Natural Ventilation –Some Design Considerations

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Abstract

Natural ventilation reduces energy consumption for fans and mechanical cooling and in most cases gives occupants control over their office space. Further benefits include no fan noise and in some cases elimination of the mechanical cooling system. The information in this paper has been presented to help building designers, owners and managers understand how certain key factors affect the performance and energy efficiency of the ventilation system, and to operate ventilation systems at minimal energy cost. Improving the air tightness of older buildings will reduce air leakage and cold drafts, and help reduce energy use by improving the performance of ventilation systems. There are three strategies for achieving acceptable indoor air quality: ventilation, source control and cleaning/filtration. Depending on the building and the specific characteristics of its location, these strategies may be used singly or in combination. When identifiable contamination sources are present in a building, it is necessary to reduce contamination sources as much as possible either by using environmentally friendly furnishings, materials and products, or by exhausting contaminants at the source, if possible. General Ventilation should then be used. For buildings where the number of occupants varies significantly with time, such as office complexes and schools, it may be possible to further improve energy efficiency by turning off ventilation systems during the non-occupied periods and controlling their ventilation rates during occupied periods based on the actual number of occupants at a given time.

Natural Ventilation

Natural ventilation relies on the natural porosity of the building and/or a combination of vents, chimneys and open able windows to provide the primary source of ventilation. Small extractor fans may be used to augment needs (e.g. in 'wet' rooms such as kitchens, bathrooms etc.).

Throughout the world many buildings are naturally ventilated. While natural ventilation may mean little more than relying on a arbitrary combination of uncontrolled air infiltration and window opening, the present need for energy efficiency and good indoor air quality now demands well designed natural ventilation systems. This can be achieved by understanding the flow mechanisms and evaluating the impact on air change of the natural driving forces of wind and temperature

Natural ventilation systems rely on pressure differences to move fresh air through buildings. Pressure differences can be caused by wind or the buoyancy effect created by temperature differences or differences in humidity. In either case, the amount of ventilation will depend critically on the size and placement of openings in the building. It is useful to think of a natural ventilation system as a circuit, with equal consideration given to supply and exhaust. Openings between rooms such as transom windows, louvers, grills, or open plans are techniques to complete the airflow circuit through a building.

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Code requirements regarding smoke and fire transfer present challenges to the designer of a natural ventilation system. Historic buildings used the stairway as the exhaust stack, a technique now prevented by code requirements in many cases

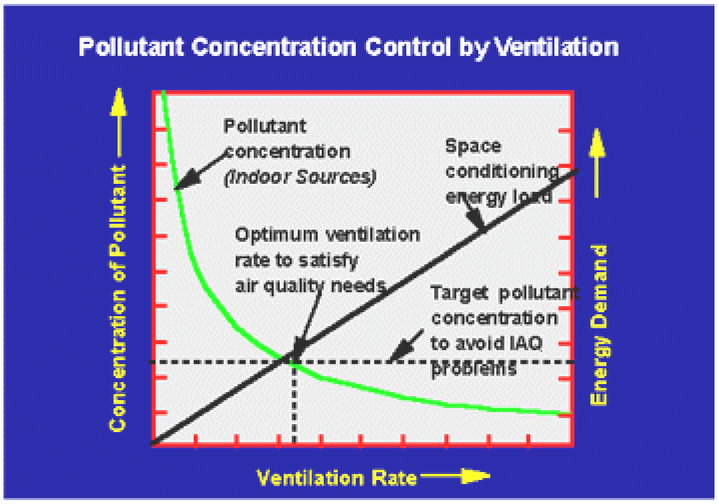


Fig. 1.1 Pollutant Concentration Control by Ventilation

The indoor pollution emissions are controlled by 'diluting' or 'displacing' indoor air with 'clean' outdoor air. For a fixed emission rate, the steady state concentration level is reduced as the ventilation rate is increased. If the air is 'conditioned' (i.e. heated or cooled to maintain optimum thermal comfort.

Technical Information

There are two basic types of natural ventilation effects: buoyancy and wind. Buoyancy ventilation is more commonly referred to as temperature-induced or stack ventilation. Wind ventilation supplies air from a positive pressure through apertures on the windward side of a building and exhausts air to a negative pressure on the leeward side.

Wind

Wind causes a positive pressure on the windward side and a negative pressure on the leeward side of buildings. To equalize pressure, fresh air will enter any windward opening and be exhausted from any leeward opening. In summer, wind is used to supply as much fresh air as possible while in winter, ventilation is normally reduced to levels sufficient to remove excess moisture and pollutants

Sometimes wind flow prevails parallel to a building wall rather than perpendicular to it. In this case it is still possible to induce wind ventilation by architectural features or by the way a casement window opens. For example, if the wind blows from east to west along a north-facing wall, the first window (which opens out) would have hinges on the left-hand side to act as a scoop and direct wind into the room. The second window would hinge on the right-hand side so the opening is down-wind from the open glass pane and the negative pressure draws air out of the room.

It is important to avoid obstructions between the windward inlets and leeward exhaust openings. Avoid partitions in a room oriented perpendicular to the airflow. On the other hand, accepted design avoids inlet and outlet windows directly across from each other (you shouldn't be able to see through the building, in one window and out the other), in order to promote more mixing and improve the effectiveness of the ventilation.

Buoyancy

Buoyancy ventilation may be temperature-induced (stack ventilation) or humidity induced (cool tower). The two can be combined by having a cool tower deliver evaporatively cooled air low in a space, and then rely on the increased buoyancy of the humid air as it warms to exhaust air from the space through a stack. The cool air supply to the space is pressurized by weight of the column of cool air above it. Although both cool towers and stacks have been used separately, the author feels that cool towers should only be used in conjunction with stack ventilation of the space in order to ensure stability of the flow. Buoyancy results from the difference in air density. The density of air depends on temperature and humidity (cool air is heavier than warm air at the same humidity and dry air is heavier than humid air at the same temperature). Within the cool tower itself the effect of temperature and humidity are pulling in opposite directions (temperature down, humidity up). Within the room, heat and humidity given off by occupants and other internal sources both tend to make air rise. The stale, heated air escapes from openings in the ceiling or roof and permits fresh air to enter lower openings to replace it. Stack effect ventilation is an especially effective strategy in winter, when indoor/outdoor temperature difference is at a maximum. Stack effect ventilation will not work in summer (wind or humidity drivers would be preferred) because it requires that the indoors be warmer than outdoors, an undesirable situation in summer. A chimney heated by solar energy can be used to drive the stack effect without increasing room temperature, and solar chimneys are very widely used to ventilate composting toilets in parks.

An expression for the airflow induced by the stack effect is:

$$Q_{stack} = C_d * A[gh(T_i - T_o)/T_i]^{1/2} \qquad \text{....(1.1)}$$

where
Q_{stack} = volume of ventilation rate (m³/s)
C_d = 0.65, a discharge coefficient.
A = free area of inlet opening (m²), which equals area of outlet opening.
g =9.8 (m/s²). the acceleration due to gravity
h = vertical distance between inlet and outlet midpoints (m)
T_i = average temperature of indoor air (K), note that 27°C = 300 K.
T_o = average temperature of outdoor air (K)

The cool tower ventilation is only effective where outdoor humidity is very low. The following expression for the airflow induced by the column of cold air pressurizing an air supply is based on a form developed by Thompson (1995), with the coefficient from data measured at Zion National Park Visitor Center. This tower is 7.4 m tall; 2.4 m square cross section, and has a 3.1 m² opening.

$$Q_{cooltower} = 0.49 * A * [2gh(T_{db} - Twb)/T_{db}]^{1/2} \qquad \text{....(1.2)}$$

where
$Q_{cool\ tower}$ = volume of ventilation rate (m³/s)
0.49 is an empirical coefficient calculated with data from Zion Visitor Center, UT, which includes humidity density correction, friction effects, and evaporative pad effectiveness.
A = free area of inlet opening (m²), which equals area of outlet opening.
g =9.8 (m/s²). The acceleration due to gravity
h = vertical distance between inlet and outlet midpoints (m)
T_{db} = dry bulb temperature of outdoor air (K), note that 27°C = 300 K.
T_{wb} = wet bulb temperature of outdoor air (K)

The total airflow due to natural ventilation results from the combined pressure effects of wind, buoyancy caused by temperature and humidity, plus any other effects from sources such as fans. The presence of mechanical devices that use room air for combustion, leaky duct systems, or other external influences can significantly affect the performance of natural ventilation systems.

DESCRIPTION

Natural ventilation, unlike fan-forced ventilation, uses the natural forces of wind and buoyancy to deliver fresh air into buildings. Fresh air is required in buildings to alleviate odors, to provide oxygen for respiration, and to increase thermal comfort. At interior air velocities of 160 feet per minute (fpm), the perceived interior temperature can be reduced by as much as 5°F. However, unlike true air-conditioning, natural ventilation is ineffective at reducing the humidity of incoming air. This places an upper limit on the application of natural ventilation in warm humid climates.
In order for air to move through or around a space, there needs to be some driving force. One often sees the obligatory blue and red arrows indicating the movement of air through an architect's latest design. Unfortunately, these arrows seldom make it into the final building, leaving the air confused and unsure of where to go next. It is then left up to natural forces to direct the air through the building.

The building form and construction determines the relative strength of these natural forces. This basically comes down to the size and location of air inlets and outlets as well as any ability to capture or funnel prevailing breezes. The building form can be designed to enhance ventilation, using atria, narrow building depths, open plan environments, massive concrete structures, sun-assisted chimneys, wind-wings and twin facades. In hybrid systems, motorised windows can be used as active regulators to achieve control over air change rates and heat load reduction.

Inducing Air Movement

Air will move only when it is pushed, pulled, heated up or cooled down. In a passive design, the pushing and pulling has to be done by the prevailing wind, whilst the heating and cooling can be done by solar radiation, evaporation and/or thermal mass.

Wind-Driven Ventilation

Air can only be pushed and pulled by producing localised areas of high or low pressure. Thus building form is fundamental to any wind-driven natural ventilation system. Anything that diverts or changes the path of the air will act to impede its flow. This impedance is significantly higher if the air is forced to move upwards or downwards to navigate a barrier without any corresponding increase or decrease in temperature.

Wind causes a positive pressure on the windward side and a negative pressure on the leeward side of buildings. To equalise this pressure, outside air will enter any windward openings and be drawn out of leeward openings. In summer, wind is usually used to supply as much fresh air as possible while in winter ventilation is normally reduced to levels sufficient only to remove excess moisture and pollutants.

Stack-Effect Ventilation

Buoyancy results from differences in air density. The density of air depends on temperature and humidity. Cool air is heavier than warm air at the same humidity and dry air is heavier than humid air at the same temperature. Thus, heat and humidity given off by occupants and other internal sources tend to make air rise. The stale, heated air escapes from openings in the ceiling or roof, drawing fresher air in through lower openings to replace it.

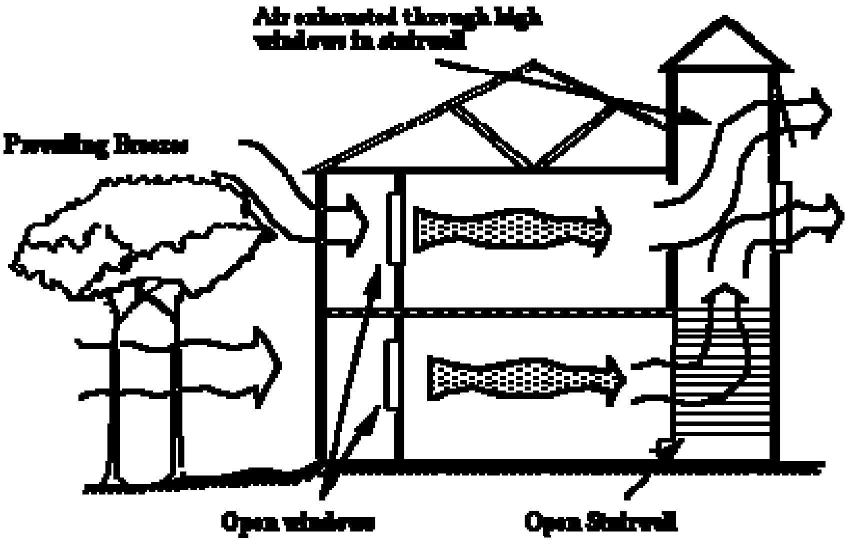


Fig. 1.2 Stack Effect Built into Home

Thermo-Syphon Effect

Operating in much the same way as the stack effect, a thermo-syphon makes use of direct sunlight to warm the air in a building. This requires a large amount of equator-facing glass. Dark surfaces beneath the glass absorb the direct sunlight, increase in temperature and re-radiate long-wave infrared radiation heat back into the enclosed space. As glass is opaque to long-wave infrared radiation, the heat energy is trapped within the space and eventually absorbed by the air. This is basically the greenhouse effect at work.

If allowed to vent out the top, the heated air will rise - drawing new cooler in at the bottom. This causes quite a strong convection current within the building. By not venting the warm air out the top, but letting it move through internal vents, this convection current can be used for heating in winter, even on a relatively cloudy day.

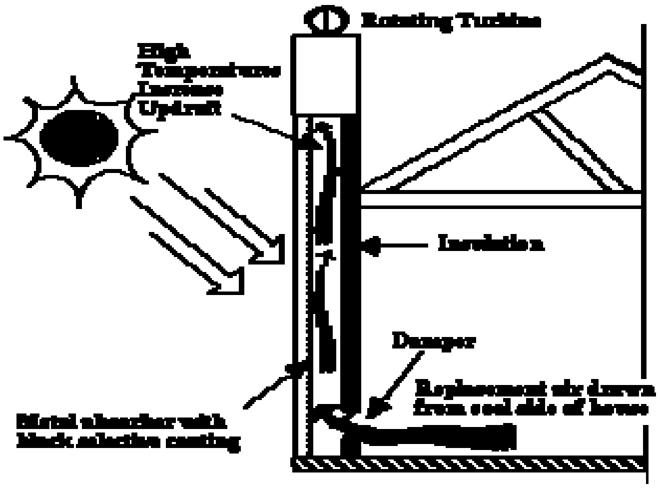


Fig. 1.3 Thermal Chimney

Principles Of Natural Ventilation

Natural ventilation methods date back to the first time animals were confined in shelters, when farmers left the barn door open to reduce moisture or heat buildup. Today's naturally-ventilated livestock shelters, although more sophisticated, operate on exactly the same principles. Natural ventilation occurs primarily because of the difference in wind pressure across a building, and to a lesser extent because of a difference in inside and outside temperature. A natural system works best in a building with no ceiling but having small openings at the eaves and ridge (peak) of the roof, and having large sidewall openings (Figure 1.4).

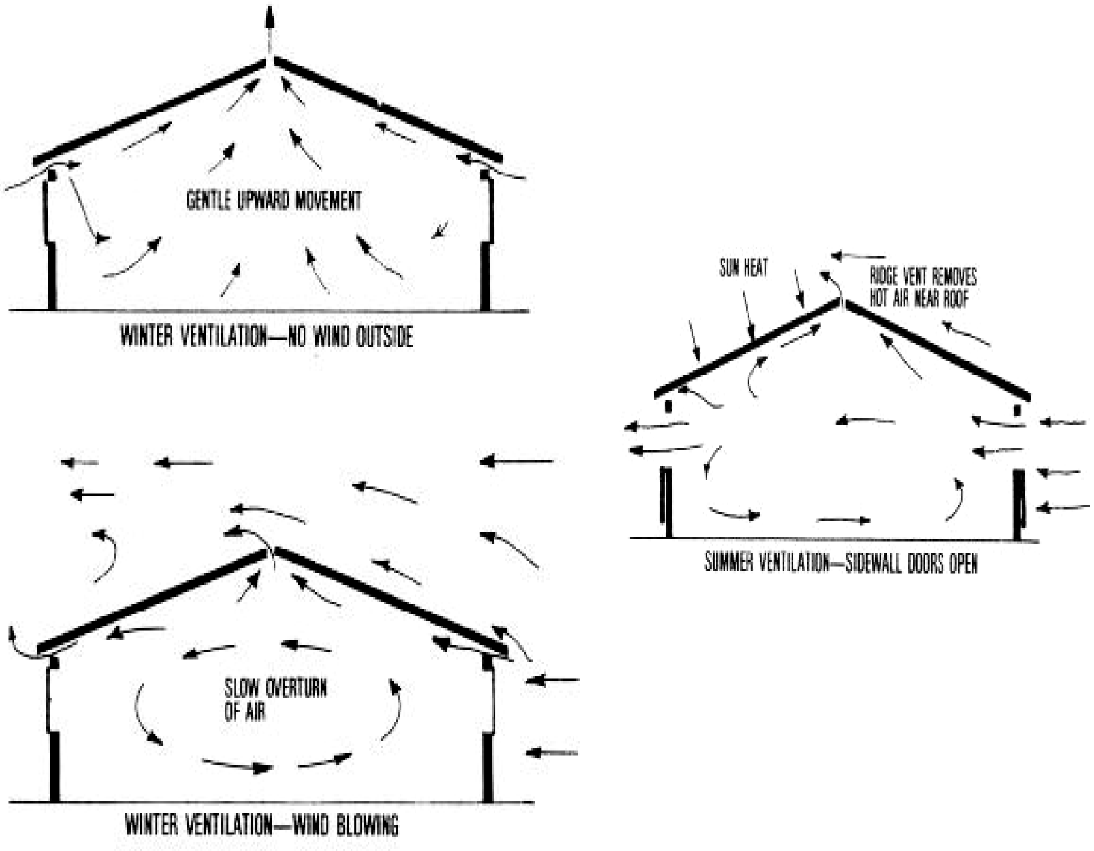


Fig. 1.4 Natural ventilation in a gable-roof building occurs primarily because of the wind blowing over the ridge and, to a lesser degree, because of the temperature difference inside and out.

Winter ventilation occurs as wind blows across the open ridge of the gable-roof building. Suction is created which draws warm, moist air out of the building and fresh air in through the eave openings. If wind velocity is great enough, the downwind (leeward) eave openings can also act as air outlets. On calm winter days, the hot, moist air still rises and eventually finds its way out the ridge opening. This chimney or `stack' effect accounts for only about 10 percent of the total ventilation, because there is not a great difference between inside and outside temperatures in most naturally-ventilated buildings, except on very cold days.

Summer ventilation is provided by opening up large portions (typically one-third to one-half) of each sidewall to allow a cross-flow of air; the ridge opening has little effect in summer.

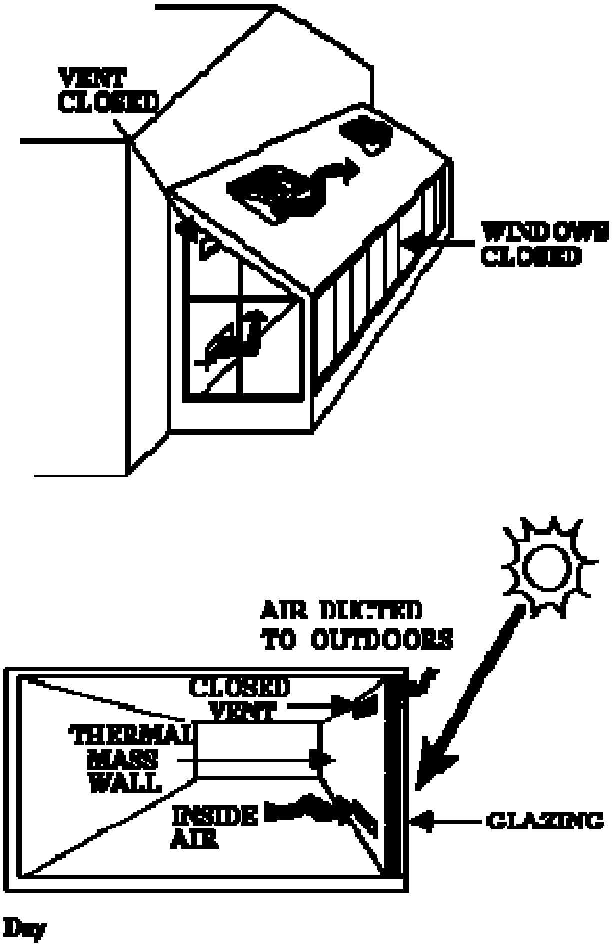


Fig.1.5 Summer Venting Thermal MassWall

Design Recommendations

The specific approach and design of natural ventilation systems will vary based on building type and local climate. However, the amount of ventilation depends critically on the careful design of internal spaces, and the size and placement of openings in the building.

- Maximize wind-induced ventilation by siting the ridge of a building perpendicular to the summer winds.
  - Approximate wind directions are summarized in seasonal "wind rose" diagrams available from the National Oceanographic and Atmospheric Administration (NOAA). However, these roses are usually based on data taken at airports; actual values at a remote building site can differ dramatically.
  - Buildings should be sited where summer wind obstructions are minimal. A windbreak of evergreen trees may also be useful to mitigate cold winter winds that tend to come predominantly from the north.
- Naturally ventilated buildings should be narrow.
  - It is difficult to distribute fresh air to all portions of a very wide building using natural ventilation. The maximum width that one could expect to ventilate

naturally is estimated at 45 ft. Consequently, buildings that rely on natural ventilation often have an articulated floor plan.

- Each room should have two separate supply and exhaust openings. Locate exhaust high above inlet to maximize stack effect. Orient windows across the room and offset from each other to maximize mixing within the room while minimizing the obstructions to airflow within the room.
- Window openings should be operable by the occupants.
- Provide ridge vents.
  - A ridge vent is an opening at the highest point in the roof that offers a good outlet for both buoyancy and wind-induced ventilation. The ridge opening should be free of obstructions to allow air to freely flow out of the building.

Operable windows that permit natural ventilation can be used in offices and other commercial structures.

Fig. 1.6

- Allow for adequate internal airflow.
  - In addition to the primary consideration of airflow in and out of the building, airflow between the rooms of the building is important. When possible, interior doors should be designed to be open to encourage whole-building ventilation. If privacy is required, ventilation can be provided through high louvers or transoms.
- Consider the use of clerestories or vented skylights.
  - A clerestory or a vented skylight will provide an opening for stale air to escape in a buoyancy ventilation strategy. The light well of the skylight could also act as a solar chimney to augment the flow. Openings lower in the structure, such as basement windows, must be provided to complete the ventilation system.
- Provide attic ventilation.
  - In buildings with attics, ventilating the attic space greatly reduces heat transfer to conditioned rooms below. Ventilated attics are about 30°F cooler than unventilated attics.
- Consider the use of fan-assisted cooling strategies.
  - Ceiling and whole-building fans can provide up to 9°F effective temperature drop at one tenth the electrical energy consumption of mechanical air-conditioning systems.
- Determine if the building will benefit from an open- or closed-building ventilation approach.
  - A closed-building approach works well in hot, dry climates where there is a large variation in temperature from day to night. A massive building is ventilated at night, then, closed in the morning to keep out the hot daytime

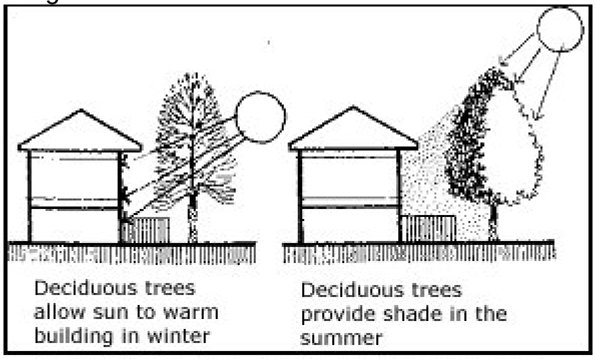
  air. Occupants are then cooled by radiant exchange with the massive walls and floor.
  - An open-building approach works well in warm and humid areas, where the temperature does not change much from day to night. In this case, daytime cross-ventilation is encouraged to maintain indoor temperatures close to outdoor temperatures.
- Use mechanical cooling in hot, humid climates.
- Try to allow natural ventilation to cool the mass of the building at night in hot climates.
- The long façade of the building and the majority of the openings should be oriented with respect to the prevailing summer breezes (i.e., north-south orientation if prevailing westerly wind).
- Exhaust vents or outlets should be on the leeward side as high as possible in the building.
- Vegetation and site objects should not obstruct inlet openings.
- Rooms should have inlet and outlet openings located in opposing pressure zones, e.g. windward and leeward walls, windward wall and roof.
- Inlets should supply air low in the room. Outlets should be located across the room and at high level.
- The vertical distance between the inlet and exhaust openings should take advantage of the stack effect.
- all occupied spaces should have an inlet and outlet opening, one or both of which may be an operable window
- The total area of outlet openings should be operable and accessible by the occupants.
- Inlet openings should not be obstructed by furniture and interior partitions.
- Enclosed staircases used to take advantage of stack effect ventilation should be designed such that their function as fire exits is not compromised.
- Floor to ceiling heights should be at least 3 m.

In order for natural ventilation to be effective as a space cooling system, it is important to keep solar and internal gains to a minimum. The lower these gains are, the less air flow is required to remove the heat and the greater the likelihood that a mechanical cooling system can be avoided. Some techniques to reduce solar and internal gains are given below.

- Window areas should not be excessive and be protected by exterior shading devices.

Shading with Vegetation

- Design for high thermal capacity and exposed ceilings for night cooling.
- Minimize warming of the walls by the sun through use of light-coloured building exteriors, trees and shrubs to provide shading and evaporative cooling, grass and other groundcover to keep ground temperatures low, and ponds and fountains to enhance evaporative cooling



Examples of side landscape features that help to conserve energy

Fig. 1.7

- Internal loads should be low, e.g. high-efficacy lighting, lighting controls, high-efficiency mechanical equipment, pipe and duct insulation

Natural ventilation in most climates will not move interior conditions into the comfort zone 100% of the time. Make sure the building occupants understand that 3% to 5% of the time thermal comfort may not be achieved. This makes natural ventilation most appropriate for buildings where space conditioning is not expected. As a designer it is important to understand the challenge of simultaneously designing for natural ventilation and mechanical cooling. It can be difficult to design structures that are intended to rely on both natural ventilation and artificial cooling. A naturally ventilated structure often includes an articulated plan and large window and door openings, while an artificially conditioned building is sometimes best served by a compact plan with sealed windows. Moreover, interpret wind data carefully. Local topography, vegetation, and surrounding buildings have an effect on the speed of wind hitting a building. Wind data collected at airports may not tell you very much about local microclimate conditions that can be heavily influenced by natural and man-made obstructions. Hints about what type of natural ventilation strategies might be most effective can often be found in a region's historic and vernacular construction practices.

Materials and Methods of Construction

Some of the materials and methods used to design proper natural ventilation systems in buildings are solar chimneys, wind towers, and summer ventilation control methods. A solar chimney may be an effective solution where prevailing breezes are not dependable enough to rely on wind-induced ventilation and where keeping indoor temperature sufficiently above outdoor temperature to drive buoyant flow would be unacceptably warm. The chimney is isolated from the occupied space and can be heated as much as possible by the sun or other means. Air is simply exhausted out the top of the chimney creating suction at the bottom which is used to extract stale air.

Wind towers, often topped with fabric sails that direct wind into the building, are a common feature in historic Arabic architecture, and are known as "malqafs." The incoming air is often routed past a fountain to achieve evaporative cooling as well as ventilation. At night, the process is reversed and the wind tower acts as a chimney to vent room air. A modern variation called a "Cool Tower" puts evaporative cooling elements at the top of the tower to pressurize the supply air with cool, dense air.

In the summer, when the outside temperature is below the desired inside temperature, windows should be opened to maximize fresh air intake. Lots of airflow is needed to maintain the inside temperature at no more than 3-5 °F above the outside temperature. During hot, calm days, air exchange rates will be very low and the tendency will be for inside temperatures to rise above the outside temperature. The use of fan-forced ventilation or thermal mass for radiant cooling may be important in controlling these maximum temperatures.

Analysis & Design Tools

Handbook methods such as those presented in ASHRAE's *Handbook of Fundamentals* or Bansal and Minke's *Passive Building Design: A Handbook of Natural Climatic Control* are very useful in calculating airflow from natural sources for very simple building geometries.

Computational Fluid Dynamics (CFM): In order to predict the details of natural airflow, numerical computational fluid mechanics models can be used. These computer simulations are detailed and labor intensive, but are justified where accurate understanding of airflow is important. They have been used to analyze new buildings including the atrium of a courthouse in Phoenix and the hangar of an air and space museum in the Washington, DC area.

An extensive list of journals, books, and other reference material regarding natural ventilation and other passive technologies is included in the Solstice Archive. For example,

BTS Building Standards & Guidelines Program (BSGP)
EREC Fact Sheet: Cooling Your Home Naturally

Software packages for natural ventilation analysis include:

FLUENT: A computational fluid dynamics program useful in modeling natural ventilation in buildings. It models airflow under specified conditions, so additional analysis is required to estimate annual energy savings.
AIRPAK: provides calculation of airflow modeling, contaminant transport, room air distribution, temperature and humidity distribution, and thermal comfort by computational fluid dynamics.
FLOVENT: calculates airflow, heat transfer, and contamination distribution for built environments using Computational Fluid Dynamics.

Building models incorporate very limited features for deliberate natural ventilation, but they do include the calculation of natural air infiltration as a function of temperature difference, wind speed, and effective leakage area, or schedules and user defined functions for infiltration rates.

DOE-2: A comprehensive hour-by-hour simulation; daylighting and glare calculations integrate with hourly energy simulation. IBM or compatible Pentium is advisable.
Designing Low Energy Buildings with Energy-10: An hour-by-hour simulation program designed to inform the earliest phases of the design process. Runs on IBM-compatible platforms. Best operated with Pentium or higher processor and 32 Megs of RAM.
ENERGY PLUS: A building energy simulation program designed for modeling buildings with associated heating, cooling, lighting, ventilating, and other energy flows.

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