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Natural Ventilation as a Design Strategy for Energy Saving

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***Abstract*—Ventilation is a fundamental requirement for occupant health and indoor air quality in buildings. Natural ventilation can be used as a design strategy in free-running buildings to:

- Renew indoor air with fresh outside air and lower room temperatures at times when the outdoor air is cooler.
- Promote air flow to cool down the building structure (structural cooling).
- Promote occupant physiological cooling processes (comfort cooling).

This paper focuses on ways in which ventilation can provide the mechanism for heat dissipation and cooling of the building structure..It also discusses use of ventilation as a means of increasing air movement to improve comfort when indoor air temperatures are too high. The main influencing factors and design considerations and quantitative guidelines to help meet the design objectives are also discussed.

***Keywords*—Natural Ventilation, Sustainable Building, Passive Cooling, Energy Saving

I. Introduction

NATURAL ventilation occurs because of pressure differences acting on inlets and outlets of a space. This pressure difference can be created by wind or by a thermal chimney (stack ventilation). The pressure difference caused by winds may be steady (as in cross ventilation) or unsteady (as in turbulent ventilation). Steady wind-driven ventilation, i.e., cross ventilation, is usually the strongest mechanism and is produced when a prevailing wind direction creates distinct positive and negative (suction) pressures at the inlets and outlets of a volume.

Unsteady pressure differences also may be created by wind, such as changing pressure patterns over a windward wall with two widely spaced windows on the same wall. The fluctuating wind directions, typical in suburban or other rough terrain, create unsteady pressure fluctuations that can generate significant ventilation.

Another type of natural ventilation arises in rooms with only one window. Here minimal ventilation is created as some air enters the room at one time and a few seconds later some air exits because of the fluctuating static pressure of the wind. This pattern creates very minimal ventilation and will not be discussed further. The theoretical analysis of this type of "turbulent diffusion" ventilation is explained by Warren and Parkins [1].

Historically, the available airspeeds in ventilated rooms with different room geometry and window configuration have interested natural ventilation researchers. Studies were usually done by testing scale model buildings in wind tunnels. In the early 1950s, a comprehensive series of wind tunnel tests were conducted at the Texas A&M University using a uniform speed wind tunnel. A summary of those investigations is provided by Evans [2]. A detailed summary of the research results useful to the building designers is given by Reed [3]. Many of the airspeed patterns in rooms observed by the Texas A&M group have been summarised in pattern diagrams by Bowen [4].

II. Wind Towers and Solar Chimneys

Diverse strategies can be adopted to take advantage of the driving forces of natural ventilation. An example being, wind towers that draw upon the driving forces of the wind to generate air movement within the building [5]. 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 tower.

Alternatively, the chimney cap can be designed to create a low pressure region at the top of the tower, and the suction initiates air flow 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 [6].

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. The stairwell may serve as a chimney and so be completely integrated in the building architecture.

III. Windows Ventilation

The changes in airflow patterns caused by different types of windows were investigated by Holleman at Texas A&M [7]. as shown in Figure 1 Holleman found that fully open projection windows were capable of directing air at occupant level because of the slots. Such slots were also responsible for the good performance of casement windows for oblique wind incidences.

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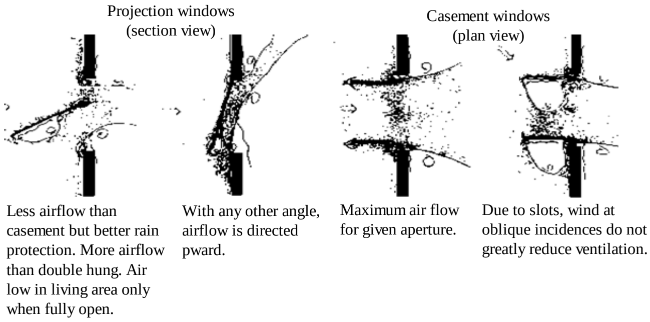

Fig. 1 Airflow patterns through windows

In the 1960s Givoni conducted another thorough set of wind tunnel studies using a uniform wind tunnel. Many of the findings can be found in Givoni [8]. But many more interesting findings regarding airspeeds in building groups and buildings with courtyards, methods to cross ventilate double-loaded corridors, and building layout for apartment buildings to enhance ventilation are only cited in the original research report by Givoni [9]. Givoni demonstrated the usefulness of adjacent windows.

He found that rooms with windows on adjacent walls ventilated better than traditional cross-ventilated rooms with windows on opposite walls when the incident wind angle was perpendicular to the inlet. At oblique wind incidences (45° incidence angle to inlet) traditional cross-ventilated rooms performed better than rooms with adjacent windows.

The estimation of room air change rates, average room surface temperatures and room air temperatures enables one to predict the cooling or heat removal rate for natural ventilation. However, it is very important to note that the room air change rate may not be related to air flow rates through the openings. Consider normal wind incidence and windward and leeward openings directly in line with one another. Depending on the ratio of the areas of opening, the air can rush through without significantly mixing and entraining room air. As a result, little heat will be removed and circulation in many parts of the room will be poor. Staggered windward and leeward openings that force the air to turn are better for ventilation. For similar reasons, winds at an oblique rather than normal incidence provide better cooling if the apertures are not staggered [10].

In the 1960s Sobin conducted another comprehensive wind tunnel study at the Architectural Association (London). Sobin was the first to use a boundary layer wind tunnel for natural ventilation studies. A boundary layer wind tunnel differs from the uniform speed wind tunnel used in aeronautical studies in that the former simulates both the variation of wind speed with height and the natural turbulence of the wind. Sobin published some of his findings in 1981[11]. Sobin investigated many interesting window types and measured room airspeeds both in section and plan. One of his most interesting findings relates to window shape. He found horizontal windows (windows that are wider than their height) created greater wind speeds than vertical windows (windows that are higher than their width). This effect was more pronounced for oblique wind incidences. It is interesting to note that Givoni's apertures were also horizontal and he also found good performance at oblique wind incidences. Aynsley et al. [12] continued airspeed measurements in a building with wind scoops.

Insect screening is a necessary consideration in ventilation in many parts of the world. Givoni [8] found that screening entire balconies produced greater airspeeds in rooms than did screening the windows. Van Straaten [13] measured the decrease in airflow caused by screens and found that it was dependent on the incident wind speed. For a 1.5 mph (0.7 m/s) wind, the airflow was reduced by 60%, whereas in a 6 mph (2.7 m/s) wind the reduction was only 28%. This difference is possibly due to the reduction of the wake region behind a cylinder as the Reynolds number increases.

Internal airspeeds can only be predicted by solving the three-dimensional turbulent flow equations, a difficult task that has been attempted by only a few [14], [15]. White of Texas A&M [16] investigated airflow reductions caused by landscaping elements such as trees and hedges. He also discovered using solid paper and landscape moss models of trees and hedges, that certain landscaping schemes are advantageous for increasing ventilation in building [17].

IV. Effect of Window Design on Natural Ventilation

The effect of various window configurations and architectural factors on indoor air movement, including wind orientation, cross-ventilation, inlet/outlet area ratio, inlet shape, window location and window accessories, was reported in an experimental wind tunnel study by Sobin [18].

A. Orientation

The effect of orientation to wind or wind angle on ventilative cooling was found to vary with the physical characteristics of the window configuration used, and in particular the characteristics of window location, shape, size and accessories. Generally speaking, for the majority of window configurations tested, orientation of inlets at 90° to the wind provided the highest average indoor speed ratios, with airflow velocities dropping off rapidly with external wind shifts to either side of 90°. Significantly enough, however, it was found that certain combinations of inlet characteristics (especially shape), while providing substantially similar results with 90° wind are also capable of providing equal or better ventilative cooling in oblique (up to 45°) winds than they do in normal (90°) winds. This is a finding of particular importance since wind direction is of course rarely if ever constant. If window systems are to take maximum advantage of wind-powered ventilation, they should be selected where possible to provide a reasonably "broad band", not a strongly "peaked" directional response providing greater effectiveness under customary conditions in which the wind changes direction over a certain range of directions on an hourly, daily, or seasonal basis. This is the case even in areas of great directional constancy, such as trade wind locations, where, as on the coastal regions of Caribbean islands, directional shifts of up to 90° take place during each 24-hour period. These directional effects are described with respect to each of the window design characteristics discussed below.

B. Cross-Ventilation

Test results confirm that for optimum ventilative cooling, sufficient effective area of inlet and outlet openings is required, with the inlet/s located in a zone of positive pressure and the outlet/s in a zone of negative pressure. Rooms equipped with inlets only tend to provide very much reduced indoor speed ratios (though demonstrating somewhat improved performance in oblique winds), especially in the case of horizontally-shaped openings. The configuration with inlets only corresponds to the frequently encountered arrangement in which rooms are provided with windows on one side of a building only. The relative improvement produced by oblique wind can amount to as much as 250%, where the single opening is located on a windward facade, but the overall result even under these conditions at best amounts to only one third of the average speed ratios provided by a cross-ventilating configuration. Smoke-tracing investigations of "one-sided" configurations show that in oblique and normal winds, a single opening functions as both inlet and outlet. Motive power for indoor airflow thus originates in pressure differences across the opening (almost always small in 90° wind, but somewhat more substantial in oblique wind).

C. Inlet Outlet Area Ratio

Test results confirmed that where inlet and outlet opening are equal, as their areas increase, increases occur in the amount of indoor ventilative cooling they produce. Since, however, window sizes are not determined by ventilation alone but must also take into account other architectural factors such as day lighting, privacy, security, and solar control, a significant question for ventilation purposes is how best to distribute a given and usually limited amount of opening area. An important parameter here is the relative distribution of area as between the inlet/s and outlet/s. Sobin's preliminary test results suggest that for a given total opening area, the highest euphoric indoor speed ratios throughout rooms are achieved when the ratio A_o/A_i is approximately l.25, that is, when the inlet is slightly smaller than the outlet. Inlets substantially smaller than outlets produce high local velocities in the vicinity of the inlet itself, but lower speed ratios when results are averaged across the entire room. It thus appears advisable to provide approximately equal inlets and outlets, or a very slightly smaller inlet, where maximum ventilative cooling is required.

D. Inlet Shape

A review of test results suggests that inlet shape is the single most important window design parameter in determining the efficacy of wind driven ventilative cooling. Square and vertical inlet openings produce a sharply peaked or "narrow-range" response under conditions of changing wind direction, with both types attaining maximum performance in a perpendicular (90°) wind, but falling off rapidly in efficiency with even small departures of wind direction from the perpendicular. At 45^{o}, for example, vertical inlet performance has decreased by more than 17%, that of square inlets by more than 26%.

On the other hand, horizontal inlets not only have a substantially higher average performance for all wind angles, but in contrast to square and vertical inlets, horizontal inlets actually improve their effectiveness in angled winds, producing two maxima at wind angles in the vicinity of 45° to either side of the perpendicular, while showing a relatively flat, or "wide-range" response throughout this 90° quadrant of wind angles (or orientations). The improvement of horizontal inlets in oblique compared to perpendicular wind angles can amount to 30% or better and depends on the relative opening sizes used. For example, given equal areas of inlet and outlet, where each opening is equal to 22% of the inlet and outlet wall areas respectively, the increase in average indoor speed ratio for horizontal inlets in a 45° wind compared to a 90° wind is typically in the order of 16%. Horizontal inlets were found to increase their performance in oblique winds in fully cross-ventilated rooms (openings in opposite walls), in diagonally-ventilated rooms (openings in adjacent walls), and in rooms with inlet openings only.

From the results of Givoni's ventilation study [19], he reached the general conclusion that better ventilation is often achieved when the wind is oblique to the inlet. With respect to this conclusion, however, it should be noted that all inlet and outlet openings tested by Givoni were horizontally shaped; no "square" or "vertical" opening shapes were included in his tests. Another of Givoni's conclusions not supported by the results of the present study concerns his explanation for the superiority of oblique wind angles. Givoni suggests that when airflow has to change direction inside a room, as it must with wind oblique to the ventilation-axis (defined as a line drawn between the centre points of the inlet and outlet openings), a larger proportion of room volume becomes involved in the flow resulting in higher average velocities. Test results from the Sobin's study [20] indicate, however, that a change in direction of airflow inside a room does not necessarily lead to increased air movement, on the contrary it is often substantially reduced. Smoke-tracing shows, for example, that in oblique winds, strong directional changes take place inside rooms equipped with square or vertical inlets, yet these two inlet types consistently provide substantially lower average indoor speed ratios in oblique than in perpendicular wind, typically showing relative losses of 25% or more in a 45° wind. A more comprehensive hypothesis, capable of explaining the full range of observed changes in performance with different opening shapes appears to require inclusion of at least two factors in addition to flow patterns: (1) the influence of wind angle on the effective inlet area, and (2) external wind-pressure distributions. It should also be observed that horizontally-shaped inlets tend to produce a broader, flatter, more "room-wide" jet or sheet indoor airflow than do vertical or square ("hole-in-a-wall") shaped inlets. This fact may help to explain, at least in part, their clearly superior ability to provide higher average amounts of ventilative cooling throughout the interior of rooms.

E. Window Location

Preliminary results suggest that in general, ventilative cooling performance is improved when the inlet and outlet are arranged so that the ventilation axis is parallel to the wind. This condition occurs either (a) when the inlet and outlet are located directly in line with one another on opposite walls of a room, with the wind perpendicular to the inlet; or (b) when the inlet and outlet are located in adjacent walls of a room, and an oblique wind passes successively through the inlet, through at least one corner of the room, then passes through the outlet. It should be noted that in both of these cases, the main tube or jet of airflow passes directly from inlet to outlet without changing direction inside the room. The only previous study to have examined the diagonally-ventilated room configuration [19] and which reported a test result contrary to that attained in the present study, proceeded to use this result as a basis for concluding that ventilation is improved wherever airflow changes direction inside a room.

The Texas [16] studies found that while airflow was maximised by equal inlet and outlet areas, airspeeds in rooms were locally maximised (particularly near the inlet) if the outlet was slightly larger than the inlet. They found that while the outlet location did not affect the airflow pattern significantly, the inlet location controlled the airflow pattern. A high inlet directed airflow near the ceiling, whereas a low-to-medium height inlet directed airflow to the occupant levels. However, even a mid ceiling height level inlet at the second floor directed air to the ceiling. They also observed the "wall jet" effect. If the inlet is near a corner, the air tends to lair along the nearest wall.

F. Window Accessories

Window accessories have been traditionally designed to work as sun shading, privacy or security devices, not as airflow controls. However, window "equipment" designed to produce solar or rain protection, visual privacy. Shielding and other non-aerodynamically related purposes can frequently have unintentioned, yet at times seriously deleterious effects on wind-powered ventilative cooling. Earlier studies have recognised this problem; the present results confirm its importance.

One instance of the unfavourable effect of window equipment revealed by present test results is the aerodynamic effect of fixed or movable horizontal and vertical louvres. The effect of primarily horizontal louvres or canopies on indoor airflow speeds and patterns is chiefly manifested in section. Horizontal louvres have the tendency, when adjusted to typical angles, to direct airflow toward the ceiling, thus greatly reducing ventilative cooling effectiveness within the room's occupied zone. However, the effect of primarily vertical louvres chiefly shows up on plan. For example, horizontal louvres used on vertical inlets do nothing to alter the basically peaked, "narrow-band" and symmetrical plan-response of this type of opening to changing wind angles, regardless of the blade setting angle. The same phenomenon is created by inlet accessories which incorporate vertical elements, which also tend to produce a strongly peaked. Narrow-band directional response, provides maximum average indoor airflow when the vertical elements present the minimum degree of airflow resistance, i.e., when they are parallel to the wind. For example, when vertical louvres are set perpendicular to the plane of an inlet opening, they tend to cut off diagonal wind; yet when oriented at an oblique angle they sharply favour diagonal winds arriving at angles close to that same direction. By the addition to vertical control elements, it is also possible to "convert" the typical "broad-band" directional response of horizontal inlets, into the "narrow-band" response of square or vertical inlets.

In general, as the wind angle shifts, vertical "window furniture" produces an effective change in inlet area. The degree of change depends on the angular relationship between the accessory elements and wind direction. Increasing the angle increases "narrowing", and decreasing the angle increases effective inlet area where it is not possible or desirable to orient opening accessories to face the wind, flow-directing accessories such as louvres can be placed within or across the inlet opening to "turn" wind to enter a belladonna. But results show that considerable resistance losses of up to 50% or more are incurred by the use of such techniques, suggesting that wherever possible flow-directing accessories should be located adjacent to inlets. not within them.

V. Architectural Implications

The architectural implications of natural ventilation are discussed in detail on previous references. Some of the findings are summarised below:

a) Airflow is governed by three guiding principles:

- Air has inertia, i.e., air does not necessarily travel in the shortest path between an inlet and an outlet in an adjacent wall.
- Moving air produces friction in contact with bodies and as a result slows down or forms into eddies.
- Air moves due to pressure differences.

b) Local topographical conditions, landscaping and adjacent buildings can dramatically influence winds at the site. Thus, recorded wind speeds and direction data at a nearby meteorological station may be of little value.

c) A study of the external airflow patterns is necessary to determine the best locations for windows or other apertures. Inlets should be placed in the high pressure regions and outlets in the low pressure regions.

d) Window inlets must be so designed and placed as to provide maximum airspeeds at the desired locations (sitting level in living rooms, just above the bed level in bedrooms).

e) Window types greatly influence the airflow direction in a room. One of the best type of window for natural ventilation purposes seem to be awning or louvred windows which can be manually rotated to direct the wind to desired locations inside the room. Such windows will also generally provide the maximum aperture area, afford protection from the rain and allow installation of bug screens. Although window types affect the airflow direction, they do not significantly affect the overall ventilation rate.

f) The best location for an inlet is near the vertical and longitudinal centre of a wall which is perpendicular to the wind. This is where the pressure is the highest. If the inlets are too high or are near to the side edge of a wall, overhangs or wing walls should be provided to induce a high pressure zone.

g) The outlet should be exposed to the eddy or wind shadow which is the low pressure zone. The outlet may be placed high, near the ceiling, to take advantage of the stack effect, if any. However, it may be ill advised in locations without a prevailing wind direction, or in some coastal areas where the prevailing wind fluctuates between two opposite directions.

h) In many cases, oblique winds at 45° provide better or equally well ventilation as normal winds. Consider a cross-ventilated room with inlet and outlet windows directly in line with each other. Winds normal to the windows will have a tendency to move through the building without mixing well with the room air. Therefore, regions near the wall will not be well ventilated. Whereas, oblique winds will create a circulating airflow pattern in the entire room providing greater ventilation rates and lower local airspeeds. This has profound design implications in those humid areas where the prevailing summer breezes are easterly or westerly, the direction most difficult to shade and ventilate at the same time. If the prevailing breeze is easterly, one can orient the inlet wall to face south east or north-west, directions which are easier to shade with long overhangs. Thus simultaneous shading and ventilation are possible.

i) Although windows on only one side of a room do not induce appreciable ventilation, it is possible to design vertical projections (wing walls) to induce appreciable ventilation under oblique winds.

j) For cross-ventilated rooms, both inlet and exit window sizes need to be increased to increase ventilation rates. However, making the inlet smaller than the outlet creates higher wind speeds near the inlet wall, which may be desirable.

k) The effect of indoor partitions is greatest when they are close to the inlet window. But on the average, the ventilation rate is not greatly reduced.

l) Fly screens a necessity in bug-infested hot and humid regions, result in a percentage decrease in total air flow that is greater (50-60 percent) at low wind speeds (1.5-2 mph) than at higher wind speeds (25 percent at 10 mph), for normal incidences. Wind direction effects are significant. Screening a whole balcony produces more ventilation than screening the window.

m) Extended eaves and end walls are very effective for ventilation with oblique winds for buildings on the ground. Their effectiveness is further increased when the building is elevated above the ground.

Hedges and trees can significantly aid or deter ventilation, depending on plant height and spacing from building..

VI. Conclusion

For natural ventilation to be effective during warm periods, it is not sufficient to meet the basic rules for passive cooling design (minimise transmission heat gain by insulating the envelope; avoid direct heat gain by effective shading; keep the internal thermal inertia large by exposing thermal mass), but it is important to have the ventilation strategy under strict control. For natural ventilation to be an acceptable cooling technique for designers, practical solutions have to be found for ventilation openings which satisfy security requirements.

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