**PDHonline Course M253 (3 PDH)**

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# HVAC – Natural Ventilation & Infiltration

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# HVAC – Natural Ventilation & Infiltration

***A. Bhatia, B.E.***

## OVERVIEW OF NATURAL VENTILATION

Ventilation is the process by which fresh air is introduced and stale air is removed from an occupied space. This two-way air flow is necessary to remove indoor pollutants, to provide oxygen for respiration, and to increase thermal comfort. Ventilation has some rules:

1. One cubic meter (cubic feet) of air moved out of the space equals one cubic meter (cubic feet) of air moved in.
2. Three elements are needed to produce ventilation (air movement): the Air, an opening and a driving force.
3. High pressure always goes toward lower pressure.
4. Ventilation strategies operate by dilution.

### Mechanical ventilation

A mechanical ventilation system uses one or more electrical blowers, and sometimes a system of ductwork, to move air in and out. The primary advantage of this approach is the consistency and controllability of the rate of ventilation, provided that the building envelope is tight enough. Other advantages include opportunities to precondition outside air (filtration, dehumidification, preheating) and to apply various techniques of heat and energy recovery. The disadvantages are the cost of the mechanical equipment, the energy consumed by the blowers, the noise of operation, and perhaps maintenance requirements.

There are many specialized applications where mechanical ventilation is vital, such as ventilation for industrial processes, mines, tunnels, laboratory hoods and underground development. However, in this course we will focus only on natural ventilation.

### *Natural Ventilation*

Natural ventilation is the circulation of air in and out of a building by natural forces, unaided by mechanical equipment. It results due to air pressure difference between the inside and outside of the building and depends on air temperature differences inside and outside and on height of the building. Greater the temperature difference and/or greater the height of the building; more effective will be the natural ventilation.

Natural ventilation may be divided into two categories:

1. Controlled natural ventilation is intentional displacement of air through specified openings such as windows, doors, and ventilations by using natural forces (usually by pressures from wind and/or indoor-outdoor temperature differences). It is usually controlled to some extent by the occupant.
2. Infiltration is the uncontrolled random flow of air through unintentional openings driven by wind, temperature-difference pressures and/or appliance-induced pressures across the building envelope. In contrast to controlled natural ventilation, infiltration cannot be so controlled and is less desirable than other ventilation strategies, but it is a main source of ventilation in envelope-dominated buildings.

**Purposes of ventilation**

The purpose of ventilation is to provide fresh (or at least outdoor) air for comfort and to ensure healthy indoor air quality by diluting contaminants. A ventilation system should be able to meet the following criteria:

1. Provide sufficient supply of air/oxygen for the physiological needs of human beings (a minimum of 7.5 l/s/person [15 CFM per person] is recommended by ASHRAE standard 62.1 - 89).
2. Provide sufficient supply of air/oxygen for industrial, agricultural and other processes. Air is required in for certain appliances (range hoods, clothes dryers, central vacuums, fireplaces, etc) to function as designed. Oxygen is required for burning and combustion processes.
3. Remove the products of respiration and bodily odor (including those from smoking) of human and/or animal occupants
4. Remove contaminants or harmful chemicals generated by processes or from building materials. Air moving through houses can remove moisture and increase the longevity of the building materials.
5. Remove heat generated by people, lighting and equipment, which lowers the temperature inside an occupied area. At interior air velocities of 0.80 m/s [160 feet per minute (fpm)], the perceived interior temperature can be reduced by as much as 5°F.
6. Create some degree of air movement which is essential for feelings of freshness and comfort (usually a velocity of 0.1 to 0.3 m/s [20 to 60 fpm] is required).
7. The purpose of ventilation systems is to avoid explosions by removing flammable gases. Industrial ventilation generally involves the use of supply and exhaust ventilation to control emissions, exposures, and chemical hazards in the workplace by removing hazardous material and gases. Properly installed ventilation systems greatly reduce the chance of a

life-threatening explosion. Natural ventilation alone is usually not effective in such circumstances.

8. Traditionally, non-industrial ventilation systems commonly known as heating, ventilating, and air-conditioning (HVAC) systems were built to control temperature, humidity, and odors. However, unlike true air-conditioning, natural ventilation is ineffective at reducing the humidity of incoming air. This places a limit on the application of natural ventilation in humid climates.

**Principles of Natural Ventilation**

There are two primary forces that drive natural ventilation - thermal buoyancy and wind pressure.

Ventilation driven by thermal buoyancy is often referred to as the "stack effect." When the indoor and outdoor air temperatures are different, the respective air densities differ accordingly. 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 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. Also in cold weather, the warmer, less dense indoor air escapes through cracks, vents, or open windows higher in the building, while the cooler, denser outside air enters lower in the building.

Wind-driven ventilation occurs due to pressure differences around the outside perimeter that arise when the wind blows on a building. Higher pressures on the upwind side(s) drive air in through cracks, vents, or open windows, while lower pressures on the downwind side(s) draw air out of the building.

The pressures generated by buoyancy are quite low (typical values: 0.3 Pa to 3 Pa) while wind pressures are usually far greater (~1 Pa to 35 Pa). Therefore, majority of buildings rely mostly on wind driven ventilation. The most efficient design for a natural ventilation building should implement both types of ventilation. The amount of ventilation arising from the wind and stack effects can be estimated using ASHRAE Standard 136 (ASHRAE, 1993).

**WIND EFFECT**

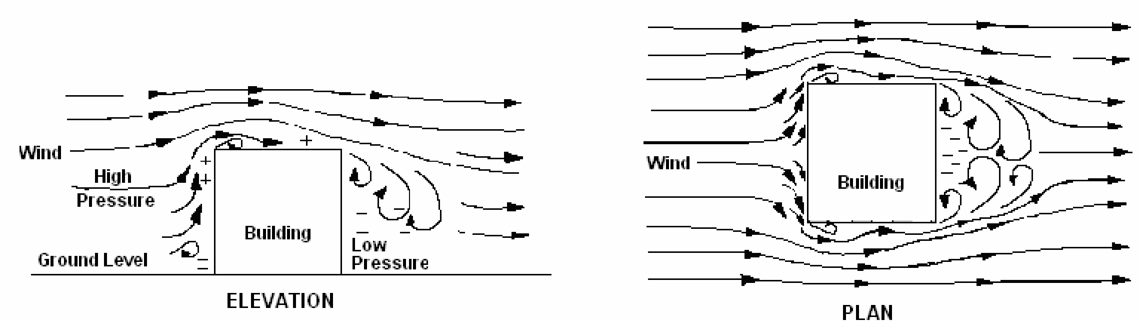
Wind driven ventilation is one of two methods of providing natural ventilation. When wind blows against a barrier, it is deflected around and above the barrier (in this case, a building).

Wind causes a positive pressure on the windward side and a negative pressure on the leeward side of buildings. To equalize pressure, outdoor air will enter through available openings on the windward side and eventually be exhausted through the leeward side. Pressure is not uniformly distributed over the entire windward face, but diminishes outwards from the pressure zone. The pressure difference between any two points on the building envelope will determine the potential for ventilation, if openings were provided at these two points. The airflow is directly proportional to the effective area of inlet openings, wind speed, and wind direction.

The terrain surrounding the building can also create wind flow changes affecting building pressures. Surface roughness of the surrounding terrain (the size and location of surrounding buildings) influences the relationship of wind velocity to building height, which will affect the pressure patterns around the building's exterior, including the roof. The occurrence and change of wind pressures on building surfaces depend on:

1. Wind speed and wind direction relative to the building
2. The location, shape, orientation and surrounding environment of the building
3. Window typologies and operation
4. Other aperture types (doors, chimneys)
5. Construction methods and detailing (infiltration)

The pressure distribution patterns due to wind in a number of cases are illustrated in Figure below.




**Detail of Airflow around a Building**

The impact of wind on a building affects the ventilation and infiltration rates through it and the associated heat losses or heat gains. Wind speed increases with height and is lower towards the ground due to frictional drag.

Theoretically, an expression for the volume of airflow induced by wind is:

$Q_{wind} = K \times A \times V$

Where

- $Q_{wind}$ = volume of airflow, $m^3/s$ [CFM]
- A = area of smaller opening, $m^2$ [$ft^2$]

- V = outdoor wind speed, m/s [fpm]
- K = coefficient of effectiveness (assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.36 for diagonal winds)

The coefficient of effectiveness depends on the angle of the wind and the relative size of entry and exit openings. It ranges from about 0.3 for wind hitting an opening at a 45° angle of incidence to 0.6 for wind hitting directly at a 90° angle. *The greatest pressure differential around the building occurs when wind strikes it perpendicularly (largest wind shadow so largest suction effect).*

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.

For a building with numerous partitions and openings, it is under various pressures depending on the relative sizes of the openings and the wind direction. With large openings on the windward face, the building tends to be under positive pressure. The reverse is true if the openings are smaller than those downstream.

Natural ventilation systems are often designed for wind speeds of half the average seasonal velocity because from climatic analysis there are very few places where wind speed falls below half the average velocity for many hours in a year. 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.

<u>Major factors affecting ventilation wind forces include:</u>

- Average wind speed;
- Prevailing wind direction;
- Seasonal and daily variation in wind speed and direction;
- Local obstructing objects, such as nearby buildings and trees;
- Position and characteristics of openings through which air flows; and

- Distribution of surface pressure coefficients for the wind

Wind driven ventilation has several significant benefits:

- Greater magnitude and effectiveness
- Readily available (natural occurring force)
- Relatively economic implementation
- User friendly (when provisions for control are provided to the occupants)

Some of the important limitations of wind driven ventilation:

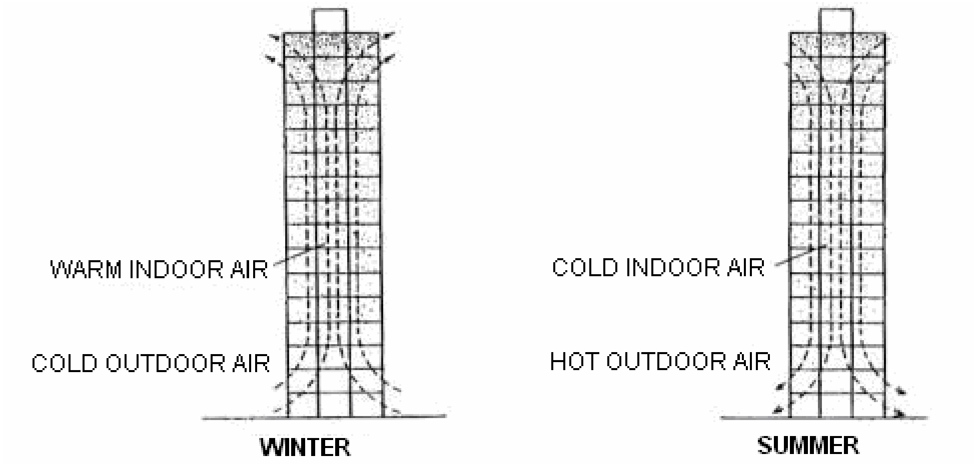
- Unpredictable and difficulties in harnessing due to speed and direction variations
- The quality of air it introduces in buildings may be polluted for example due to proximity to an urban or industrial area
- May create strong drafts, discomfort

***STACK EFFECT***

Stack effect or chimney effect as it is often called occurs when the temperature inside a building is not equal to the outdoor air temperature. The warmer air will have lower density and air will thus rise above the cold air creating an upward air steam. The temperature difference causes density differentials, and therefore pressure differences, which drive the warmer indoor air to rise and escapes the building at higher apertures, while colder, denser air from the exterior enters the building through lower level openings.

At least two ventilation apertures need to be provided; one closer to the floor and the other high in the space. Warmed by internal loads (people, lights, equipment), the indoor air rises. This creates a vertical pressure gradient within the enclosed space. If an aperture is available near the ceiling, the warmer air at the upper levels will escape as the lower aperture draws in the cool outside air. Higher indoor temperatures are essential for causing a pressure difference such that the upper openings act as the outlet and cool air intake is induced at the lower opening. The airflow induced by thermal force is directly proportional to the height of the building, the effective area of the aperture, and the inside-outside temperature differential.




***Stack effect***

The stack effect is most noticeable in multistory buildings when outdoor air temperatures are considerably less than indoor air temperatures. This results in pressure differences of some magnitude between upper and lower floors. Upper floors are of a positive pressure relative to the atmosphere while the lower floors are negative. The result is an upward air flow, generally through the elevator shafts and stair wells.

The reverse will occur during the summer when the indoor temperature is less than the outdoor temperature, but the effect will be reduced if the temperature and corresponding pressure differential between indoors and outdoors is low. During the cooling season, the temperature difference generally is not greater than 30°F compared to a possible 80°F temperature difference during the winter. *Therefore, the infiltration of air in summer is at the upper floors and the exfiltration of air at lower floors.* Resulting air flow is down through the building and is minimal. Thus, the stack effect ventilation will not work effectively in summer (wind or humidity drivers would be preferred) because it requires that the indoors be warmer than outdoors, an undesirable situation in summer.

In the absence of wind, when thermal force is acting alone, the neutral plane or neutral pressure level (NPL) in a building occurs where the interior and exterior pressures are equal. At all other levels, the pressure difference between the interior and exterior depends on the distance from the neutral pressure level and the difference between the densities of inside and outside air. At standard atmospheric pressure, the pressure difference due to normal or reverse stack effect is expressed as

$$\Delta P_s = (\rho_e - \rho_i) \cdot g \cdot (h - h_{neutral}) = \rho_i \cdot g \cdot (h - h_{neutral}) \cdot \frac{T_i - T_a}{T_e}$$

Where

- $\Delta P_s$ = pressure difference due to stack effect, N/m$^2$ [PSI ~ 144 * lb/sq-ft ]
- ρ= density of air, kg/m$^3$ [lb/ft$^3$]
- g = gravitational constant = 9.81 m/s$^2$ [32.17 ft/s$^2$]
- h = height of observation, m [ft]
- h neutral = height of neutral pressure level, m [ft ]
- T = absolute temperature, K [°R]

(Subscripts *i* = inside and *o* = outside)

*For normal stack effect, ΔP/h the pressure difference is positive above neutral plane and negative below it. For reverse stack effect, ΔP/h the pressure difference is negative above neutral plane and positive below it.*

**Flow caused by Stack Effect (thermal forces alone)**

If the building's internal resistance is not significant, the natural ventilation flow rate caused by stack effect may be estimated with this equation:

$$Q_s = C_d \; A \sqrt{2 \, g \, H_d \, \frac{T_I - T_O}{T_I}}$$

Where

- $Q_S$ = Stack vent airflow rate, m$^3$/s [ft$^3$/s]
- A = cross-sectional area of opening, m$^2$ (assumes equal area for inlet and outlet) [ft$^2$]
- $C_d$ = Discharge coefficient for opening
- g = gravitational acceleration, 9.807 m/s$^2$ [32.17 ft/s$^2$]
- $H_d$ = Height from midpoint of lower opening to neutral pressure level (NPL), m [ ft]
- NPL = location/s in the building envelope with no pressure difference between inside and outside (ASHRAE 2001, p.26.11)
- $T_I$ = Average indoor temperature between the inlet and outlet, K [°R]
- $T_O$ = Outdoor temperature, K [°R]

**Stack driven ventilation has several significant benefits:**

- Does not rely on wind: can take place on still, hot summer days when it is most needed
- Natural occurring force (hot air rises)

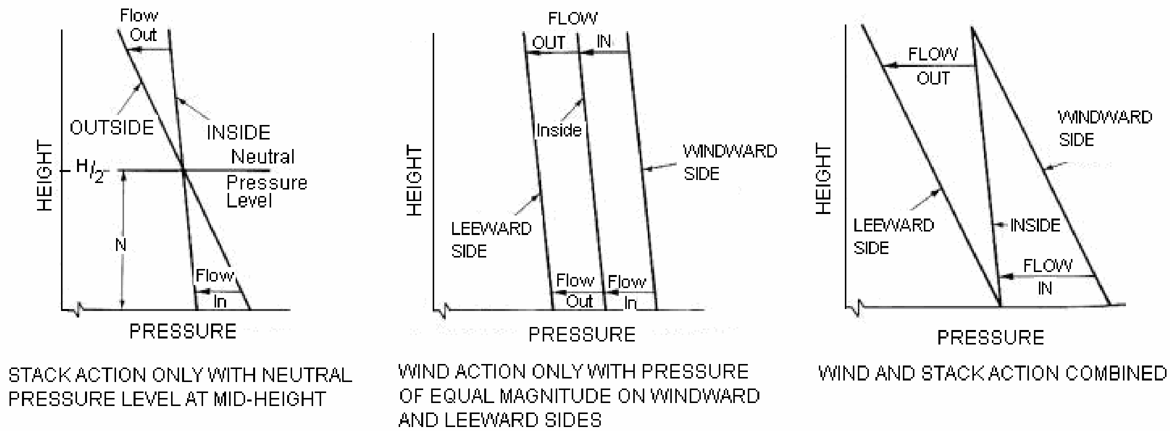
- Relatively stable air flow (compared to wind)
- Greater control in choosing areas of air intake
- Sustainable method

**Limitations of stack driven ventilation:**

- Lower magnitude compared to wind ventilation
- Relies on temperature differences (inside/outside)
- Design restrictions (height, location of apertures) and may incur extra costs (ventilator stacks, taller spaces)
- The quality of air it introduces in buildings may be polluted for example due to proximity to an urban or industrial area

**COMBINATION EFFECT (Wind & Stack)**

In most cases, natural ventilation depends on the combined pressure effects of wind, buoyancy caused by temperature and humidity, plus any other effects from sources such as fans. The pressure patterns for actual buildings continually change with the relative magnitude of thermal and wind forces. Figure below shows the combined effect of wind and thermal forces. The pressures due to each effect are added together to determine the total pressure difference across the building envelope.




*Combined effects of wind and thermal forces*

The relative importance of the wind and stack pressures in a building depends on building height, internal resistance to vertical air flow, location and flow resistance characteristics of envelope openings, local terrain, and the immediate shielding of the building structure.

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.

**DESIGN OF NATURAL VENTILATION**

The design of controlled natural ventilation systems requires identification of the prevailing wind direction, the strategic orientations and positions of openings on the building envelope. These openings include windows, doors, roof ventilators, skylights, vent shafts, and so forth.

**Ventilation rates**

When designing a ventilation system, the ventilation rates are required to determine the sizes of fans, openings, and air ducts. The methods that can be used to determine the ventilation rates include:

**Maximum allowable concentration of contaminants**

A decay equation can be used to describe the steady-state conditions of contaminant concentrations and ventilation rate, like this

$C_i = C_o + F / Q$

*Where*

- $C_i$ = maximum allowable concentration of contaminants
- $C_o$ = concentration of contaminants in outdoor air
- F = rate of generation of contaminants inside the occupied space, lps [CFM]
- Q = ventilation rate, lps [CFM]

**Heat generation**

The ventilation rate required to remove heat from an occupied space is given by:

$$Q = \frac{H}{c_p \cdot \rho \cdot (T_i - T_o)}$$

Where

- Q = ventilation rate, lps
- H = heat generation inside the space, W
- $c_p$ = specific heat capacity of air, J/kg -K
- ρ = density of air, kg/m$^3$
- $T_i$ = indoor air temperature, K
- $T_o$ = outdoor air temperature, K

Empirically, in American units, the relation can be written as

$$Q = \frac{H}{1.08 \times (T_i - T_0)}$$

Where:

- Q = volume flow rate, in cubic feet per minute (CFM) of outdoor air introduced
- H = sensible heat exchange due to ventilation (Btu/h)
- $T_i$ = indoor air temperature [F]
- $T_o$ = outdoor air temperature [F]
- 1.08 = A constant derived from the density of air at 0.075 lb/ft$^3$ under average conditions, multiplied by the specific heat of air (heat required to raise 1 lb of air 1°F), which is 0.24 Btu/lb °F, and by 60 min/h. The units of this constant are Btu min/*cu ft °F* h.

**Air Change Method**

Most professional institutes and authorities have set up recommended ventilation rates, expressed in air change per hour, for various situations. The ventilation rate is related to the air change rate by the following equation:

$$Q = \frac{V \cdot ACH}{3600} \cdot 1000$$

Where

- Q = ventilation rate, lps
- V = Volume of space, m$^3$
- ACH = air change per hour

In American units

Q = V x ACH / 60 min/hr

Where

- Q = ventilation rate, CFM
- V = Volume of space, ft$^3$
- ACH = air change per hour

In this equation, Q is the volume flow rate of air being calculated, and ACH is the number of air changes per hour expected, based on the type of construction (tight, medium, or loose) under the given conditions. Table below gives some recommended air change rates for typical spaces (ASHRAE 1989).

**Recommended air change rates**

| Space | Air change rates per hour |
|---|---|
| Car parks | 6 |
| Kitchen | 20 - 60 |
| Lavatory | 15 |
| Bathrooms | 6 |
| Boiler rooms | 15 - 30 |

Table below provides some examples of outdoor air requirements for ventilation.

**Outdoor air requirements for ventilation**

| Application | Estimated maximum occupancy (persons per 100 $m^2$ floor area) | Outdoor air requirements (l/s/person) |
|---|---|---|
| **Offices** | | |
| - office space | 7 | 10 |
| - conference room | 50 | 10 |
| **Retail's Stores** | | |
| - street level | 30 | 5 |
| - upper floors/arcades | 20 | 5 |
| **Education** | | |
| - classroom | 50 | 8 |
| - auditorium | 150 | 8 |
| - library | 20 | 8 |
| **Hospitals** | | |
| - patient rooms | 10 | 13 |

| Application | Estimated maximum occupancy (persons per 100 m$^2$ floor area) | Outdoor air requirements (l/s/person) |
|---|---|---|
| - operating rooms | 20 | 15 |

Data source: *ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality*.

**INFILTRATION & AIR LEAKAGE**

In addition to intentional ventilation, air inevitably enters a building by the process of 'air infiltration'. This is the uncontrolled flow of air into a space through adventitious or unintentional gaps and cracks in the building envelope. The corresponding loss of air from an enclosed space is termed 'exfiltration'. The rate of air infiltration is dependent on the porosity of the building shell and the magnitude of the natural driving forces of wind and temperature.

Understanding infiltration requires understanding the pressures that cause the flow and the flow characteristics of the openings in the building shell. Building pressure is determined by how much air is being introduced compared to how much is being exhausted. If more air is introduced than is exhausted, the difference should pressurize the building and leak out through cracks. Therefore, the size of the cracks, or "porosity" of the structure, is an important factor in building pressurization.

Air infiltration not only affects the building pressurization but may also distort the intended air flow pattern. Control of infiltration is needed to assure thermal comfort and to minimize building energy use. Normally, infiltration may be lessened by reducing the air leakage of the building shell (for example, increase air tightness) and reducing the surface pressures driving the air flow, for instance, through changing the landscaping in the vicinity of the building. Some countries have introduced air-tightness standards to limit infiltration losses.

**Air leakage area and performance**

Building air leakage area is a physical property of a building determined by its design, construction, seasonal effects, and deterioration over time. The larger the air leakage area, the larger will be the infiltration rate. However, no simple relationship exists between a building's air tightness and its air exchange rate, although some empirical methods have been developed to estimate the values.

The designer should first identify the leakage paths, estimate their size and then calculate the airflow that will be needed to create and maintain the required pressure difference across the leakage paths. A constant air supply of this magnitude has then to be delivered to the space it is designed to pressurize. This is the condition when all the doors are closed. To determine the amount of air required to maintain a specified pressure differential, the following equation is applied:

$$A_L = 1000 \cdot Q_r \cdot \frac{\sqrt{\frac{\rho}{2 \cdot \Delta p_r}}}{C_D}$$

Where

- $A_L$ = effective air leakage area (cm$^2$)
- $O_r$ = predicted air flow rate at Δ $p_r$ (m$^3$/s)
- ρ = density of air (kg/m$^3$)
- Δ p = reference pressure difference (Pa)
- $C_D$ = discharge coefficient

The discharge coefficient depends on the geometry of the flow path, as well as turbulence and friction. As per ASHRAE HVAC Application handbook-1995, the flow coefficient is generally in the range of 0.6 to 0. 7.

**Fan Pressurization**

The air leakage in buildings may be determined by pressurization testing or tracer gas measurement. The fan pressurization method, sometimes called the "Minneapolis Blower Door," is used in measuring the amount of infiltration into the building and in locating leaks.

This method measures the building leakage rate independent of weather conditions.

Equipment required for a quantitative measurement includes a blower (variable speed fan), a flow meter, a pressure gauge, and (optionally) a smoke source or an infrared scanning device to locate leaks. Also, a means of sealing the fan into the doorway is required so the only air going through the doorway passes through the fan.

The fan is generally used to move a large stream of air out of the building so that even the most minute streams of air (leaks) coming in may be detected. Moving air into or out of the building causes a different air pressure inside the building relative to the outside air pressure. If air is being forced out, the inside pressure is lower and vice versa.

When the inside pressure is low, air leaks into the building through any hole it can find in the exterior envelope of the structure. Leak locations can be found by checking suspected trouble spots for drafts with a smoke stick, an infrared camera, or even a person's hand.

The air leakage performance level for buildings is sometime presented as leakage classes (such as Class A, B, C and so on) and the appropriate classes are specified in building regulations based on climate. Some of the common leak locations are shown in table below, which shows the percentages distribution of air leakage for residential building components. It can be seen that the walls is the most important component, followed by ceiling details and heating system.

**Percentages of air leakage for residential building components**

| Components | Percentage of whole-building air leakage area | |
|---|---|---|
| | Range | Mean |
| Walls | 18 - 50% | 35% |
| Ceiling details | 3 - 30% | 18% |
| Heating system (furnace, ducts) | 3 - 28% | 18% |
| Windows and doors | 6 - 22% | 15% |
| Fireplaces | 0 - 30% | 12% |
| Vents in conditioned spaces | 2 - 12% | 5% |
| Diffusion through walls | <1% | |

**Estimation of infiltration rates**

In the absence of any detailed information about the building, a simplified procedure may be used to roughly estimate the infiltration rates arising from both wind and stack effects. The degree of shielding and the building height are the factors taken into account in this method.

$$I = \frac{A_e}{V_r} \times \sqrt{A \cdot \Delta T + B \cdot V_W^2}$$

Where

- I = infiltration rate ($m^3/h$)
- $A_e$ = effective leakage area ($cm^2$)
- $V_r$ = volume of the room ($m^3$)
- A = stack coefficient ($m^6/h^2/cm^4/K$)
- B = wind coefficient ($m^6/h^2/cm^4/(m/s)^2$)
- $V_W$ = average wind speed at local weather station (m/s)
- ΔT = average indoor-outdoor temperature difference (°C)

The values of stack coefficient and wind coefficient with respect to the different shielding levels are indicated below:

**Stack coefficient and wind coefficient**

| Description | Number of storey | | |
|---|---|---|---|
| | **One** | **Two** | **Three** |
| ***Stack coefficient*** | 0.00188 | 0.00376 | 0.00564 |
| ***Wind coefficient*** | | | |
| - no obstruction or local shielding | 0.00413 | 0.00544 | 0.00640 |
| - light shielding, few obstructions | 0.00319 | 0.00421 | 0.00495 |
| - moderate local shielding | 0.00226 | 0.00299 | 0.00351 |
| - heavy shielding | 0.00135 | 0.00178 | 0.00209 |
| - very heavy shielding | 0.00041 | 0.00054 | 0.00063 |

**Air leakage of building component**

The building envelope of large commercial buildings is often thought to be quite air tight, but in fact many cases indicate that some components and the workmanship of them may affect the performance significantly. Vents and other openings incorporated into a building as part of ventilation design can also become routes for unintentional air flow when the pressures acting across such openings are dominated by weather conditions (wind) or induced driving forces (such as pressures resulting from operation of mechanical exhaust).

Table below shows effective air leakage areas for some building components. The values in the table below give results in terms of air leakage area per unit component, per unit surface area, or per unit length of crack or sash, whichever is appropriate. The air leakage areas may be converted to the results at other reference pressures, air flow rates, or flow coefficients using some empirical equations.

**Effective air leakage areas of building components**

| Building components | Unit | Best estimate | Range |
|---|---|---|---|
| ***Ceiling*** | | | |
| - general | $cm^2/m^2$ | 1.8 | 0.79 - 2.8 |

| **Building components** | **Unit** | **Best estimate** | **Range** |
|---|---|---|---|
| - drop | $cm^2/m^2$ | 0.19 | 0.046 - 0.19 |
| - recessed lights | $cm^2$/each | 10 | 1.5 - 21 |
| - surface-mounted lights | $cm^2$/each | 0.82 | |
| ***Doors*** | | | |
| - single, not weather stripped | $cm^2$/each | 21 | 12 - 53 |
| - single, weather stripped | $cm^2$/each | 12 | 4 - 27 |
| - double, not weather stripped | $cm^2/m^2$ | 11 | 7 - 22 |
| - double, weather stripped | $cm^2/m^2$ | 8 | 3 - 23 |
| - interior (stairs) | $cm^2$/lmc | 0.9 | 0.25 - 1.5 |
| - mail slot | $cm^2$/lmc | 4 | |
| ***Walls (exterior)*** | | | |
| - cast-in place concrete | $cm^2/m^2$ | 0.5 | 0.048 - 1.8 |
| - clay brick cavity wall (finished) | $cm^2/m^2$ | 0.68 | 0.05 - 2.3 |
| - precast concrete panel | $cm^2/m^2$ | 1.2 | 0.28 - 1.65 |
| - low-density concrete block (unfinished) | $cm^2/m^2$ | 3.5 | 1.3 - 4 |
| - low-density concrete block (painted) | $cm^2/m^2$ | 1.1 | 0.52 - 1.1 |
| - high-density concrete blk. (unfinished) | $cm^2/m^2$ | 0.25 | |
| ***Windows*** | | | |
| - awning, not weather stripped | $cm^2/m^2$ | 1.6 | 0.8 - 2.4 |

| Building components | Unit | Best estimate | Range |
|---|---|---|---|
| - awning, weather stripped | $cm^2/m^2$ | 0.8 | 0.4 - 1.2 |
| - casement, not weather stripped | $cm^2$/lmc | 0.28 | |
| - casement, weather stripped | $cm^2$/lmc | 0.24 | 0.1 - 3 |
| - double-hung, not weather stripped | $cm^2$/lmc | 2.5 | 0.86 - 6.1 |
| - double-hung, weather stripped | $cm^2$/lmc | 0.65 | 0.2 - 1.9 |
| - single-hung, weather stripped | $cm^2$/lms | 0.87 | 0.62 - 1.24 |
| - single horizontal slider, weather stripped | $cm^2$/lms | 0.67 | 0.2 - 2.06 |
| - single horizontal slider, wood | $cm^2$/lms | 0.44 | 0.27 - 0.99 |
| - single horizontal slider, aluminum | $cm^2$/lms | 0.8 | 0.27 - 2.06 |
| - storm inside, heat shrink | $cm^2$/lms | 0.018 | 0.009 - 0.018 |
| - window sill | $cm^2$/lmc | 0.21 | 0.139 - 0.212 |
| ***Electrical outlets/switches*** | | | |
| - no gaskets | $cm^2$/each | 2.5 | 0.5 - 6.2 |
| - with gaskets | $cm^2$/each | 0.15 | 0.08 - 3.5 |
| ***Piping/plumbing/wiring penetrations*** | | | |
| - un-caulked | $cm^2$/each | 6 | 2 - 24 |
| - caulked | $cm^2$/each | 2 | 1 - 2 |
| ***Vents*** | | | |

| Building components | Unit | Best estimate | Range |
|---|---|---|---|
| - bathroom with damper closed | $cm^2$/each | 10 | 2.5 - 20 |
| - bathroom with damper open | $cm^2$/each | 20 | 6.1 - 22 |

**Notes**

1. lmc = linear meter of crack
2. lms = linear meter of sash
3. Data based on a pressure difference of 4 Pa and $C_D$ = 1
4. Data source: *1997 ASHRAE Fundamental Handbook*, Chp. 25

The infiltration calculations usually focus on doors and windows which are the obvious weak points. But the other components can also lead to significant air leakages. It is therefore necessary that the construction quality should be very good. If the construction is of concrete, it will probably be satisfactorily leak-proof. But if the construction is of block/ brick work it will probably need to be plastered to make it leak proof.

Lift, stair, service shaft walls; floors; and other internal partitions are the major separating elements of concern in large buildings. For instance, if there is a lobby, that separates the staircase from the accommodation area and the lobby has doors to lifts and toilets, the lobby should be separately pressurized. The lobby pressure should be equal to or slightly below the pressure in the staircase, (not below 5 Pa).

Internal partitions are also very important for evaluating internal air flow. Their leakage characteristics are needed to determine infiltration through exterior walls and air flow patterns within the building. These internal resistances are vital for two important considerations:

1. In the event of a fire, to predict smoke movement patterns and determine smoke management strategies; and
2. To support air movement calculations when designing air distribution systems.

**Moisture and Infiltration**

Buildings, like our bodies, exchange moisture and air with the environment, as well as exchanging heat. Although most of this moisture exchange occurs during the exchange of fresh air, some exchange occurs through a building's skin. This can cause problems in either hot, humid climates or very cold ones.

In hot, humid conditions, cool inside surfaces are often encountered—for example, the ceiling directly below a roof pond used for passive cooling. As hot and humid air contacts such a surface, condensation can occur. The moisture vapor in the air condenses to form visible droplets of water on the ceiling. The result can be mildly annoying water drips on the head, or serious water stains, eventually with mold growing on surfaces.

In cold climates, cold interior surfaces also occur, especially at windows. Although the air indoors may not be particularly humid (40 to 50 percent RH is common), it contains enough moisture to permit condensation on cold surfaces. Again, mild annoyance or more serious damage can result. A much less visible moisture threat occurs within walls, ceilings, or floors. Almost all common building materials, including gypsum board, concrete, clay masonry, and wood, are easily permeated by moisture. Most surface finishes are also permeable. In cold climates, the air outside contains relatively little moisture, even though the RH may be high. By contrast, inside air contains much more moisture per unit of volume, despite its probably lower RH. The result is a flow of vapor from high vapor pressure to low vapor pressure (typically warm to cold).

Such a flow occurs when the temperature within the wall (floor, etc.) drops low enough for this vapor to condense. Insulation can then become wet and thereby less effective, since water conducts heat far better than the air pockets it has filled. If wet insulation compacts, these air pockets are permanently lost. Worse yet, moisture damage can occur, such as dry rot in wood structural members. The usual remedy for such a potential problem is to install a vapor barrier within the building envelope. These barriers are commonly made of plastic film installed with as few holes as possible.

A substantial benefit of plastic films is that they reduce air flow through construction. Outdoor air is always infiltrating a building, gradually replacing the indoor air. This unintentional source of fresh air becomes a problem when temperatures outside are very different from those inside, especially when strong winds force outdoor air indoors fast enough to produce noticeably cold (or hot) drafts.

## NATURAL VENTILATION GUIDELINES

Several general guidelines should be followed when designing for natural ventilation. Some design tips are given below:

1. 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.
- In hot, humid climates, air velocities should be maximized in the occupied zones for bodily cooling.

2. Orient buildings to maximize the cooling potential of prevailing winds

- Use open, elongated, or segmented plans, which are set at a slight angle to prevailing winds with the narrow building ends facing east and west. This approach will reduce solar heat gain on east and west facades and will provide maximum opportunities for cross ventilation.
- 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 for westerly wind)
- Naturally ventilated buildings should be narrow - It is difficult to distribute fresh air to all portions of a very “wide” building using natural ventilation. <u>The maximum width that one could expect to ventilate naturally is estimated as 45 ft.</u>

3. Provide ample spacing between buildings in the direction of wind flow

- Spacing buildings by a distance of at least five times the height of the upwind building provides greater natural ventilation opportunities for the down wind building.

4. Arrange buildings to provide for good air flow around all structures

Air flow around a building creates a high-pressure zone on the windward face and low-pressure zones on the leeward face and on sides that are parallel to the wind direction. Buildings aligned with the wind direction create “wind shadows” and poor ventilation conditions. Ventilation around buildings can be improved by orienting the buildings at an angle to the predominant wind direction. Note the following-

- A linear arrangement of homes lined up parallel to the wind direction creates poor airflow.
- A staggered arrangement of homes creates good airflow regardless of wind direction.
- A linear arrangement of homes lined up at an angle to the wind direction provides good airflow.

5. Use landscaping elements to improve air flow around structures

- Hedges or planting close to a house can restrict airflow and deflect breezes downward. Better airflow is achieved with hedges farther from the home.
- Use open floor plans with a minimum of interior partitions to improve air circulation throughout the home.
- Use louvered doors and shutters to allow air to circulate freely through spaces while maintaining visual privacy.
- Rooms that produce heat and humidity such as kitchens, laundry rooms, and bathrooms require special planning. They should be well ventilated and placed on the leeward side of the house to prevent hot humid air from spreading into other living spaces.
- Protect exterior doors from rain with generous eaves and screens if they are to be used for natural ventilation. Hinged doors should have stops and hold-open devices.
- Use louvers or catches on interior doors.
- Separate garages or place them on the leeward side of the home so they do not block needed airflow.

6. Room Orientation for improve air flow

   - Rooms oriented 45° relative to the prevailing wind direction will see 20% improved air flow.

7. Other Architectural Treatment

   - Use architectural features like wing walls and parapets to create positive and negative pressure areas to induce cross ventilation.
   - Air inlet and outlets should be designed to minimize noise transfer from the exterior to the interior and to adjacent occupied spaces.
   - For spaces with openings on adjacent walls, place windows far apart and at a diagonal
     - Air flow is limited when windows are placed close together. Improved airflow is achieved when windows are spaced further apart. Casement windows are a better choice in this situation because the window's glazing acts as a small wing wall and maximize airflow.
   - The incoming air may be cooled through good site planning, landscaping, and planting strategies. If a water body is planned for the site, place it on the windward side to pre-cool the incoming air through evaporative cooling. Planting tall deciduous trees on the windward side will lower the temperature of the inflow and shade the openings.

- Use features like overhangs, awning windows, eaves, and porches to protect the openings from rain and to minimize excess heat gain from direct sunlight. Awning windows work very well for cross ventilation because they provide more airflow than double hung windows (for the same glazed area) and also provide protection from rain. Casement windows provide maximum airflow in both perpendicular and oblique wind conditions. Ensure that vents and windows are accessible and easy to use. Avoid blocking windows with exterior objects such as shrubs and fences, but do not eliminate shading.

8. Inlet – Exhaust Arrangement

Air speed inside a space varies significantly depending on the location of openings. As far as possible, provide openings on opposite walls.

- Keep inlet openings slightly smaller than outlet openings. Cross ventilation is optimum well when inlet openings are slightly smaller in total area than outlet openings (1:1.25 is a good ratio).
- The inlet location affects airflow patterns far more significantly than outlet location. Inlet location should be a higher priority (if faced with a choice) as a high inlet will direct air towards the ceiling and will almost bypass the occupied level.
- Intake apertures should be placed on windward side of the building at a low or medium height.
- Exhaust vents or outlets should be on the leeward side as high as possible in the building.
- Orient intake and outlet windows across the room and offset from each other to maximize mixing within the room while minimizing the obstructions to airflow within the room.
- Keep vertical distance between the inlet and exhaust openings as high as possible to take advantage of the stack effect.
- The total area of outlet openings should be operable and accessible by the occupants.
- Inlet openings should not be obstructed by nearby objects such as furniture and interior partitions.
- Horizontal windows are generally better than square or vertical windows. They produce more airflow over a wider range of wind directions and are most beneficial in locations where prevailing wind patterns shift.

9. 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.

10. 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.

11. 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.

12. Vertical shafts and Staircases

- Vertical shafts and open staircases may be used to increase and generate stack effect.
- Enclosed staircases used to take advantage of stack effect ventilation should be designed such that their function as fire exits is not compromised. Also, enclosed staircases intended for evacuation during a fire should not be used for ventilation.

13. 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.
- A certain vertical distance should be kept between openings for temperature to produce stack effect; floor to ceiling heights should be at least 3 m

14. 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. The 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 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.

15. Use mechanical cooling in hot, humid climates

- Try to allow natural ventilation to cool the mass of the building at night in hot climates.
- Open staircases provide stack effect ventilation, but observe all fire and smoke precautions for enclosed stairways.

14. Building Load Reduction

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
- 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
- Internal loads should be low, e.g. high-efficacy lighting, lighting controls, high-efficiency mechanical equipment, pipe and duct insulation
- Use shading devices to like overhangs, awnings, and fins to control solar gains.

HVAC systems should be designed to work in harmony with natural ventilation. The objective of a concurrent natural ventilation system is to meet the outside air requirement using the least possible opening area. The objective of a changeover natural ventilation system is to meet the outside air requirement as well as provide cooling. The HVAC and natural ventilation system are mutually dependent.

## COMMON METHODS FOR PROPER VENTILATION

Some of the methods used to design proper natural ventilation systems in buildings are solar chimneys, wind towers, and summer ventilation control methods.

1. A chimney heated by solar energy can be used to drive the stack effect. 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. The solar chimneys are very widely used to ventilate composting toilets in parks.

2. 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.

3. 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.

**DESIGN CODES & STANDARDS**

Naturally ventilated buildings should be designed to provide thermal comfort, to achieve adequate moisture and contaminant removal, and to meet or exceed Government Energy Conservation Performance Standards.

1. Standards for building thermal comfort have been defined by ASHRAE 55.

2. Standards for adequate ventilation rates and contaminant levels can be found in ASHRAE 62.

3. Additional standards effecting ventilation practice have been developed by:

    - American Conference of Governmental Industrial Hygienists (ACGIH): provides threshold limit values for chemical substances and physical agents and biological exposure indices.

    - Occupational Safety and Health Administration (OSHA) (1989), Air Contaminants: examines Air Contaminants-Permissible Exposure limits (Title 29, Code of Federal Regulations, Part 1910.1000).

4. Federal energy standards: The U.S. Department of Energy (DOE) has updated 10 CFR 435 to reflect the codified version of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc./Illuminating Engineering Society of North America (ASHRAE/IESNA) Standard 90.1 to be closer to the existing voluntary sector code. This new federal standard, 10 CFR 434 Energy Code for New Federal Commercial and Multi-

Family High Rise Residential Buildings, is mandatory for all new federal buildings. For existing buildings, refer to ASHRAE 100 Energy Conservation in Existing Buildings. For residential buildings, the applicable standard is ASHRAE 90.2 Energy Efficient Design of Low –Rise Residential Buildings. Methodology and Procedures for Life-Cycle Cost Analysis are described in 10 CFR 436.

5. Observe all codes and standards regarding transport of smoke and fire when deciding on the applicability of natural ventilation and in the design of the system.

**DESIGN TOOLS & SOFTWARE**

Many computer programs are available for predicting ventilation patterns. Some that use the "zonal" method may be used to predict ventilation rate (mechanical and natural), magnitude and direction of air flow through openings, air infiltration rates as a function of climate and building air leakage, pattern of air flow between zones, internal room pressures, pollutant concentration, and back drafting and cross contamination risks. These models take the form of a flow network in which zones or rooms of differing pressure are interconnected by a set of flow paths. This network is approximated by a series of equations representing the flow characteristics of each opening and the forces driving the air flow process.

In order to predict the details of natural airflow, numerical computational fluid dynamics (CFD) program is a more accurate and complex tool for modeling airflow through a space based on pressure and temperature differentials. These programs can simulate and predict room airflow, airflow in large enclosures (atria, shopping malls, airports, exhibitions centers, etc.), air change efficiency, pollutant removal effectiveness, temperature distribution, air velocity distribution, turbulence distribution, pressure distribution, and airflow around buildings.

These computer simulations are detailed and labor intensive, but are justified where accurate understanding of airflow is important. Software packages for natural ventilation analysis include:

1. AIRPAK - provides calculation of airflow modeling, contaminant transport, room air distribution, temperature and humidity distribution, and thermal comfort by computational fluid dynamics.
2. FLOVENT - calculates airflow, heat transfer, and contamination distribution for built environments using computational fluid dynamics. This software is particularly geared towards ventilation calculations including natural and forced convection currents. It also accurately calculates air density as a function of temperature and predicts the resulting buoyancy forces that can give rise to important thermal stratification effects.
3. 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. FLUENT is a sophisticated analysis technique that can, among other things, model and/or predict fluid flow behavior, transfer of heat, and behavior of mass.

4. STAR-CD - STAR-CD uses computational fluid dynamics to help civil engineers, architects and project managers who need better and more detailed understanding of issues involved in heating and ventilation, smoke and pollutant dispersal and fire hazard analysis, and clean room design.
5. 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.
6. DOE -2 - A comprehensive hour-by-hour simulation; day lighting and glare calculations integrate with hourly energy simulation.
7. ENERGY PLUS - A building energy simulation program designed for modeling buildings with associated heating, cooling, lighting, ventilating, and other energy flows.

In general all these software's 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.

## FREQUENT ASKED QUESTIONS

1) **What is ventilation?**

Ventilation is the exchange of air between the inside and outside of the building. It is used to remove heat from solar radiation, to replenish carbon dioxide and to help control the levels of relative humidity.

**2.) What is a ventilation rate?**

The ventilation rate refers to the amount of ventilation per unit area. It is measured as liter per second per sq-m of area [cubic feet of air-per-minute (CFM) per square foot of floor area) because the heat load derives from solar radiation and is directly proportional to floor area.

**3.) Why ventilation is necessary?**

Ventilation is necessary to provide

- air motion
- Heat removal
- dissipation of contaminating fumes

4) **The Required Amount of Ventilation**

Numerous standards quantify the amount of ventilation that is required for acceptable IAQ. In the United States, the predominant ventilation standard for site-built housing is ASHRAE 62 (ASHRAE, 1999). In UK it is CIBSE.

The ventilation rate procedure is the method most often used to meet the requirements of the standard. The basic criterion is to supply at least 0.35 air changes per hour (ACH) or 15 CFM per person (whichever is greater), with some variation in these figures for special cases. In the public review draft of ASHRAE Standard 62.2P dated 8/11/00, the prescribed ventilation rate amounts to 15 CFM per person plus 0.075 ACH. More recently, lower rates are being considered.

5) **What is the difference between natural and mechanical ventilation?**

Natural ventilation results from the wind and stack action from ventilator sashes.
Mechanical ventilation is created by electric fans and related equipment.
There is definitely a trend toward tighter building envelopes and the use of mechanical ventilation systems in production housing. All of the Building America teams are pursuing this approach; three states require it; and the new draft ASHRAE residential ventilation standard nearly requires it. This seems to be a good trend, in that it promotes more consistent ventilation. However, the value of the added consistency is difficult to evaluate, because of the ambiguity of the ASHRAE standards in this regard.

6) **What affects ventilation?**

Ventilation can vary according to:

- wind velocity and direction
- inside and outside temperature differential
- size and positions of windward and leeward openings
- interference of surrounding obstructions to the air flow

7) **What are the benefits of Natural Ventilation**

The obvious advantages of natural ventilation are its simplicity, economy, and quietness. Mechanical equipment, with its associated first cost, fan energy consumption, and noise, is avoided. The main disadvantage is that the rate of outside air exchange varies widely in a somewhat uncontrolled manner. An effort may be made to design a building envelope for an *annual average* ventilation rate of 0.35 ACH. However, at times when the indoor and outdoor temperatures are similar and there is no wind, there is virtually no driving force for the ventilation, so IAQ may be inadequate. Then, during very cold or windy periods, excessive ventilation may result.

8) **What is circulation?**

Circulation is the movement and mixing of air in a building to promote uniformity in temperature and to provide proper air motion throughout the building.

9) **What is cross ventilation?**

Cross ventilation occurs when inlet and exhaust openings are placed on the opposite walls. Two openings are necessary for proper cross-ventilation: one is an inlet (windward side) and the other is an outlet (leeward side).

10) **What is Gravity ventilation?**

Gravity ventilation takes advantage of thermal buoyancy. Vents at different levels in interior spaces draw cool air in through the lower inlet, while forcing warmer air out through the higher outlet (chimney, stack effect).

11) **How do I choose a system?**

The selection and arrangement of the ventilating and cooling equipment is determined by the size and type of building structure, the direction of the airflow through the building, and the velocity of the airflow through the house. Allowances also should be made for air density, light intensity and the permissible temperature variation through the house.

12) **How do I get the best results from my system?**

For optimum performance, it is necessary to properly size and arrange air inlet openings to produce a uniformly distributed, non-turbulent airflow pattern in the growing area to avoid the mixing of the lower air with the hot air in the upper section of the building. A definite airflow pattern in a given direction requires an air inlet opening continuous for the entire side or end of the building. The inlet opening should introduce the air in a horizontal direction at crop level, should not be deflected up or down and should have a low velocity to minimize turbulence and mixing.

13) **What happens to the cooled air as it moves through the house?**

As the cooled air moves through the house, it picks up solar heat and increases in temperature by the time it reaches the exhaust fans. This temperature increase is a result of the heat removal process and will vary depending on design. Increasing the airflow or reducing the light intensity can reduce the temperature change. Increased fan capacity can produce increased airflow; shading can reduce light intensity; and good maintenance can minimize the infiltration of air leakage.

14) **Is elevation a factor in creating ventilation and cooling systems?**

The air's capacity to remove heat depends on its weight, not its volume. Because air is less dense at higher altitudes, the elevation of the building must be considered in design calculations. At higher elevations a greater volume of air is needed to provide the equivalent weight of air required at elevations that have been established as normal.

15) **Is winter and summer ventilation systems the same?**

Essentially winter and summer ventilation systems are two separate systems having different characteristics and requirements. However, they must tie in with each other to switch from one system to the other during spring and fall. The transition is very important as it determines the inside to outside temperature difference available on a mild, sunny day, and it establishes the airflow design capacity of the winter ventilation system.

16) **Do I need to ventilate differently in the winter?**

Winter calls for different airflow principals. In the winter, outdoor air is too cold to introduce directly on the plants. The goal of winter ventilation is to introduce the cold air in a turbulent manner. This causes the cold air to mix with the warmer air in the building, without producing cold drafts at plant level. This mixing is the result of using small high-velocity jets. In a building, it is desirable to have many small, well-distributed openings rather than one large one for winter ventilation. It is important that all areas of the building are at the same temperature. To achieve this, the ventilating system must distribute the air uniformly throughout and maintain positive air movement and continuous circulation.

17) **What are the Advantages to Natural Ventilation?**

Some of the advantages to Natural Ventilation are:

a. 85% Reduction in Cost of Electricity

b. Reduced Dust

c. Reduced Heating Cost

d. 15 Year Warrantee

e. Reduced Operating Costs

f. Reduced Noise Level

g. Improved Odor and Humidity Control

h. Ventilation Functions in the Event of a Power Failure

i. Daylight Brightens Buildings

j. Summer Ventilation Rates are High

Since there are fewer moving parts to a natural ventilation system, maintenance and related costs are lower than with a fan system.

18) **What are limitations of Natural Ventilation Systems?**

- Greater temperature swings than normal with mechanically cooled spaces will occur and have to be acceptable to the occupants.
- Air flow rate varies with outdoor conditions.
- Occupants must be willing to open and close vents and windows to regulate thermal comfort
- Not as effective during warm, humid summer months
- Difficult to retrofit in buildings
- Fire codes may restrict design options

19) **What are main barriers to the application of natural ventilation?**

A successful application of natural ventilation strategies is only possible when there are no problems in many areas at various levels from the design stage to actual operating demands placed on the building users. These potential barriers include:

1. Barriers during building operations
    - Safety concerns
    - Noise from outdoor
    - Dust and air pollution
    - Solar shading covering the openings
    - Draught prevention
    - Knowledge of the users about how to take the best advantage of natural ventilation
2. Barriers during building design
    - Building and fire regulations
    - Need for acoustic protection
    - Difficult to predict pattern of use
    - Devices for shading, privacy & day lighting may hamper the free flow of air
    - Problems with automatic controls in openings
    - lack of suitable, reliable design tools

3. Other barriers

- Impact on architectural & envelope design
- Fluctuation of the indoor conditions
- Design a naturally ventilated building requires more work but could reduce mechanical system (design fee on a fixed percentage of system's cost)
- Increase risk for designers
- Lack of universal standards

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