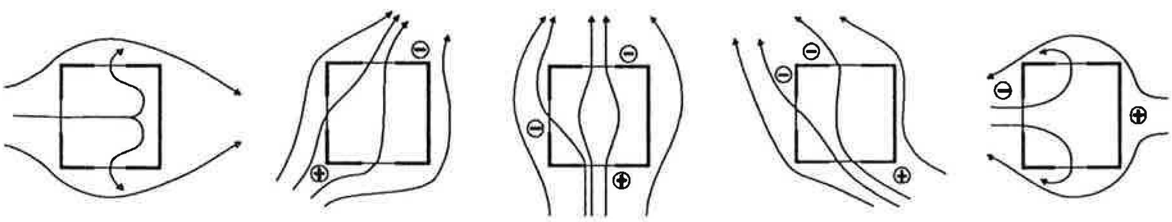


If the wind is oblique to the openings, the air flow circulates in the entire building.

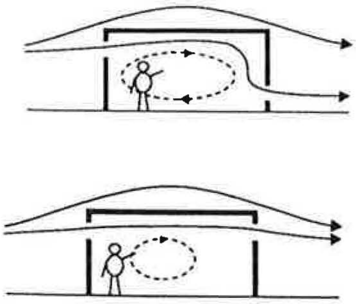


If the wind is parallel to the opening, no significant movement occurs within the occupied space.

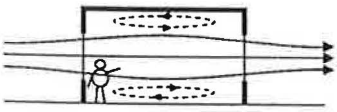
Cross ventilation can be further enhanced by placing two outlets on the building sidewalls. This design option also addresses the frequent shift in wind direction.



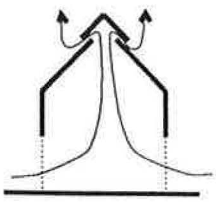
The distribution of the openings on the building façade is a key element for efficient natural ventilation. Ventilation is a three dimensional function and correct location of the window is also essential. The position of the inlet dominates the air flow pattern within the space. The position of the outlet is of secondary importance.



High inlets do not generate a strong air velocity in the occupied zone and represent a poor design for occupant cooling. However, this configuration is often interesting for night ventilation because the air stream is directed toward the storage element, for example a massive ceiling. Moreover, high positions offer better security against intruders.



When the openings are at body height, good cross ventilation occurs for occupant cooling.

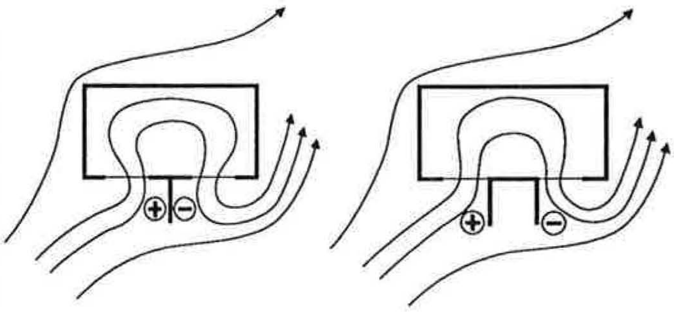


When the building is too deep to offer cross ventilation, or when opposing openings are not possible, roof openings or clerestories may be used to encourage an anabatic flow. The roof opening should be designed to create a low pressure region next to the opening to enhance the natural stack effect.

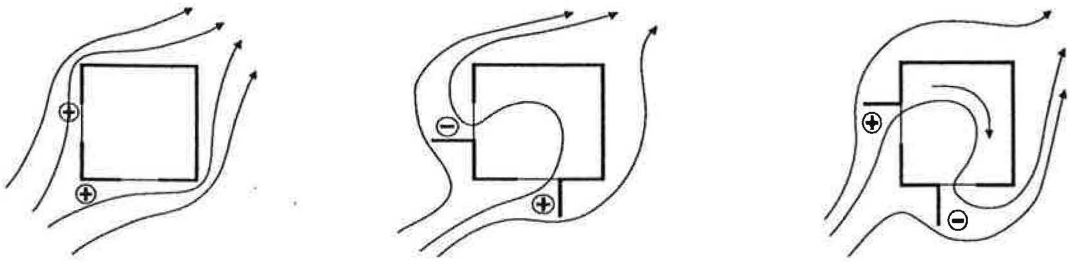
4.4. Building Shape

Cross ventilation is optimum if a room has three openings on different facades. Unfortunately, this configuration is rare. Many rooms have only one external wall. With one open window, the ventilation is mainly due to the turbulent fluctuations of the wind, and air movement is not significant. Ventilation can be improved if two windows can be placed on the facade, as far apart as possible. Wind fluctuations generate pressure differences between the two windows and induce air circulation within the space.

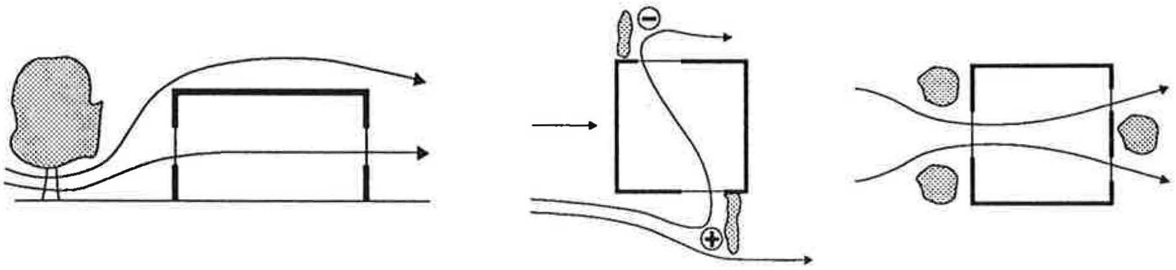
Wingwalls for windward windows can enhance the pressure differences between the two windows and induce air circulation within the space. Wingwalls for windward windows considerably increase cross ventilation in the room. Some pertrusion may serve as cupboard and be accounted for interior surface. Unfortunately, wingwalls are ineffective for leeward facades.



If the room has apertures on adjacent walls, wingwalls could considerably enhance cross-ventilation [9]. On the other hand, wingwalls modify the initial flow within the space.

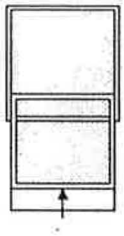
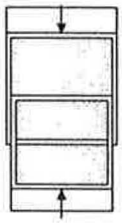
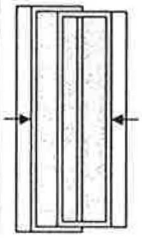
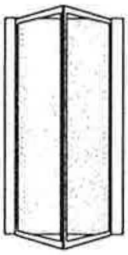
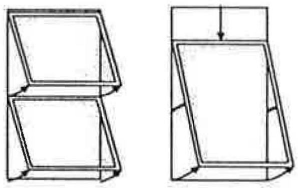
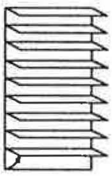


Vegetation can affect the air flow pattern in the same way as outside buildings or wingwalls [10]. Moreover, it also offer air filtering, noise reduction and shading.



4.5. Window selection

The window should be as large as possible to optimize cross ventilation. However, a compromise has to be realised between daylighting, weatherproofing, structural strengh, solar gain, operation, maintenance, cost and air movement control. Horizontally shaped windows should be prefered to vertically ones because they induce a higher air velocity within the occupied zone [11]. Turbulence fluctuations develop more easily in the floor plan and therefore favor air movement within the space, especially with single sided rooms. The window "à la française" which is the most commonly used over Europe [12] allows variable and 100 % opening of the gross total aperture. However, it could be refined to make intermediate openings more stable. The following table illustrates the main characteristics of the various other window styles as far as ventilation is concerned.

Window type	Advantage	Drawback
 Single Hung	Adjustment of the opening area. Air enters the openings and continues inside in the same direction as the outside wind.	Opening limited to 50 % of the window size. Winter leakage.
 Double Hung	Adjustment of the opening area. Adjustment of the sashes for directing air streams to a specific area.	Opening limited to 50 % of the window size. Winter leakage.
 Horizontal sliding	Adjustment of the opening area to direct air streams to a specific area.	Opening limited to 50 % of window size. Width/height small ratio does not favor hight efficiency for every wind direction.
 Side hunged	100 % openable. Sash can act as a wingwall and redirect the flow. Good sealing.	Difficult window treatment. Low market penetration
 Projection and awning	Excellent rain protection.	At low opening angles, the airflow is deflected upward, outside the occupied zone. Reduced opening area
 Jalousie	Take benefit of all wind direction. 100 % openable. Can direct the flow.	Excessive infiltration
 Basement and Hopper	Excellent for night ventilation and for air intake and exhaust. Can stay opened.	Reduced opening.

4.6. Other architectural features

4.6.1. Buffer Spaces

According to their design and location, verandahs, balconies, decks may increase significantly the air velocity within the spaces because they can generate high and low pressure regions and increase the pressure differences [13]. Special design considerations are involved because such features may also reduce cross ventilation. Orientable shutters may be used to direct the air stream to a specific location : the storage mass or the occupant.

4.6.2. Building Layout

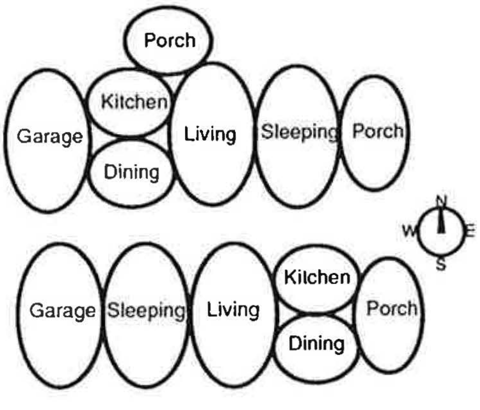
Wind direction and intensity can be modified by features around the building itself. Neighbouring buildings are a major pertubation obstacle. Their effects can be significant to channel the wind or to create a calm zone.

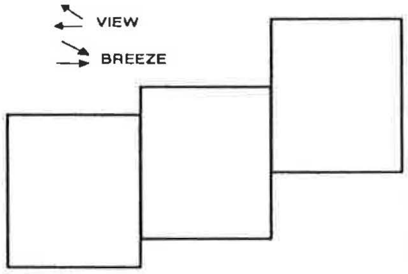
For an isolated building, the leeward wake extends roughly horizontally four times the ground to eave height. Therefore, if the gap between buildings is smaller, those in the wake are poorly ventilated. This situation is often encountered when the buildings are in a row. But, if they are positioned in a staggered pattern, the flow of air is deflected on each building and induces contrasting high and low pressure ones. This configuration is also favorable for pedestrian comfort because Venturi effects increase air velocities.

The building shape and height modify the air movement around the building. For a long building, most of the air is deviated over the top. For a tall building, air passes over the sidewalls. Roof-forms also affect the size of the protected area. The depth of the wake will be increased with a pitched roof. However, predicting the effect of buildings of various heights and sizes on air movement, in a complex urban area, requires extensive skills and expertises.

4.6.3 Building Plans

Building plans do not usually present large latitudes because of many constraints : city planning, lot size, building regulations, ... However, we should adopt an orientation compatible with the most frequent wind direction and with the minimum solar gain exposure. The building should offer the least resistance to wind. The position of the room should be selected according to their use and the concomittance of optimum comfort within this room.





With multifamily housing, the buildings can be distributed so that they catch maximum wind.

4.7. Ventilation of adjacent Spaces

Crawl spaces can be easily vented to avoid possible problems of moisture or radon with a use of gable vents on each side of the space. Attics should be vented to reduce their temperature and limit the heat transfer to the interior space. Continous soffit vents associated with exit at ridge is an efficient strategy. Gable vents, wind turbine or attic powered vent fan are other alternatives.

4.8. Nightime Ventilation

All the discussed design strategies apply as well to nightime ventilation as to daytime ventilation. But nightime ventilation may offer a higher potential for building cooling because of the lower outside temperature. If the outside temperature is lower than the inside one, flushing of the building is possible and the incoming air should be directed toward the massive structure. However, special care should taken in the design and operation of the openings. Are opened windows compatible with building security and occupant privacy ?

The efficiency of nigthttime ventilation is difficult to evaluate because various heat transfer phenomena (internal and external) occur in a dynamic way. Our existing knowledge is quite limited on the convective exchange within the building.

4.9. Limits

Wind induced ventilation would be an ideal strategy if winds were steady in direction and intensity (>3ms). Unfortunately, winds are extremely variable and weather data not available at most sites. Tracking wind systems are difficult to realise. Taking advantage of prevailing winds in a complex changing environment represents a difficult exercise in a multidisciplinary design. No major tools can bring a clear answer to the designer.

An air change rate of 20 to 50 should be achieved to maximise the cooling benefits of ventilation. If nighttime temperature remains above the interior operative temperature, nightime ventilation is a problem rather than a help. Moreover, induced latent loads should not be ignored in energy calculations.

In the absence of wind, buoyancy driven ventilation can represent a secondary technique but its effects are more limited in time and in intensity. Stack effect may exhaust a large quantity of heat in a short time but has not a continuous effect in summer conditions. In these situations, forced ventilation greatly extends the opportunities for using ventilation cooling.

5. FANS TO EXTEND SUMMER COMFORT

A box fan, an oscillating fan or a ceiling fan could supplement the weakness of natural ventilation by increasing the interior air velocities and convection exchange [14,15].Wu and al. [16,17] have demonstrated the capability of fans to extend the summer confort within the building outside the typical comfort zones (ASHRAE, Bioclimatic Chart). The following table illustrates their results.

Fans	Dry Bulb(°C)	Relative Humidity	Air Velocity
Ceiling	27.7°C 29.6°C 31°C	73% 50% 39%	1.02 m/s 1.02 m/s 1.02 m/s
Oscillating	31°C 32°C 33°C	50% 39% 30%	1.52 m/s 1.52 m/s 1.52 m/s

Oscillating fans present high potential at the local level to reduce the cooling load of the building. More research is needed to present guides on the use and potentials of fans in hot climates.

6. DESIGN GUIDELINES

It is always difficult to give general recommandations outside the context of a project. However, we may suggest design guidelines to assist the architect in his approach for a better use of natural ventilation as a cooling strategy.

- Analyse the climatic and building conditions to choose the most appropriate strategies : nighttime ventilation, daytime ventilation, occupant cooling.
- Design the building to respond well to winds from any direction.
- Take benefit of the building layout to catch any dominant breezes.
- Provide both an air inlet and an outlet for air flow in each space; locate them such that the air flow stream through the occupied zone or the storage mass and avoid stagant area and shortcircuiting.
- Prefer low inlet for occupant comfort but high outlet are more appropriate for exhausting air, especially in a multistorey building.
- Provide for both horizontal and vertical air flow using wind induced and stack effect.
- Favour ventilation with roof cupolas and clerestory windows.
- Maximise the opening sizes in a multidisciplinary approach. Do not forget the possibly conflicting demands of daylighting, noise, solar gains, ...
- Minimize the building air flow flow resistance. Prefer rooms in parallel than in series.
- Prefer French doors for interior doors because they do not present air resistance.
- Use full opening and operable windows. Prefer horizontally shaped windows to take benefits of various wind directions.
- Make sure that the natural ventilation features are accessible and easy to use.
- Avoid blocking windows with exterior object like shrubs and fences but do not compromise shading.
- Concentrate ventilation openings in spaces most likely to require cooling.
- Locate rooms where they provide the most comfort when in use.
- Use overhangs, porches, balconies to protect ventilation openings from rain and to increase the pressure differences.
- Have screened porches or balconies instead of window screens.
- Be certain that all ventilation openings can be effectively sealed during winter and air conditioning. Avoid jalousie windows.
- Respect privacy for occupants and do not neglect safety consideration.
- Use electric fans to supplement natural ventilation and to extend the comfort zone.
- Consider parasitic power requirement and latent loads in your energy calculation.
- Vent the crawl space to reduce problems of moisture and radon by placing a vent on each side of the space.
- Vent the attic with continuous vents.

A design tool has been proposed by the Florida Solar Energy Center [7] to size windows. The method, based on an optimum air change rate, takes in account the prevailing breeze (direction and wind speed), implements correction factors for the site and the selected windows and determines the required gross total operable area. This window sizing methodology could be completed to include the role of the window position on the efficiency of the natural ventilation. Other critera such as the shape of the window, the location of the mass could be implemeted to refine the method.

7. CONCLUSIONS AND FUTURE RESEARCH ACTIONS

Design recommandations do exist for ventilative cooling but they do not belong to the architect's toolbox. Research results should be transfered to building partners in user-friendly forms (checklist, sizing form, ...). Major mistakes in the design could be avoided if implemented. However, more research is needed in various directions.

The following are suggested as topics for future research :

1 Identification of the ventilative resource next to the building in relation with the known characteristics of weather data and site topography.

2 Relationship between the ventilative resource (wind speed, direction, turbulence intensity, temperature) and the interior air characteristics (velocity, turbulence intensity) according to the building envelope (opening, shading, wind features, ...). Field test and wind tunnel experiments.

3 Development of comfort models to take into account fluctuating air velocity in space as well as in and time. Role of turbulence intensity.

4 Refinement of the comfort zone on the psychometric chart.

5 Determination of the convective heat transfer coefficients at room surfaces for a better understanding of structural cooling.

6 Numerical and experimental evaluation of the potential of night cooling; Impact of mechanical fan enhancement.

7 Integration of ventilative cooling into air conditioned building controls strategy.

8 Potential of ceiling fans to extend summer comfort.

9 Efficiency of various fans (ceiling, box, oscillating). Classification of ceiling fans.

10 Development of new effective components such as chimney caps, roofvent, etc.

11 Design guidelines for the sizing and distribution of openings.

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