Lesson
40
Ventilation For Cooling

The specific objectives of this chapter are to:

1. Discuss the use of ventilated air for cooling of buildings and cooling of occupants (*Section 40.1*)

2. Make a comparison between natural ventilation and mechanical ventilation (*Section 40.2*)

3. Discuss characteristics of natural ventilation and estimation of airflow rate due to wind and stack effects (*Section 40.3*)

4. List the general guidelines for natural ventilation (*Section 40.4*)

5. Discuss briefly forced ventilation using electric fans (*Section 40.5*)

6. Discuss interior air movement using interior fans, unit ventilators, whole house fans and solar chimneys (*Section 40.6*)

At the end of the lecture, the student should be able to:

1. Discuss the effectiveness of ventilated air for cooling of buildings and occupants

2. Compare natural ventilation with mechanical ventilation

3. Estimate airflow rates due to wind effect and stack effect and combined wind and stack effects

4. List the general guidelines for natural ventilation

5. Discuss the benefits of mechanical ventilation using fans

6. Discuss the benefits of interior air movement and ways and means of achieving interior air movement such as the use of fans, ventilators, solar chimneys etc.

40.1. Introduction:

In a previous chapter, ventilation has been defined as "supply of fresh air to the conditioned space either by natural or by mechanical means for the purpose of maintaining acceptable indoor air quality". However, when outdoor conditions are suitable, the ventilation can also be used for cooling of the buildings, for cooling of the occupants or both.

40.1.1. Ventilation for cooling of buildings:

When the ambient dry bulb temperature is lower than the building temperature, then the outdoor air can be used for cooling the building. Normally due to solar and internal heat gains, buildings can become hotter than the ambient air. This provides an opportunity for cooling the building at least partly, by using the freely available outdoor air. This can significantly reduce the load on air conditioning plants. Though the cooling of buildings during daytime may not be possible on all days, in an year there are many days during which outdoor air can act as a heat sink for the building. Greater opportunities exist for cooling the buildings especially during the night, when the outdoor air is considerably cooler. This is especially effective for hot and dry climates where the diurnal temperature variation is quite large.

40.1.2. Ventilation for cooling of occupants:

Under certain circumstances, outdoor air can also be used very effectively for cooling the occupants of a building directly. By allowing the outdoor air to flow over the body at a higher velocity, it is possible to enhance the heat and mass transfer rates from the body, thus leading to a greater feeling of comfort. As a thumb rule, studies show that each increase in air velocity by 0.15 m/s will allow the conditioned space temperature to be increased by $1^{o}C$. As mentioned before, maintaining the conditioned space at a higher temperature can give rise to significant reduction in the energy consumption of the air conditioning system. However, in general the air velocity if it exceeds about 1.0 m/s may give rise to a feeling of draft or irritation to the occupants.

The cooling effect provided by ventilated outdoor air is mainly sensible in nature, even though, it may also extract latent heat from the occupants if it is cool and dry. The sensible cooling rate provided by the outdoor air Q_v is given by:

$$\mathbf{Q_v = \dot{m}_v . c_p (T_{ex} - T_o)} \qquad (40.1)$$

where $\dot{m}_v$ is the mass flow rate of ventilated air, T_o and T_{ex} are the temperature of the outdoor air and temperature of the exhaust air (after cooling), respectively.

40.2. Natural versus mechanical ventilation:

As the name implies, if ventilation is provided by natural means such as the wind or stack effects (i.e. due to temperature difference), then it is called as natural ventilation. If ventilation is provided by using mechanical means such as fans and blowers, then it is called as mechanical ventilation.

Ideally, natural ventilation should be used whenever possible. It is considered as the first line of defense against summer heat. However, relying only on natural ventilation for cooling either buildings and/or occupants may not always be possible or it may impose severe restrictions upon building design. This is due to the uncertain nature of natural ventilation, which depends on outdoor conditions such as the wind and ambient temperatures – two highly variable parameters.

Mechanical ventilation though requires external power input, extends the application of ventilation for cooling. It is also highly controllable and is available as and when required (of course, subject to the availability of electricity) with a relatively small expense of electrical energy. Thus a sensible building design must be such that it makes use of both natural and mechanical ventilation in an optimum manner.

40.3. Natural ventilation:

The principle of natural ventilation is very well known and is widely studied. Most of the older buildings before the advent of electricity relied on natural ventilation for maintaining comfortable conditions. However, as mentioned before relying only on natural ventilation imposes several restrictions on building design. For example, windows on opposite walls have to be provided to all the rooms to meet natural ventilation requirements. As a result, large buildings have to be designed in simple **T**-, **L**- or **H**- shapes. The ceiling height has to be high to improve natural ventilation etc. In addition to this, the amount of airflow due to natural ventilation is also uncertain as it depends on:

a) Magnitude and direction of prevailing winds
b) Ambient air temperature
c) Landscaping and adjacent structures
d) Design of the building and position of windows, doors etc.
e) Location of furniture
f) Movement of the occupants, etc.

Due to its uncertain nature, natural ventilation is treated as a secondary objective in the design of modern buildings. Natural ventilation, as discussed in an earlier chapter depends on wind effect and stack effect.

40.3.1. Wind induced, natural ventilation:

When wind blows over a building, a static pressure difference is created over the surface of the building. The pressure difference depends on the wind speed, wind direction, surface orientation and surrounding structures. As shown in Fig.40.1, in an undisturbed air stream, the pressure is positive on the windward direction and negative on the leeward direction. The static pressure on the other surfaces depends upon the angle of attack. This pressure is called as wind pressure. In general, the magnitude of the wind pressure (P_w) is proportional to the velocity pressure, and in an ideal case it is given by:

$$\mathbf{P_w = C_p \frac{\rho V_w^{\ 2}}{2}} \qquad (40.2)$$

where C_p is surface pressure coefficient, ρ is the air density and V_w is the wind speed. The value of Cp depends on several factors such as the wind direction, orientation of the building etc. Analytical evaluation of C_p is quite complicated, even though these values have been measured experimentally for simple structures.

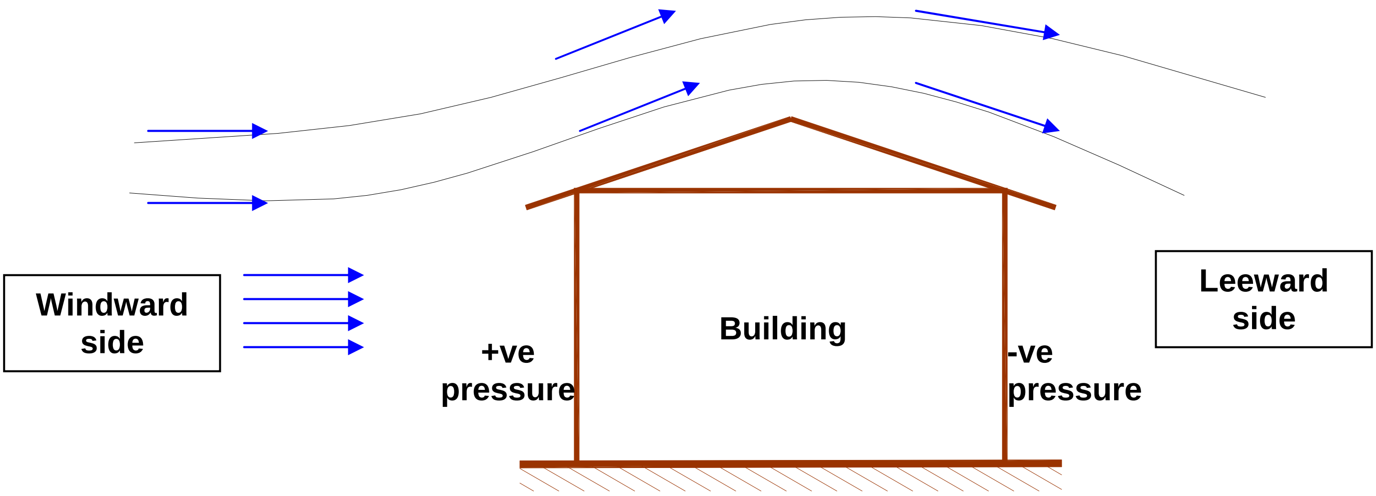

Fig.40.1: Wind pressure on a building

The pressure difference across the building due to wind creates a potential for airflow through the building, if openings are available on the building. The airflow rates through the buildings due to wind effect can be obtained approximately using the equation suggested by ASHRAE:

$$\dot{Q}_w = C.R.A.V_w \qquad (40.3)$$

Where $\dot{Q}_w$ is the airflow rate in m^3/s, A is the area of opening (m^2), C is a constant that takes the value of 0.55 for perpendicular winds and 0.30 for oblique winds, and R is a factor that is function of inlet and outlet areas (A_i and A_o) of the openings. The factor R varies from 1.0 to about 1.38 depending upon the ratio of inlet and outlet areas.

Estimation of wind speed is difficult, however, data provided by the meteorological departments can be used for calculation purposes. Since the wind speed varies with season, for design calculations 50 percent of the summer wind speed as provided by the meteorological data can be used.

Since the airflow rate due to wind effect is a strong function of the opening or window area, suitable values should be used for design calculations. The areas to be used in the calculations are the net free area of the openings, not the total opening areas. The distribution of opening areas between inlet and outlet is also important. It is shown that the flow rate is maximum when the inlet area is equal to the outlet area. When inlet and outlet areas are not equal, an effective area has to be used in Eqn.(40.3). It is given by:

$$A_{eff} = \frac{(A_o / A_i)}{\left(A_o^2 + A_i^2\right)^{0.5}} \qquad (40.4)$$

When outlet area is greater than the inlet area ($A_o > A_i$), then greater speeds are obtained at the inlet compared to the outlets and vice versa. Thus manipulating the areas, for example by opening or closing some windows, it is possible to achieve higher velocities in certain areas compared to others.

The shape of the window also plays role, if the wind is not perpendicular. For oblique winds, short and wide windows provide better airflow compared to square or narrow and tall windows. In general any window treatment such as curtains, blinds etc. reduce the airflow rate due to wind effect. Architectural features such as overhangs, balconies can be used beneficially to improve the airflow due to wind effect.

40.3.2. Ventilation due to stack effect:

When there is a temperature difference between the indoor and outdoor, airflow takes place due to buoyancy or stack effect. During winter, the indoor air is generally warmer compared to outdoor air, as a result, if there are openings in the building, then warm air inside the building rises due to buoyancy and leaves from the openings provided at the top, while cold outdoor air enters into the building through the openings near the base of the building. The reverse happens during summer, when inside is cooler compared to outside, warm outdoor air enters the building from the top openings and cold indoor air leaves the building from the bottom openings. Generally, due to stack effect, in a building at a particular height, the internal and external pressures become equal. This height is known as Neutral Pressure Level (NPL). Obviously, if openings are provided at the NPL, then no airflow takes place due to stack effect. Knowledge of NPL thus is useful in enhancing airflow due to stack effect. However, estimation of NPL is extremely difficult as it depends on several factors such as distribution of the openings, the resistance of the openings to airflow, the resistance to vertical airflow within the building etc. In an ideal case, when the openings are uniformly distributed and there is no internal resistance to vertical airflow, the NPL is at a mid-height of the building. A large number of theoretical and experimental studies have been carried out to estimate NPL for a wide variety of buildings. In general these studies show that for tall buildings, the NPL lies between 0.3 to 0.7 times the total building height.

ASHRAE suggests the following equation for estimating airflow rate due to stack effect:

$$\dot{Q}_{st} = C.A.\left(h.\Delta T/T_w\right)^{0.5} \qquad (40.5)$$

In the above expression, h is the height difference between the inlet and exit in m, T_w is the warm air temperature in K, ΔT is the temperature difference between warm and cold air, A is the free area of the inlets or outlets in m^2 and C is a constant that takes a value of 0.0707 when inlets and outlets are optimal (about 65% effective) and 0.054 when inlets or outlets are obstructed (about 50% effective). From the above equation, it can be seen that compared to the height h and temperature difference ΔT, the airflow rate due to stack effect depends more strongly on the area of the openings.

40.3.4: Natural ventilation due to combined wind and stack effects:

Complications arise when it is required to estimate the airflow rate due to the combined effects of wind and stack effects. Generally, the total airflow rate has to be obtained using the combined pressure difference due to wind and stack effect, and not by adding up airflow rates due to stack effect and wind effect separately. This is due to the non-linear dependence of flow rate on pressure difference across the openings. In general, taller the building with small internal resistance, stronger will be the stack effect, and higher the area of exposure of the building, stronger will be the wind effect. Several models have been proposed to estimate the airflow rate due to combined effects of wind and stack. For example, one such model uses the equation given below for estimating the total airflow rate due to stack and wind effects.

$$\dot{Q}_{total} = \left[\dot{Q}_w^{\,2} + \dot{Q}_{st}^{\,2}\right]^{1/2} \qquad (40.6)$$

40.4. Guidelines for natural ventilation:

As far as possible, the following guidelines should be followed for getting the maximum benefit from natural ventilation for cooling of the building and occupants:

1. In hot and humid climates, maximize air velocities in the occupied zone for body cooling, while, in hot and dry climates, maximize the airflow throughout the building for structural cooling, especially during the nights.
2. The buildings should be shaped such that the maximum surface area is exposed to the external winds.
3. Locate the windows suitably. Windows on opposite walls increase the airflow rate, while windows on the adjacent walls provide airflow over a greater area.
4. In buildings with only one external wall, higher airflow rates are obtained by two widely spaced windows.
5. The windows should be placed as far as possible from the NPL to maximize stack effect.
6. Wide and short windows are generally better than square or vertical windows as they provide higher airflow over a wider range of wind directions.
7. Windows should be accessible to and operable by the occupants for greater control of natural ventilation.

40.5. Forced ventilation using electric fans:

As mentioned before, compared to natural ventilation, the use of fans for providing ventilation offers greater flexibility and control. Ventilation using electric fans is less sensitive to outdoor conditions, and hence is more certain. In general, depending upon the specific design, the fan-assisted ventilation can aid or oppose the natural ventilation. Obviously if the aim is to use outdoor air for cooling, then the design should be such that the mechanical and natural ventilations complement each other, rather than oppose. In general, the fan power consumption is quiet small and can be estimated using the equation:

$$W_{fan} = \frac{\dot{Q}_{fan} . \Delta P_{fan}}{\eta_{fan}} \qquad (40.7)$$

where W_{fan} is the power consumption of the fan in Watts, $\dot{Q}_{fan}$ is the airflow rate provided by the fan in m^3/s, ΔP_{fan} is the pressure rise due to fan in Pascals and η_{fan} is the efficiency of the fan. The efficiency of the fan may vary from about 0.35 for small shaded pole, single-phase motor (≈1/6 HP) to about 0.85 for large, three-phase motors of about 5 HP capacity.

40.6. Interior air movement:

Interior fans such as the ceiling or pedestal fans can remove heat from the occupants, but not from the buildings. Though interior fans do not decrease the indoor air temperature (in fact they may slightly increase the temperature as the work input to fan is dissipated as heat), they may certainly provide comfort by significantly enhancing the convective heat and mass transfer coefficients between the air and the body. However, they may be objectionable sometimes as they may create excessive air velocity and/or noise.

Both ceiling and pedestal type fans can be very effective and can even substitute the air conditioning system, or at least partly offset the air conditioning load. In general, larger fans provide higher airflow rates with less noise. The following table gives an example of the recommended blade diameter of a ceiling fan for area served:

Area served, ft^2	Fan diameter, inches
150	42
225	48
375	52

***Table 40.1**: Recommended ceiling fan diameter based on area served*

Generally for best performance, a ceiling fan should be placed such that the blade height is about 7 to 8 feet from the floor and there should be a minimum gap of 1 to 2 feet between the ceiling and the blades.

Studies show that by using ceiling fans in combination with air conditioning systems, the thermostat setting can be raised from about **25°C** to about **29 -30°C**. It is reported that this can reduce the energy consumption by as much as **30 to 45%**. This is particularly suitable in areas with high humidity as the ceiling fan can enhance the dehumidification rate. Thus an intelligent combination of air conditioning systems with interior fans can provide substantial savings.

In addition to fans, a wide variety of devices are used in practice to improve internal air circulation. **Attic ventilators** are installed in attic spaces. They draw the cold air from the outside and simultaneously exhaust the hot and humid indoor air collected near the attic. These attic ventilators are normally actuated by a thermostat, which turns the ventilator on when the attic air temperature exceeds a cut-in point of say 40^{o}C and turns off the ventilator when the attic temperature drops to a cut-out temperature of say 9^{o}C. A **whole-house fan** simultaneously provides outdoor air to the occupied zone and removes hot and humid air from the attic space.

In some houses, **solar chimneys** are used to boost the ventilation due to stack effect. A solar chimney is basically a passive solar air heater installed normally on the roof, with its inlet connected to the interior of the house. Figure 40.2 shows the schematic of a solar chimney. Due to solar heating, the air in the solar chimney gets heated up and flows out to be replaced continuously by air from the interior. This induces flow of outdoor air into the building. Thus a continuous air movement can be obtained by using solar radiation. Though solar chimneys appear to be simple, optimized design of solar chimney could be complicated due to the effect of wind. The wind may assist the flow of air due to solar chimney or it could oppose the flow. In a worst case, due to the wind effect, the flow direction could get reversed, resulting in the entry of heated outdoor air into the building through the solar chimney. Keeping the solar chimney on the leeward direction, can prevent the flow reversal.

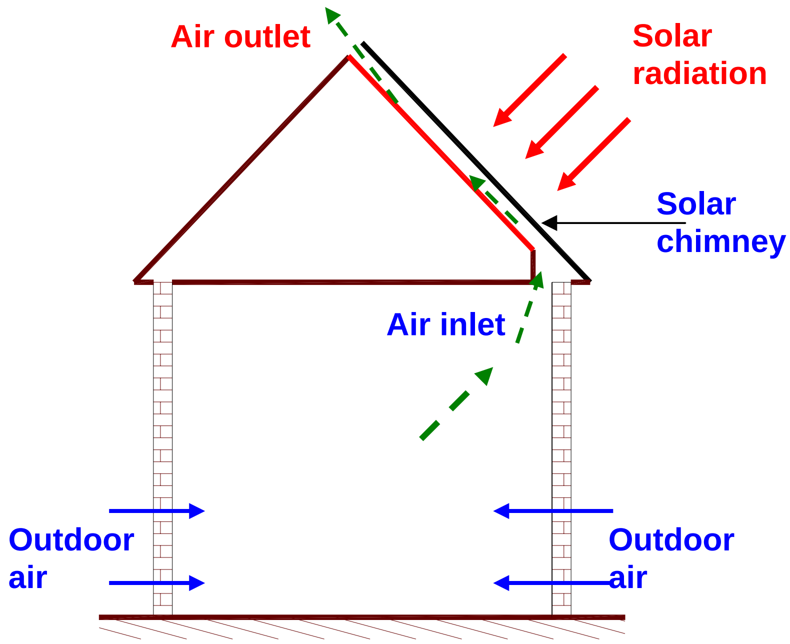

Fig.40.2: Schematic of a solar chimney

Questions and answers:

1. State which of the following statements are TRUE?

a) Ventilated outdoor air can be used for cooling of the buildings throughout the year in all locations
b) Ventilated outdoor air can be used for cooling of the buildings during many days of the year in most of the locations
c) Ventilated air has greater potential for cooling of buildings in hot and humid areas
d) Ventilated air has greater potential for cooling of buildings in hot and dry areas

Ans.: b) and d)

2. State which of the following statements are TRUE?

a) Ventilated outdoor air can extract both sensible and latent heat from the occupants
b) Increased air motion due to ventilated air increases the convective heat and mass transfer coefficients between the human body and surrounding air
c) Ventilated outdoor air can also enhance radiant heat transfer from the body
d) All of the above

Ans.: a) and b)

3. State which of the following statements are TRUE?

a) Natural ventilation is preferable to mechanical ventilation as it is more effective in the cooling of buildings and occupants
b) Natural ventilation is preferable to mechanical ventilation as it does not rely on external power input such as electricity
c) Mechanical ventilation offers greater flexibility and control compared to natural ventilation
d) Natural ventilation is highly uncertain as it depends on external elements which cannot be controlled

Ans.: b), c) and d)

4. State which of the following statements are TRUE?

a) Due to wind effect, outdoor air enters the building from openings provided on the windward direction and leaves from openings provided on the leeward direction
b) Due to wind effect, outdoor air enters the building from openings provided on the leeward direction and leaves from openings provided on the windward direction
c) Wind effect is a strong function of air density and wind speed
d) Wind effect is a strong function of area of openings and wind speed

Ans.: a) and d)

5. State which of the following statements are TRUE?

a) Stack effect takes place when outdoor air is warmer than indoor air
b) Stack effect takes place when outdoor air is cooler than indoor air
c) Stack effect depends on temperature difference between indoor and outdoor air
d) Stack effect does not depend on building height

Ans.: c)

6. State which of the following statements are TRUE?

a) Due to stack effect, in winter outdoor air enters from openings provided at the base of the building and leaves from the openings provided at the top
b) Due to stack effect, in winter, outdoor air enters from openings provided at the top of the building and leaves from the openings provided at the bottom
c) Due to stack effect, in summer, outdoor air enters from openings provided at the base of the building and leaves from the openings provided at the top
b) Due to stack effect, in summer, outdoor air enters from openings provided at the top of the building and leaves from the openings provided at the bottom

Ans.: a) and d)

7. State which of the following statements are TRUE?

a) For effective utilization of outdoor air, both natural and mechanical ventilation should be used in a building
b) Design of windows and other openings in the buildings plays a major role in natural ventilation
c) For maximum airflow rate, the openings should be as close to the neutral pressure level as possible
d) All of the above

Ans.: a) and b)

8. State which of the following statements are TRUE?

a) Ceiling fans provide greater comfort by reducing the temperature of air in the buildings
b) Ceiling fans provide greater comfort by increasing the temperature of air in the buildings
c) Ceiling fans provide greater comfort by increasing the heat and mass transfer rates from the body to the surroundings
d) Ceiling fans can be used for cooling of the buildings also

Ans.: c)

9. State which of the following statements are TRUE?

a) By improving the internal air movement, the energy consumption of the air conditioning system can be reduced substantially

b) By increasing air movement, the thermostat of the air conditioning system can be set at a lower temperature
c) By increasing air movement, the thermostat of the air conditioning system can be set at a higher temperature
d) Solar chimneys are ideal under all conditions

Ans.: a) and c)

10. A building consists of a 1.5 m x 1.5 m window on the wall facing the wind and an opening of 1.5m x 1.0 m on the opposite window. The center-to-centre distance between the windows in the vertical direction is 2.5 m. The outdoor temperature is 313 K, while the indoor is maintained at 303 K. Calculate the airflow rate due to the combined effect of wind and stack effects, if the wind blows at a speed of 25 kmph.

Ans.: a) Airflow rate due to wind effect: The expression to be used is:

$$\dot{Q}_w = C.R.A.V_w$$

Take the value of C as 0.55 for perpendicular wind and a value of 1.18 for R (based on the ratio of areas of openings)

The effective area of openings is given by:

$$A_{eff} = \frac{(A_o / A_i)}{\left(A_o^2 + A_i^2\right)^{0.5}} = \frac{(1.5x1.0/1.5x1.5)}{\left[(1.5x1.0)^2 + (1.5x1.5)^2\right]^{0.5}} = 0.2465 \text{ m}^2$$

wind velocity V_w **= 25 X 1000/3600 = 6.944 m/s**

Substituting these values:

$$\dot{Q}_w = C.R.A.V_w = 0.55x1.18x0.2465x6.944 = 1.111 \text{ m}^3/\text{s}$$

b) Airflow rate due to stack effect: The expression to be used is:

$$\dot{Q}_{st} = C.A.\left(h.\Delta T / T_w\right)^{0.5}$$

Assuming optimal distribution of areas, take a value of 0.0707 for C and area of the smaller opening for calculation of airflow rate. Substituting these values we obtain:

$$\dot{Q}_{st} = C.A.\left(h.\Delta T / T_w\right)^{0.5} = 0.0707x1.5x(2.5x10/313)^{0.5} = 0.03 \text{ m}^3/\text{s}$$

Hence the total airflow rate due to the combined effect is:

$$\dot{Q}_{total} = \left[\dot{Q}_w^2 + \dot{Q}_{st}^2\right]^{1/2} = \left[1.111^2 + 0.03^2\right]^{0.5} \approx 1.1114 \text{ m}^3/\text{s} \qquad \textbf{(Ans.)}$$

It can be seen that compared to wind effect, airflow rate due to stack effect is negligible.

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