5 Ventilation and air conditioning

Learning objectives

Study of this chapter will enable the reader to:

1. recognize the physiological reasons for fresh air ventilation of buildings;
2. calculate fresh air requirement;
3. understand the basic design criteria for air movement control;
4. describe the four combinations of natural and mechanical ventilation;
5. describe the working principles of air-conditioning systems;
6. calculate ventilation air quantities;
7. understand psychrometric cycles for humid air;
8. calculate air-conditioning heating and cooling plant loads;
9. describe the various forms of air-conditioning system;
10. state where reciprocating piston, screw and centrifugal compressors are suits;
11. understand the coefficient of performance;
12. explain the states of refrigerant occurring within a vapour-compression refrigeration cycle;
13. explain the operation of refrigeration equipment serving an air-conditioning system;
14. comprehend the absorption refrigeration cycle;
15. explain how ventilation rates are measured;
16. choose suitable materials for air-conditioning ductwork;
17. understand the relationship between CFCs and the environment;
18. know the uses of CFCs, and good practice and handling procedures;
19. be able to discuss the problem of SBS;
20. know the symptoms, causes and possible cures for SBS;
21. relate the daily cyclic variation of air temperatures to the need for air conditioning.

Key terms and concepts

absorption 154; air change 127; air-conditioning systems 147; air flow rate 127; air temperature variation 161; air velocity 127; anemometer 156; biocide treatment 160;

carbon dioxide (CO_2) production 126; centrifugal compressor 152; chlorofluorocarbon (CFC) 158; Coanda effect 148; coefficient of performance 152; criteria for air movement around people 127; dew-point temperature 141; dual duct 148; duct size 135; ductwork materials 158; dynamic thermal analysis 132; energy recovery 134; energy-saving systems 130; evaporative cooling 133; fan coil 149; fresh air required per person 127; humidity control 141; hydrogen fluorine alkaline (HFA134A) 159; induction 150; latent heat gains 138; low-cost cooling 132; lubrication 153; maintenance 161; mechanical ventilation 128; Montréal Protocol 159; natural ventilation 128; ozone depletion potential (ODP) 159; packaged units 150; pollutants 127; pressure–enthalpy diagram 153; primary energy 129; psychrometric chart and cycles 141; R12, R22 152; reasons for ventilation 128; recirculated air 129; refrigeration 151; screw compressor 152; sensible heat gains 137; shading 130; shutters 130; sick building syndrome (SBS) 159; single duct 147; smoke 156; stack effect 128; supply air moisture content 141; supply air temperature 138; total environmental loading 160; tracer gas 156; vapour compression 151; variable volume 148; ventilation rate measurement 156.

Introduction

The reasons for ventilation lead into an understanding of the necessary combinations of natural and mechanical systems and air conditioning, which means full mechanical control of air movement through the building (Kut, 1993). The calculation of air changes and air flow rates from basic human requirements, and then for removal of heat gains, is fundamental. The sizing of air ducts and the calculation of heater and cooler loads utilizing the psychrometric chart of humid air properties is shown.

Systems of air conditioning ranging from small self-contained units to large commercial applications are described. Appropriate refrigeration elements are developed, from thermodynamic principles, into complete installations in a form that is easily understood. Both vapour-compression and vapour-absorption cycles are explained.

Sick building syndrome (SBS) has been attributed to air conditioning, but has been found to be due to an amalgam of possible causes, none of which is singly identifiable as the culprit. The possible causes and solutions relating to user complaints are discussed.

Chlorofluorocarbons (CFCs) were widely used in thermal insulation and refrigeration until their potential for environmental damage resulted in the Montréal Protocol agreement. The effects of this agreement on the building services industry are discussed.

Ventilation requirements

An attempt to calculate the quantity of ventilation air needed for habitation can be made by considering the CO_2 production P m^3/s of a sedentary adult, the concentration C_s% of CO_2% in outdoor air and the maximum threshold CO_2 concentration C_r% for the occupied space. Normally, $P = 4.7 \times 10^{-6}$ m^3/s per person, $C_s = 0.03\%$ and $C_r = 0.5\%$. If Q m^3/s is the rate of fresh air flowing through a room to provide acceptable conditions, a CO_2 balance can be made:

CO_2 increase in ventilation air = CO_2 produced by occupant

Now,

$$\text{flow rate of } CO_2 \text{ entering room} = QC_s \text{ m}^3/\text{s}$$

$$\text{flow rate of } CO_2 \text{ leaving room} = QC_r \text{ m}^3/\text{s}$$

Therefore,

$$QC_r - QC_s = P \text{ m}^3/\text{s}$$

Hence,

$$Q(C_r - C_s) = P \text{ m}^3/\text{s}$$

and,

$$\begin{aligned} Q &= \frac{P}{C_r - C_s} \text{ m}^3/\text{s} \\ &= \frac{4.7 \times 10^{-6}}{(0.5 - 0.03) \times 10^{-2}} \text{ m}^3/\text{s} \\ &= 0.001 \frac{\text{m}^3}{\text{s}} \times \frac{10^3 \text{ l}}{1 \text{ m}^3} \\ &= 1 \text{ l/s} \end{aligned}$$

Other factors have a stronger influence on ventilation requirement:

1. bodily heat production, about 100 W per person during sedentary occupation;
2. moisture exhaled and evaporated from the skin, about 40 W per person for sedentary occupation;
3. body odour;
4. fumes from smoking.

These factors greatly outweigh the CO_2 requirement. The recommended fresh air supply per person is 10 l/s, which is increased by up to 50% in the event of expected heavy tobacco smoke. Building Research Establishment Digest 206: 1977 gives design curves for open-plan and small offices of room height 2.7 m and floor space per person 4.5 m^2. A small office requires 2.25 air changes/h of outdoor air, and this will normally be provided by natural ventilation. A single-person workstation occupies around 10 m^2 floor area when half of the walkway is included, so an outdoor air supply of 10 l/s per person equates to 1 l/s m^2 floor area.

The ventilation system should not produce monotonous draughts but preferably variable air speed and direction. Facilities for manual control of ventilation terminals allow sedentary workers some freedom of choice over their environment. Careful location of ventilation grilles and control of both the temperature and velocity of moving air in mechanical systems can ensure that neither cool nor hot draughts are caused. The maximum air velocity that can be perceived at neck level is related to its temperature. If the values given in Table 5.1 are not exceeded, then annoyance should be avoided.

Table 5.1 DIN criteria for air movement at the neck.

Moving-air temperature (t_{ai}°C)	20	22	24	26
Maximum air speed (v m/s)	0.10	0.20	0.32	0.48

Source: Reproduced from the *IHVE Guide* (CIBSE, 1986 [IHVE, 1970]) by permission of the Chartered Institution of Building Services Engineers.

Grille manufacturers' data reveal the length of the jet of air entering the room for particular air flow rates. Additionally, the air jet may rise or fall depending on whether it is warmer or cooler than the room air. Moving air currents tend to attach themselves to a stationary surface and follow its contours, the Coanda effect. When this boundary layer flow either comes to the end of, say, a wall or hits a bluff body, such as a beam or luminaire, it may be suddenly detached and cause turbulent flow; this appears as a draught, which is an uncomfortable air movement.

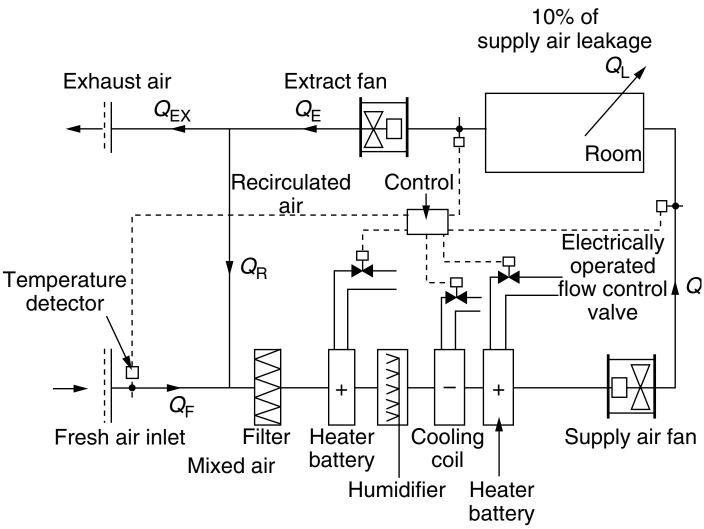
An air jet entering a room should be allowed to mix with the room air before entering the occupied space. This can be done either above head height with cooling systems or in circulation spaces at low level with heating systems. The design criteria for ventilation systems are as follows:

1. correct fresh air quantity, minimum normally 10 l/s per person;
2. avoidance of hot or cold draughts by design of the air inlet system;
3. some manual control over air movement;
4. mechanical ventilation to provide a minimum of 4 air changes/h to ensure adequate flushing of all parts of rooms;
5. air change rates that can be increased to remove solar and other heat gains;
6. air cleanliness achieved by filtration of fresh air intake and recirculated room air.

Natural and mechanical systems

The four possible combinations of natural and mechanical ventilation are as follows.

1. Natural inlet and outlet: utilizing openable windows, air bricks, louvres, doorways and chimneys. Up to about 3 air changes/h may be provided, but these depend upon prevailing wind direction and strength, the stack effect of rising warm air currents, and adventitious openings around doors and windows.
2. Natural inlet, mechanical outlet: mechanical extract fans in windows or roofs and ducted systems where the air is to be discharged away from the occupied space owing to its contamination with heat, fumes, smoke, water vapour or odour. This system can be used in dwellings, offices, factories or public buildings. A slight reduction in air static pressure is caused within the building, and external air flows inwards. This inflow is facilitated by air inlet grilles, sometimes situated behind radiators or convector heaters. There is no filtration of incoming impurities. This system is used particularly for toilet or kitchen extraction, smoke removal from public rooms and heat or fume removal from industrial premises. Heating of the incoming air is essential for winter use.
3. Mechanical inlet, natural outlet: air is blown into the building through a fan convector or ducted system to pressurize the internal atmosphere slightly with a heated air supply. The air leaks out of the building through adventitious openings and permanent air bricks or louvres. This system can be used for offices, factories, large public halls or underground boiler plant rooms.
4. Mechanical inlet and outlet: where natural ventilation openings would become unable to cope with large air flow rates without disturbing the architecture or causing uncontrollable draughts, full mechanical control of air movement is assumed. This may augment natural ventilation at times of peak occupancy or solar heat gain. When a building is to be sealed from the external environment, then a full air-conditioning system is used. Figure 5.1 shows the basic arrangement of a single-duct system.



5.1 Single-duct air-conditioning system.

The designers of new buildings bear a heavy responsibility for the future environmental condition of the planet. A building that is a large user of primary energy, that is, fossil fuel, to power its mechanical systems, usually air conditioning, is a charge on society for 50 or more years. Such buildings are unlikely to have their mechanical heating, cooling, lifts, lighting and computer power supply networks removed for reasons of economy by future tenants. Once the pattern of energy use is set for a building by the architect and original client, it remains that way until it is demolished.

The increasing need for comfortably habitable buildings in the temperate climate of the British Isles since the 1960s led to demands for air conditioning. Warm weather data for the UK shows that an external air temperature of 25°C d.b. is normally only exceeded during 1% of the summer period June to September (CIBSE, 1986, figure A2.11). (Compare this to those areas of the world within 45°C of latitude from the equator, where the outside air temperature exceeds 30°C d.b.; people living and working in such areas would probably consider the use of air conditioning in the UK a waste of energy resources.) These 4 months total 120 days and include weekends, a public holiday and many people's annual holidays from their places of work. Therefore, only one day per summer is likely to have an outdoor air temperature that exceeds 25°C d.b. When a long, hot summer is experienced in southern England, there can be several days which exceed 25°C d.b., but this may not be repeated for a few years. In the rest of the UK, lower outdoor air temperatures are experienced most of the time. The UK has a basically maritime climate, with the Atlantic Ocean, English Channel and North Sea providing humid air flows at air temperatures that are modified by the evaporative cooling effect of the seas. Long, hot summers are produced by strong winds from eastern Europe. These winds have travelled across the hot and dry land mass of northern Europe and then been reduced in temperature due to the evaporation of water from the North Sea. Such evaporation of sea water is aided by high wind speed. Sea water is evaporated into the wind and a change of phase occurs in the water. In order to evaporate water into moisture that is carried by the air stream, the water is boiled into steam, a change of phase. This phase change can only take place with the removal of sensible heat from the air and the water, as the latent heat of evaporation has to be provided, just as in a steam boiler.

Removal of sensible heat from the air lowers its dry-bulb temperature. This is the principle of evaporative cooling that is employed in cooling towers and in the evaporative cooling heat exchangers that are used for indoor comfort cooling in hot, dry climates. The occasional long, hot summers in the UK coincide with the increase of outside air wet-bulb temperature that is associated with the evaporative cooling effect from the sea. The result is warm and humid weather in south-east England. It is the combined effect of the higher dry- and wet-bulb outdoor air temperatures which produces the humid air that many people find uncomfortable. The building designer has to decide how to address periods of discomfort due to warm outdoor weather conditions and explain the likely outcome to the client.

The principal source of indoor thermal discomfort in the UK is the manner in which modern buildings are designed and then filled with people and heat-producing equipment. Buildings that were constructed of masonry and brick, with small, openable windows, overhanging eaves from pitched tiled roofing, hinged wooden external or internal slatted shutters; permanent ventilation openings from air bricks, chimneys and roof vents, and north light windows for industrial use, have a large thermal storage mass to smooth out the fluctuations of the outdoor air temperature. Such buildings from the designs of the late nineteenth and early twentieth centuries are better able to provide shaded and cool habitable zones than the exposed glazing high-rise buildings that have been popular since the 1960s. Deep core floor plan buildings that are unreachable by outdoor air to provide the required ventilation and exterior façades which are deliberately exposed to solar heat gain with no provision for external shading screens, trees or shadows cast from surrounding buildings are designed to create interior discomfort. Current buildings are also packed to capacity with productive workers who each need a personal computer and permanent artificial illumination in order to carry out their tasks. The other mistake is to employ people to work in these glass boxes only during daylight hours that coincide with the peak cooling-load times. The Mediterranean countries close many of their businesses during the afternoons, close the wooden window shutters and sleep during the hottest part of the day, coming out in the late afternoon to start work again.

Energy conservation engineers can assist the building maintenance manager to make the best use of what has been built. There will be many technical methods that are available to reduce the use of energy by the mechanical and electrical systems within the building, but at best, these are likely to reduce energy use by a maximum of 25%, often much less can be achieved. Retrofitting a building with energy-saving systems may accompany a change of use or an overall refurbishment. There has been a strong move in the direction of low-energy-use buildings within the UK during recent years. Greenfield sites in the mild climate of the British Isles have provided building designers with more options than are available in more extreme climates. The outdoor air temperatures that are used for the design of the heating and cooling systems in the UK are within the range of −3°C d.b to 30°C d.b. The minimum overnight outdoor air temperature may drop to −17°C d.b. once per year during a severe winter. The extreme low and high outdoor air temperatures that can be experienced are of little importance to the designers of commercial and most industrial buildings, unless indoor air temperatures are of critical importance for the condition of products, human or animal safety, or industrial processes. The users of most buildings are expected to withstand colder or warmer indoor temperatures for a few days per year and not complain too much. In extreme cases, workplace agreements are made to allow work to be stopped for short periods so that the occupants of the building can move away from the workstation for recuperation. An example is a production factory where 10 min breaks in an 8 h shift are agreed for production-line workers to go outside the building when the indoor air temperature exceeds 30°C d.b., which it does frequently during long, hot summers, due to the minimalist thermal insulation value of the building's walls and roofing.

The design team of a new building need to develop a method of solving the complex issues surrounding the task of providing a building which satisfies the:

- basic needs of the owner;
- architectural and local planning design philosophy;
- requirements of legislation;
- access, spatial, visual, aural and thermal comfort needs of the occupants;
- use of energy during the 50-year service period of the building;
- sources of energy that are available for the building and the maintainability of the whole complex.

Those matters which relate to the need, or otherwise, for air conditioning can be summarized as follows:

1. the local design weather conditions;
2. the indoor design set points for zone air temperature and relative humidity;
3. the allowable variation in the indoor design air conditions;
4. the number of occasions during each year that divergence from the specified indoor design conditions are allowable;
5. the time periods when the building will be occupied by the main users and the service personnel;
6. the sources of primary energy available for the building, their long-term reliability, storage requirements and safety considerations;
7. whether renewable energy can be used on the site;
8. the building usage;
9. the means by which the building can be heated;
10. the outdoor air ventilation quantity requirements;
11. the peak energy requirements for heating and cooling;
12. the location and sizes of plant and service shaft spaces available;
13. whether natural ventilation or assisted natural ventilation can provide the required air flow through the building;
14. whether mechanical cooling systems are needed to maintain the specified peak design conditions;
15. the need to provide accurate indoor environmental conditions for equipment, material storage and handling, or an industrial process;
16. whether low-cost cooling systems can be used;
17. whether there is a real need to provide a mechanical means of air conditioning;
18. if there is a process requirement for closely conditioned air within the building;
19. energy recovery strategies available;
20. the maintainability of the mechanical services and how replacement plant can be provided without major structural works becoming necessary.

These considerations all have an impact on the building design team's decision-making process. The local weather conditions that create the maximum heating and cooling loads during the occupied part of the day, or night, will determine the size of the heating and cooling plant that are required. Occupancy times can sometimes be varied in order to minimize the plant capacity that is needed, for example, by using the Mediterranean region off-peak working principle, however unpalatable this may seem to northern European practices. The architectural and engineering designers have the option to experiment with the thermal insulation value of the exterior envelope of the building in varying the area of glazing, walling and roofing and the thermal transmittance of each component. Life-cycle costing of each alternative thermal design will reveal the total cost of constructing and using the building for 50 years, with reasonable assumptions on price changes each year and the cost of refitting the building every 20 years because of improvements in technology.

Selection of the indoor design air set points for temperature and relative humidity will be determined by legislative and comfort standards. Short-term variances within an allowable range can minimize the use of energy at peak times. It may be possible to avoid the installation of mechanical cooling systems where the users of the building agree to accept regular, short-term divergence from the standard design conditions. The provision of ceiling-mounted or portable fans with comfort breaks and refrigerated drinks dispensers might allow a building to avoid the installation of mechanical cooling, depending upon the number and frequency of divergences from the normal standards. Allowing the indoor air temperature to rise to 25°C d.b. in summer before switching on the air-conditioning chiller during the afternoon, and whether the building is occupied, the time is before 3.30 p.m. and the outdoor air temperature is above 25°C d.b.; all these conditions can be accessed through the computer-based building management system, if one is provided. Automatic control programming can be set to minimize the use of electrical energy by the mechanical cooling system as a deliberate strategy by the designers and operators of the building. Dynamic thermal analysis software is used to model buildings and their services systems to assess the indoor air conditions that are expected to occur.

The provision of outdoor air ventilation is a legislative requirement based on the activities of and the numbers of people within the enclosure. The minimum quantity of outdoor air must be maintained for each person to comply with the standards. Outdoor air ventilation does more than provide air for breathing; it also flushes the building with outdoor air to remove heat and to control the concentrations of odours and atmospheric pollutants that are produced within the building. Toilet exhaust air flows often partly match the inflow rate of outdoor air in commercial buildings. Any balance of flow between the exhaust quantity and inflow of outdoor air may be allowed to leak through doors, permanent ventilators and other openings in the structure, such as gaps around window frames. The inclusion of carbon dioxide sensors in the return or exhaust air ducts allows the building management system to minimize the opening of the outside air intake motorized dampers and consequently reduce the heating or cooling load of the air-conditioning plant and save energy. Carbon dioxide in air that is removed from the occupied space is a direct assessment of the number of occupants and their activity level, allowing energy use to match the instantaneous load on the building. Other means of assessing room occupancy are available from infrared or ultrasonic sensors. If the designers of the building are able to know the divergence in the patterns of occupancy of rooms or spaces, then decisions can sometimes be taken to diversify the provision of lighting, heating and cooling zones to minimize the use of mechanical and electrical plant and systems, with benefits in the initial plant capacity and in the use of energy in the long term.

Where incoming outdoor unconditioned air can be preconditioned, an air-to-air flat-plate heat exchanger may be used. This is a compact box around the size of a suitcase having counter flow passages for incoming and outgoing air separated by aluminium foil plates. Incoming winter air is warmed by the room air being exhausted; in summer, room air at the correct temperature cools the outdoor ventilation air stream.

Natural ventilation can be used in atria and industrial buildings where the stack effect of height within the building is used to create air movement. Low-level outside air intakes and roof-level air extractors or openable ventilation units can be mechanically controlled to match the heating and cooling load on the building to the flow of air through the spaces. The avoidance of draughts around sedentary occupants will always be the main challenge. Low-level radiant heating from warmed floors or overhead radiant panels can offset high rates of air movement. Anyone who has sat within cathedral ceiling spaces will recognize the potential discomfort problems in cold weather within intermittently used high thermal-mass buildings, for example, stone churches and sports halls. The use of natural ventilation in the UK is accompanied by the problem of allowing the uncontrolled ingress of the moisture that is present in the outside air. Any surface within the building that is below the dew-point temperature of the space will accumulate damp and create long-term mould growth. This becomes a comfort, health and maintenance cost if damage to the building is to be avoided. In climates where the outdoor air temperature rises above 20°C d.b. on most days of the year, the use of outdoor air natural ventilation is often out of the question. This is due to the combination of intense solar radiation heat gains in these regions and the lack of a natural cooling function by the outdoor air.

Hot dry climates within the Middle East and southern continents make use of evaporative low-cost cooling. Figure 5.2 shows an Australian type where outdoor air of above 25°C d.b. and around 10–30% saturation is drawn inwards through wetted vertical panels and blown directly into occupied rooms as quickly as possible. The only operational cost being that for a 400 W axial fan and a small water consumption in this case. Larger units serve commercial premises and may have an indirect gas-fired heat exchanger to provide winter heating. The supply air has a high humidity but is at reduced dry-bulb air temperature. All cooling is created from evaporation of water, latent heat transfer, but provides sensible cooling of the conditioned space through high air flow. Air is released from the building through window and screened door openings.

Within the tropics, the constant high moisture content of the outdoor air makes it unsuitable for natural ventilation practice in commercial buildings. Buildings in the UK that have an internal atrium have restored a historical precedent in turning the building inside-out. The exterior surfaces need less glazing as the occupants' view is directed inwards towards a planted open space that has natural daylight. The atrium can be used to return conditioned air back to the air-handling plant room without the need for a return air fan, collect exhaust air and expel it through roof openable vents and facilitate the removal of smoke during an emergency. Heat produced from the occupants, fluorescent lighting, computers and electrical equipment assists the upward flow of air away from the occupied zones. Atria are used in all climates from sub-zero through 40°C d.b. environments and fully provide indoor office, retail shopping malls, casino, hotel and entertainment spaces throughout the world.

5.2 Ducted evaporative cooler used in hot climates.

The options that are available to the designers in the selection of the method of controlling the environmental conditions within the building include the following.

1. Natural ventilation – applicable when the external climate, the use and design of the building permit it. Mild climate localities usually close to the coast where the sea is warm; internal air conditions are allowed to vary widely and are directly related to the external weather conditions; central heating system; cooling may be provided from packaged direct expansion refrigeration units within each zone; manually operated internal or external shading blinds; passive solar architecture that may include thermal storage walls; chilled-water beams or flat panels may be installed at high level within offices to provide limited cooling (the chilled water in the beams and panels is maintained at a temperature that is above the room air dew-point so that there is no condensation on the exposed surfaces or within the ceilings, avoiding dehumidification and control of the zone relative humidity); chilled beams and panels provide no ventilation air.
2. Assisted natural ventilation – a development of natural ventilation, as earlier, where applicable. Mechanically operated ventilation louvers and exhaust air fans improve the control of air flow through the occupied spaces; the incoming outside air may be cooled with a water spray evaporative cooler in hot, dry climates; evaporative cooling is a low-cost means of cooling the incoming outside air, which is exhausted by either natural openings of doors and windows, or by exhaust air fans in confined zones; the incoming outdoor air may be cooled through a specific temperature range, say 10 K, to provide limited cooling by means of direct expansion or chilled-water refrigeration plant.
3. Mechanical ventilation which only passes outside air through the zone. This usually applies to moderate climates such as the UK where minimal cooling is required; in climates where the outside air temperature exceeds 30°C d.b. the flow rate of outside air is likely to be insufficient to provide enough cooling for zone temperature control in an air-conditioning system; where it is possible to locate the exhaust air duct alongside the incoming outside air duct, within the ceiling space or a plant room, an air-to-air fiat-plate heat exchanger is used to transfer heat between the incoming and outgoing air streams; the outgoing exhaust air is already at the correct zone temperature, of around 22°C d.b. (it cannot be recycled as it is vitiated with carbon dioxide, odours and atmospheric pollutants); heat transfer works throughout the year (in winter, the incoming outdoor air is preheated by up to 10 K from the outgoing exhaust air; in summer, the incoming outdoor air is precooled by up to 10 K from the outgoing exhaust air); heat transfer efficiency is around 55%; a similar heat transfer can be obtained from a recuperative heat wheel that transfers heat from the outgoing exhaust air to the incoming outside air, generating up to a 10 K temperature change in the outside air stream; the heat transfer medium of the wheel may be strips of mylar film.
4. Mechanical ventilation with recirculated room air. The maximum quantity of conditioned room air is recirculated to save energy use at the heating and refrigeration plant; the outside air motorized dampers are modulated from closed to fully open to control the zone air temperature without the use of the mechanical refrigeration plant for as long a time as possible (this provides low cost cooling to the building); when the refrigeration plant has to be used, the outside and exhaust air motorized dampers are moved to their minimum outside air positions, often around 10% open, allowing the maximum use of recirculated room air; a range of ducted air-conditioning systems are in use, including single-duct, dual-duct, induction units, fan coil units and variable air volume systems.

The single-duct system works in the following way. Some of the air extracted from the room is exhausted to the atmosphere and as much as possible is recirculated to reduce running costs of heating and cooling plants. Incoming fresh air is filtered and mixed with that recirculated; it is then heated by a low-, medium- or high-pressure hot-water or steam finned pipe heat exchanger or an electric resistance element. The heated air is supplied through ducts to the room. The hot-water flow rate is controlled by a duct-mounted temperature detector in the extract air, which samples room conditions. The electrical signal from the temperature detector is received by the automatic control box and corrective action is taken to increase or reduce water flow rate at the electrically driven motorized valve at the heating coil.

During summer operation, chilled water from the refrigeration plant is circulated through the cooling coil and room temperature is controlled similarly.

A temperature detector in the fresh air duct will vary the set value of the extract duct air temperature – higher in summer, lower in winter – to minimize energy costs. A low-limit temperature detector will override the other controls, if necessary, to avoid injection of cold air to the room.

The building is slightly pressurized by extracting only about 95% of the supply air volume, allowing some conditioned air to leak outwards or exfiltrate.

Energy savings are maximized by recirculating as much of the conditioned room air as possible. Room air recirculation with economy-cycle motorized dampers can, sometimes, be retrofitted to existing systems as an energy conservation measure. In mild climates, such as in the UK, full outside air systems are also used. These have no recirculation air ducts; either a flat-plate heat exchanger or run-around pipe coils can be installed to preheat and precool the incoming outside air to save energy. Such heat exchangers are around 55% efficient, which is not as good as recirculation.

EXAMPLE 5.1

A room 15 m × 7 m × 2.8 m high is to have a ventilation rate of 11 air changes/h. Air enters from a duct at a velocity of 8.5 m/s. Find the air volume flow rate to the room and the dimensions of the square duct.

The air flow rate is given by:

$$Q = \frac{N \text{ air changes}}{\text{hour}} \times \frac{V \text{ m}^3}{\text{air change}} \times \frac{1 \text{ h}}{3600 \text{ s}}$$

where room volume V m^3 = 1 air change. Hence,

$$\begin{aligned} Q &= \frac{NV}{3600} \text{ m/s} \\ &= \frac{11 \times 15 \times 7 \times 2.8}{3600} \text{ m}^3\text{/s} \\ &= 0.9 \text{ m}^3\text{/s} \end{aligned}$$

Also,

$$Q \text{ m}^3\text{/s} = \text{duct cross-sectional area } A \text{ m}^2 \times \text{air velocity } v \text{ m/s}$$

Therefore:

$$A = \frac{Q}{v} = \frac{0.9}{8.5} \text{ m}^2 = 0.106 \text{ m}^2$$

If the duct side is l m, then $A = l^2$ m^2. Therefore:

$$l = \sqrt{A}\ \text{m}$$
$$= \sqrt{0.106}\ \text{m}$$
$$= 0.325\ \text{m}$$

EXAMPLE 5.2

A lecture theatre has dimensions 25 m × 22 m × 6 m high and has 100 occupants; 8 l/s of fresh air and 25 l/s of recirculated air are supplied to the theatre for each person. A single-duct ventilation system is used. If 10% of the supply volume leaks out of the theatre, calculate the room air change rate and the air volume flow rate in each duct.

$$\text{supply air quantity} = (8 + 25)\frac{\text{l}}{\text{s}} \times \frac{1\ \text{m}^3}{10^3\ \text{l}}$$
$$= 0.033\ \text{m}^3/\text{s}$$

Hence,

$$Q = 0.033 \times 110\ \text{m}^3/\text{s}$$
$$= 3.63\ \text{m}^3/\text{s}$$

Now,

$$Q = \frac{NV}{3600}$$

and hence,

$$N = \frac{3600\ Q}{V}$$
$$= \frac{3600 \times 3.63}{25 \times 22 \times 6}\ \text{air changes/h}$$
$$= 3.96\ \text{air changes/h}$$

Leakage from the theatre is:

$$Q_1 = 10\% \times Q$$
$$= 0.1 \times 3.63\ \text{m}^3/\text{s}$$
$$= 0.36\ \text{m}^3/\text{s}$$

Quantity of air extracted from the theatre is:

$$Q_e = 3.63 - 0.36\ \text{m}^3/\text{s}$$
$$= 3.27\ \text{m}^3/\text{s}$$

Quantity of fresh air entering the ductwork is:

$$Q_f = \frac{8 \times 110}{10^3} \text{ m}^3/\text{s}$$
$$= 0.88 \text{ m}^3/\text{s}$$

Quantity of recirculated air is:

$$Q_f = Q - Q_r$$
$$= 3.63 - 0.88 \text{ m}^3/\text{s}$$
$$= 2.75 \text{ m}^3/\text{s}$$

Exhaust air quantity is:

$$Q_{ex} = Q_e - Q_r$$
$$= 3.27 - 2.75 \text{ m}^3/\text{s}$$
$$= 0.52 \text{ m}^3/\text{s}$$

EXAMPLE 5.3

There are 35 people in a gymnasium, each producing CO_2 at a rate of 10×10^{-6} m^3/s. If the maximum CO_2 level is not to exceed 0.4%, find the air supply rate necessary. The outdoor air CO_2 concentration is 0.03%. Explain what this means to the ventilation designer.

$$Q = \frac{P}{C_r - C_s} \text{ m}^3/\text{s}$$
$$= \frac{35 \times 10 \times 10^{-6}}{(0.4 - 0.03) \times 10^{-2}} \text{ m}^3/\text{s}$$
$$= 0.095 \text{ m}^3/\text{s}$$

This is a very small air flow of outdoor air through a gymnasium where strenuous activity by 35 athletic people is to take place. The outdoor air of 95 l/s may be able to be provided by natural ventilation through controlled low- and high-level vents to the outside. Additional recirculated air flow to control the air temperature with heating or cooling systems is provided if the climate required mechanical air treatment.

Removal of heat gains

Ventilation air is used to remove excess heat gains from buildings. Two types of heat gain are involved: sensible and latent.

Sensible heat gains result from solar radiation, conduction from outside to inside during hot weather, warm ventilation air, lighting, electrical machinery and equipment, people and industrial processes. Such heat gains affect the temperature of the air and the building construction.

Latent heat gains result from exhaled and evaporated moisture from people, moisture given out from industrial processes and humidifiers. These heat gains do not directly affect the temperature of the surroundings but take the form of transfers of moisture. They can be measured in weight of water vapour transferred or its latent heat equivalent in watts.

The latent heat of evaporation of water into air at a temperature of 20°C and a barometric pressure of 1013.25 mb is 2453.61 kJ/kg. Thus the latent heat (*LH*) required to evaporate 60 g of water in this air is:

$$LH = 60 \text{ g} \times \frac{1 \text{ kg}}{10^3 \text{ g}} \times 2453.61 \frac{\text{kJ}}{\text{kg}}$$
$$= 147.22 \text{ kJ}$$

If this evaporation takes place over, say, 1 h, the rate of latent heat transfer will be:

$$LH = 147.22 \frac{\text{kJ}}{\text{h}} \times \frac{1 \text{ h}}{3600 \text{ s}} \times \frac{10^3 \text{ J}}{\text{kJ}} \times \frac{\text{W s}}{\text{J}}$$
$$= 40.9 \text{ W}$$

This is the moisture output from a sedentary adult.

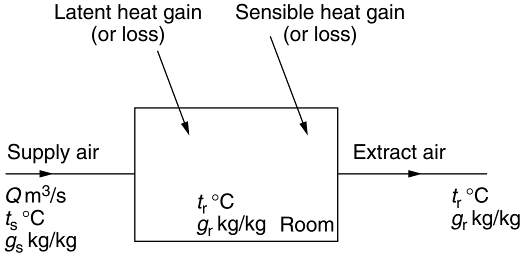
Removal of sensible heat gains to control room air temperature is carried out by cooling the ventilation supply air and increasing the air change rate to perhaps 20 changes/h. Figure 5.3 shows this scheme. The temperature and moisture content of the supply air increase as it absorbs the sensible and latent heat gains until it reaches the desired room condition. The net sensible heat flow will be into the room in summer and in the outward direction in winter.

Rooms that are isolated from exterior building surfaces have internal heat gains from people and electrical equipment, producing a net heat gain throughout the year. The heat balance is as follows:

net sensible heat flow into room = sensible heat absorbed by ventilation air

Therefore:

SH = air mass flow rate × specific heat capacity × temperature rise



5.3 Schematic representation of heating, cooling and humidity control of an air-conditioned room.

where *SH* is the sensible heat. The specific heat capacity of humid air is 1.012 kJ/kgK. The volume flow rate of air is normally used for duct design.

$$Q\ \frac{\text{m}^3}{\text{s}} = \text{air mass flow rate}\ \frac{\text{kg}}{\text{s}} \times \frac{\text{m}^3}{\rho\ \text{kg}}$$

The density of air at 20°C d.b. and 1013.25 mb is $\rho = 1.205$ kg/m^3.

The supply air temperature t_s can have any value and as density is inversely proportional to the absolute temperature, from the general gas laws,

$$SH\ \text{kW} = Q\ \frac{\text{m}^3}{\text{s}} \times 1.205\ \frac{\text{kg}}{\text{m}^3} \times \frac{(273+20)}{(273+t_s)} \times (t_r - t_s)\ \text{K} \times 1.012\ \frac{\text{kJ}}{\text{kgK}} \times \frac{\text{kW s}}{1\ \text{kJ}}$$

For summer cooling, t_r is greater than t_s during a net heat gain. For winter heating, t_r is less than t_s as there is a net heat loss, and so the temperature difference $(t_s - t_r)$ must be used in the equation. It is more convenient to rewrite the equation in the form,

$$Q = \frac{SH\ \text{kW}}{t_r - t_s} \times \frac{273 + t_s}{357}\ \text{m}^3/\text{s}$$

EXAMPLE 5.4

An office 20 m × 15 m × 3.2 m high has 30 occupants, 35 m^2 of windows, 25 (2 × 30) W fluorescent tube light fittings, a photocopier with a power consumption of 1500 W and conduction heat gains during summer amounting to 2 kW. Solar heat gains are 600 W/m^2 of window area. The sensible heat output from each person is 110 W. The room air temperature is not to exceed 24°C when the supply air is at 13°C. Calculate the supply air flow rate required and the room air change rate. State whether the answers are likely to be acceptable.

The sensible heat gains are summarized in Table 5.2. Then:

$$Q = \frac{29.3}{24 - 13} \times \frac{273 + 13}{357}\ \text{m}^3/\text{s}$$
$$= 2.13\ \text{m}^3/\text{s}$$

Table 5.2 Summary of sensible heat gains in Example 5.4.

Source	*Quantity (W/m^2 × m^2)*	*SH (W)*
Windows	600 × 35	21 000
Occupants	110 × 30	3300
Lights	25 × 2 × 30	1500
Photocopier		1500
Conduction		2000
	SH gain =	29 300
	=	29.3 kW

Some engineers prefer to calculate the mass flow rate of air flow through the air-conditioned space. This is easily found by multiplying the volume flow rate by the density of air at that location, thus,

$$\text{supply air mass flow rate} = 2.13\ \frac{\text{m}^3}{\text{s}} \times 1.205\ \frac{\text{kg}}{\text{m}^3} = 2.57\ \text{kg/s}$$

Air mass flow rate does not change with temperature, volume flow does.

$$Q = \frac{NV}{3600}$$

$$N = \frac{3600\ Q}{V}$$

$$= \frac{3600 \times 2.13}{20 \times 15 \times 3.2}\ \text{air changes/h}$$

$$= 8\ \text{air changes/h}$$

Between 4 and 20 air changes/h are likely to create fresh air circulation through an office without causing draughts and should be suitable for the application.

EXAMPLE 5.5

A room has a heat loss in winter of 32 kW and a supply air flow rate of 3.5 m^3/s. The room air temperature is to be maintained at 22°C. Calculate the supply air temperature to be used.

For winter, the equation is:

$$Q = \frac{SH}{t_s - t_r} \times \frac{273 + t_s}{357}$$

This can be rearranged to find the supply air temperature t_s required:

$$Q \times 357(t_s - t_r) = SH(273 + t_s)$$

$$Q \times 357t_s - Q \times 357t_r = 273SH + SH \times t_s$$

$$Q \times 357t_s - SH \times t_s = 273SH + Q \times 357t_s$$

Thus, for winter:

$$t_s(Q \times 357 - SH) = 273SH + Q \times 357t_r$$

$$t_s = \frac{273SH + 357Qt_r}{357Q - SH}\ ^\circ\text{C}$$

In this example:

$$t_s = \frac{273 \times 32 + 357 \times 3.5 \times 22}{357 \times 3.5 - 32}$$

$$= 29.75^\circ\text{C}$$

The heated or cooled air supply may also have its humidity modified by an air-conditioning plant so that the percentage saturation of the room air is controlled. A water spray or steam injector can be used for humidification. The refrigeration cooling coil lowers the air temperature below its dew-point to condense the moisture out of the air.

Figure 5.4 shows how the properties of humid air are determined from a psychrometric chart. If g_r and g_s are the moisture contents of the room and the supply air respectively, then a heat balance can be written for the latent heat gain absorbed by the previously calculated supply air flow rate Q:

latent heat gain to room = latent heat equivalent of moistures removed by the conditioned air

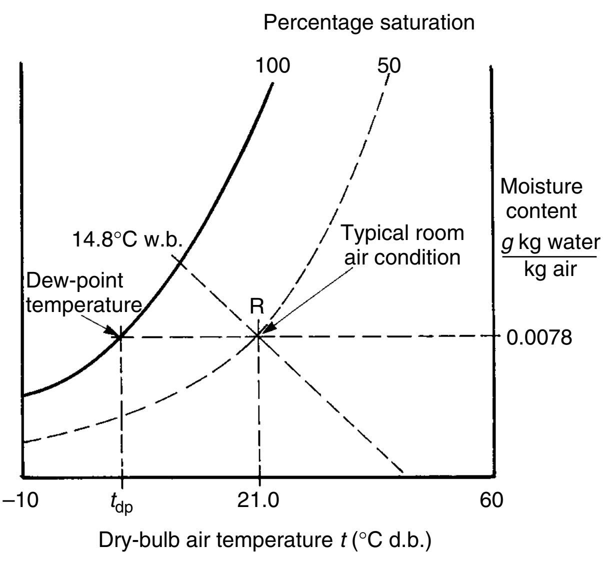
$$LH \text{ kW} = \text{moisture mass flow rate } \frac{\text{kg}}{\text{s}} \times \text{latent heat of evaporation } \frac{\text{kJ}}{\text{kg}}$$

$$= \text{air mass flow rate } \frac{\text{kg}}{\text{s}} \times \text{moisture absorbed } \frac{\text{kg } H_2O}{\text{kg dry air}} \times 2453.61 \ \frac{\text{kJ}}{\text{kg } H_2O}$$

$$LH \text{ kW} = Q \ \frac{\text{m}^3}{\text{s}} \times 1.205 \ \frac{\text{kg}}{\text{m}^3} \times \frac{273+20}{273+t_s} \times (g_r - g_s) \ \frac{\text{kg } H_2O}{\text{kg air}} \times 2453.61 \ \frac{\text{kJ}}{\text{kg } H_2O}$$

$$Q = \frac{LH}{g_r - g_s} \times \frac{273+t_s}{866\,284} \ \text{m}^3/\text{s}$$

The denominator can be rounded to 860 000 with an error of less than 1.0%.



5.4 Sketch of the CIBSE psychrometric chart.

EXAMPLE 5.6

The people in the office in Example 5.4 each produce 40 W of latent heat. Find the supply air moisture content to be maintained, given that the room air is to be at 50% saturation and the corresponding moisture content g_r is 0.008905 kg H_2O/kg air.

$$LH = 30 \text{ people} \times 40 \,\frac{\text{W}}{\text{person}} \times \frac{1 \text{ kW}}{10^3 \text{ W}} = 1.2 \text{ kW}$$

$$t_s = 13°\text{C} \quad Q = 2.13 \text{ m}^3/\text{s}$$

$$\text{air mass flow rate} = 2.13 \text{ m}^3/\text{s} \times 1.205 \text{ kg/m}^3 = 2.57 \text{ kg/s}$$

$$Q = \frac{LH}{g_r - g_s} \times \frac{273 + t_s}{860\,000} \text{ m}^3/\text{s}$$

We obtain,

$$g_r - g_s = \frac{1.2 \times (273 + 13)}{2.13 \times 860\,000} \text{ kg } H_2O/\text{kg air}$$

Hence,

$$g_s = 0.008905 - 0.000187 \text{ kg } H_2O/\text{kg air}$$
$$= 0.008718 \text{ kg } H_2O/\text{kg air}$$

Psychrometric cycles

Heating and cooling processes in air-conditioning equipment can be represented on the psychrometric chart in the following manner.

Heating

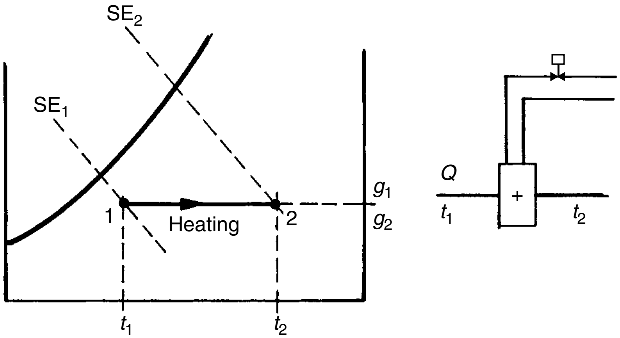
Heating is performed with a low- or high-pressure hot-water, possibly steam, finned pipe heating coil, electric resistance heater or fuel-fired heat exchanger as shown in Fig. 5.5. *SE* is the specific enthalpy, total heat content, of the air, as read from the chart.

Cooling

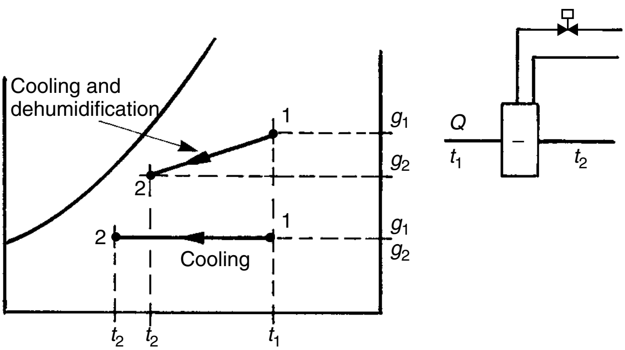
Cooling is performed by passing chilled water, brine solution or refrigerant through a finned pipe coil. When the coolant temperature is below the air dew-point, condensation occurs and the air will be dehumidified. Figure 5.6 shows the two possible cycles.

Mixing

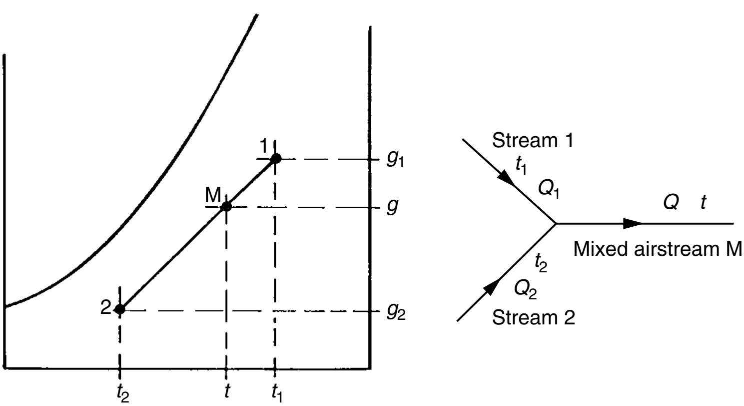
Mixing of two airstreams occurs when the fresh air intake joins the recirculated room air. The quantity of each air stream is regulated by multi-leaf dampers operated by electric or pneumatic motors under the direction of an automatic control system. Varying the intake of fresh air between the minimum amount during peak summer and winter conditions and 100% when free atmospheric cooling can be achieved during mild weather and summer evenings can result in minimizing the energy costs of the heating and refrigeration plants. Figure 5.7 shows the operational process.



5.5 Air heating depicted on a psychrometric chart.



5.6 Cooling and dehumidification.



5.7 Psychrometric cycle for the mixing of two airstreams.

The mass flow balance for the junction is:

mass flow of stream 1 + mass flow of stream 2 = mixed mass flow

or,

$$Q_1\rho_1 + Q_2 = Q\rho$$

The enthalpy balance, taking the specific heat capacity as constant, is:

$$Q_1t_1 + Q_2t_2 = Qt$$

Dividing through by Q gives,

$$\frac{Q_1}{Q}\,t_1 + \frac{Q_2}{Q}\,t_2 = t$$

The mixed air temperature and moisture content lie on the straight line connecting the two entry conditions and can be found by the volume flow rate proportions as indicated by the equation.

Humidification

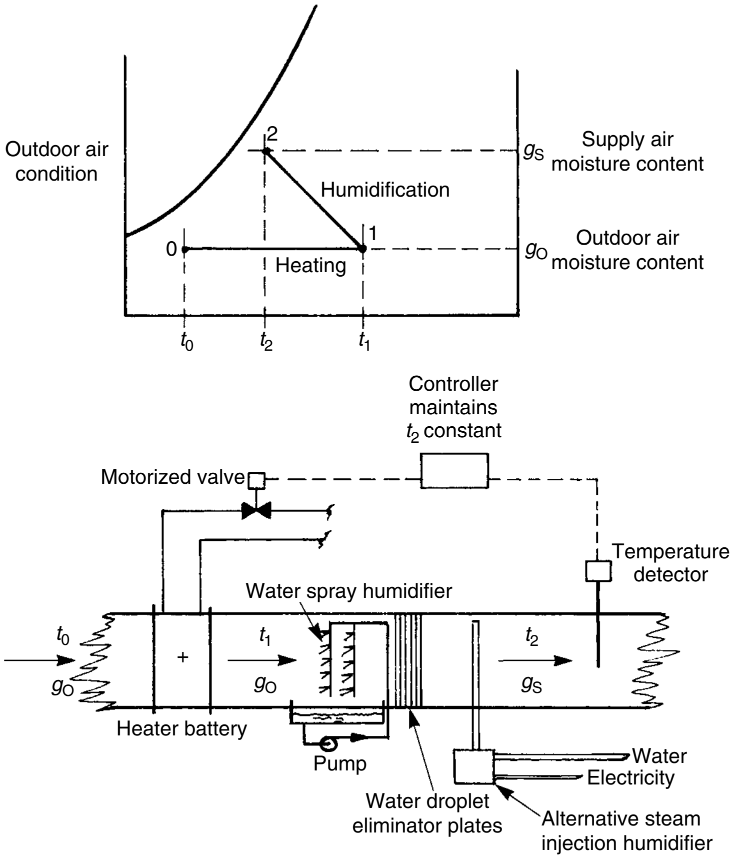
In winter, incoming fresh air with a low moisture content can be humidified by steam injection, banks of water sprays, evaporation from a heated water tank or a spinning disc atomizer. A preheater low-pressure hot-water coil usually precedes the humidifier to increase the water-holding capacity of the air. This also offsets the reduction in temperature of the air owing to transference of some of its sensible heat into latent energy, which is needed for the evaporation process. Figure 5.8 shows such an arrangement.

A temperature sensor in the humidified air is used as a dew-point control by modulating the preheater power to produce air at a consistent moisture content throughout the winter. For comfort air conditioning, the room percentage saturation will be 50% ± 10%. This permits a wide range of humidifier performance characteristics.

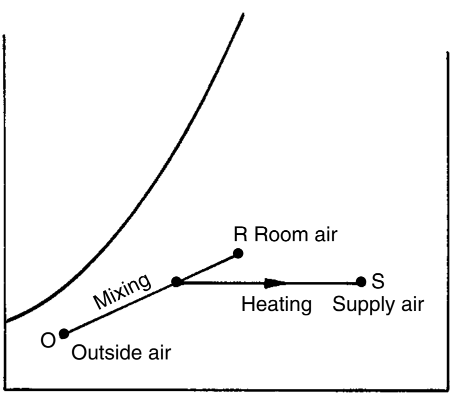
The humidification process often follows a line of constant wet-bulb temperature. The water spray temperature is varied to alter the slope of the line on the psychrometric chart. A complete psychrometric cycle for a single-duct system during winter operation is shown in Fig. 5.9. The preheating and humidification stages have been omitted, as close humidity control is deemed not to be needed in this case. A typical summer cycle is shown in Fig. 5.10.

Some reheating of the cooled and dehumidified air will be necessary because of practical limitations of cooling coil design. Part of the boiler plant remains operational during the summer. Reheating can be avoided by using a cooling coil bypass which mixes air M and air C to produce the correct supply condition. Heating and refrigeration plant capacities are found from the enthalpy changes and specific volume, read from the chart, and the air volume flow rate:

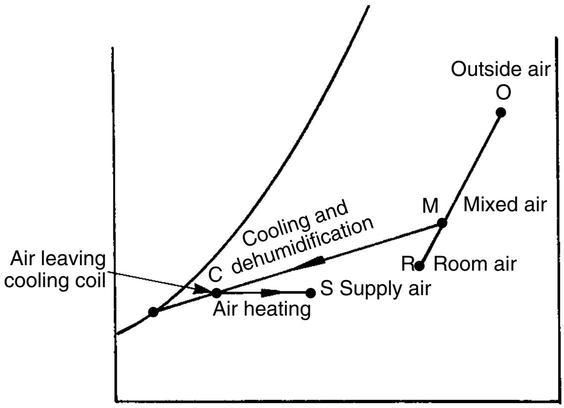
$$\text{heat transfer rate} = Q\,\frac{\text{m}^3}{\text{s}} \times \frac{\text{kg}}{v_\text{s}\,\text{m}^3} \times (SE_1 - SE_2)\,\frac{\text{kJ}}{\text{kg}} \times \frac{\text{kWs}}{\text{kJ}}$$



5.8 Preheating and humidification.



5.9 Winter psychrometric cycle for a single-duct system.



5.10 Summer psychrometric cycle for a single-duct system.

EXAMPLE 5.7

Outside air at −5°C d.b., 80% saturation enters a preheater coil and leaves at 24°C d.b. The air volume flow rate is 6.5 m^3/s. Find (a) the outdoor air wet-bulb temperature and specific volume, (b) the heated air moisture content and percentage saturation, and (c) the heating coil power.

From the CIBSE psychrometric chart:

(a) −5.9°C and 0.7615 m^3/kg;
(b) 0.00198 kg H_2O/kg air and 10%;
(c) SE_2 at 24°C d.b. and 0.00198 kg H_2O/kg is 29.0 kJ/kg
SE_1 at −5°C d.b. and 0.00198 kg H_2O/kg is −0.073 kJ/kg

$$\text{Heater duty} = 6.5\,\frac{\text{m}^3}{\text{s}} \times \frac{\text{kg}}{0.7615\ \text{m}^3} \times [29 - (-0.073)]\,\frac{\text{kJ}}{\text{kg}} \times \frac{\text{kWs}}{\text{kJ}}$$

$$= 248.2\ \text{kW}$$

EXAMPLE 5.8

A cooling coil has water passing through it at a mean temperature of 10°C, an air flow of 10.25 m^3/s air enters the coil at 28°C d.b., 23°C w.b. and leaves at 15°C d.b. Find the leaving air wet-bulb temperature and percentage saturation. Calculate the refrigeration capacity of the coil in equivalent tonnes refrigeration capacity, ton(r), when 1 ton(r) is equal to 3.527 kW(r).

Plot the cooling and dehumidification line on the psychrometric chart in the manner shown in Fig. 5.5 with a target point of 10°C on the saturation curve. The air leaves the cooling coil at 15°C d.b., 14.2°C w.b. and 91% saturation.

Specific enthalpy of the air entering the coil is 68 kJ/kg and is 40 kJ/kg on leaving. The specific volume of the air entering the coil is 0.874 m^3/kg.

$$\begin{aligned}\text{Refrigeration capacity} &= 10.25\ \frac{m^3}{s} \times \frac{kg}{0.874\ m^3} \times (68-40)\ \frac{kJ}{kg} \times \frac{kWs}{kJ}\\ &= 328.4\ kW(r)\\ &= 328.4\ kW(r) \times \frac{1\ ton(r)}{3.517\ kW(r)}\\ &= 93.4\ ton(r)\end{aligned}$$

Refrigeration capacity is commonly rated in ton(r) as this is the energy needed to freeze a US tonne of ice over a period of 24 h,

$$\begin{aligned}1TR &= \frac{2000\ lb}{24\ h} \times \frac{144\ Btu}{lb} \times \frac{1\ kWh}{3412\ Btu}\\ &= 3.517\ kW(r)\end{aligned}$$

EXAMPLE 5.9

A 6 m^3/s recirculated room air at 22°C d.b., 50% saturation is mixed with 1.5 m^3/s of incoming fresh air at 10°C d.b., 6°C w.b. Calculate the mixed air dry-bulb temperature. Plot the process on a psychrometric chart and find the mixed air moisture content.

$Q_1 = 6\ m^3/s, Q_2 = 1.5\ m^3/s, Q =$ supply air flow 7.5 m^3/s

Using the equation:

$$\begin{aligned}t &= \frac{Q_1}{Q}\ t_1 + \frac{Q_2}{Q}\ t_2\\ t &= \frac{6}{7.5} \times 22 + \frac{1.5}{7.5} \times 10\\ &= 19.6°C\end{aligned}$$

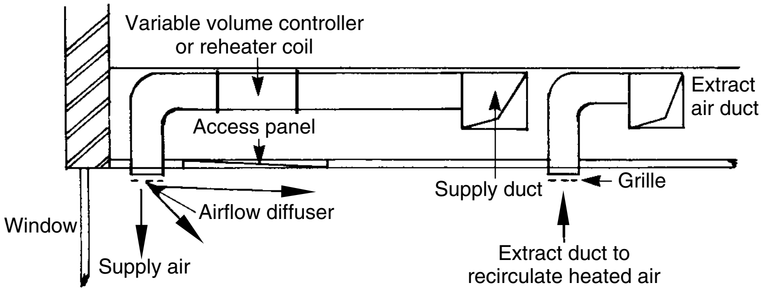
From the chart,

$g = 0.0076\ kg\ H_2O/kg\ air$

Air-conditioning systems

Single duct

The single-duct system (Fig. 5.11) is used for a large room such as an atrium, a banking hall, a swimming pool, or a lecture, entertainment or operating theatre. It can be applied to groups of rooms with a similar demand for air conditioning, such as offices facing the same side of the



5.11 Single-duct all-air installation in a false ceiling.

building. A terminal heater coil under the control of a temperature sensor within the room can be employed to provide individual room conditions.

A variable air volume (VAV) system has either an air volume control damper or a centrifugal fan in the terminal unit to control the quantity of air flowing into the room in response to signals from a room air temperature sensor. Air is sent to the terminal units at a constant temperature by the single-duct central plant, according to external weather conditions. A reducing demand for heating or cooling detected by the room sensor causes the damper to throttle the air supply or the fan to reduce speed until either the room temperature stabilizes or the minimum air flow setting is reached.

Air flow from the diffuser is often blown across the ceiling to avoid directing jets at the occupants. As a result of the Coanda effect the air stream forms a boundary layer along the ceiling and entrains room air to produce thorough mixing and temperature stabilization before it reaches the occupied part of the room. When the VAV unit reduces air flow, there may be insufficient velocity to maintain the boundary layer, and in summer cool air can dump or drop from the ceiling onto the occupants, resulting in complaints of cool draughts.

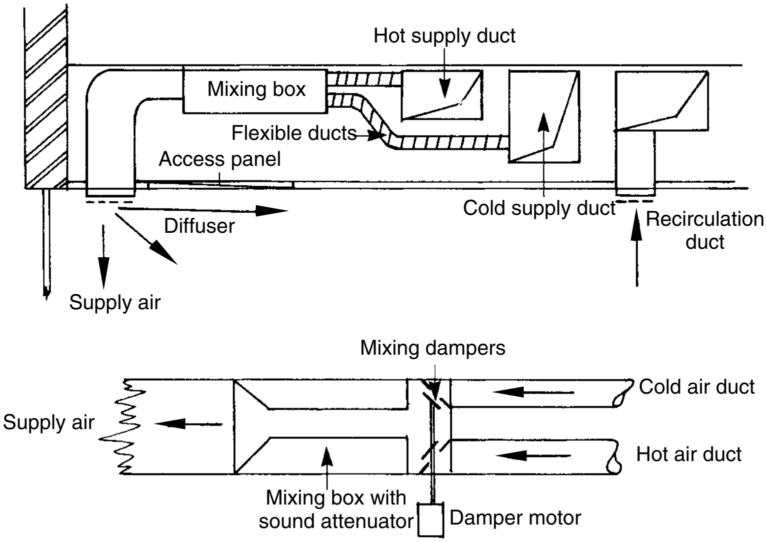
Dual duct

In order to provide for wide-ranging demands for heating and cooling in multi-room buildings, the dual-duct system, as shown in Fig. 5.12, is used. Air flow in the two supply ducts may, of necessity, be at a high velocity (10–20 m/s) to fit into service ducts of limited size. Air turbulence and fan noise are prevented from entering the conditioned room by an acoustic silencer.

In summer, the hot duct will be for mixed fresh and recirculated air, while the cold duct is for cooled and dehumidified air. The two streams are mixed in variable proportions by dampers controlled from a room air temperature detector. During winter, the cold duct will contain the untreated mixed air and the air in the hot duct will be raised in temperature in the plant room. The system is used for comfort air conditioning as it does not provide close humidity control. It reacts quickly to changes in demand for heating or cooling when, for example, there is a large influx of people or a rapid increase in solar gain.

Induction

Induction is a less costly alternative to the all-air single- and dual-duct systems for multi-room applications. The central air-conditioning plant handles only fresh air, perhaps only 25% of the supply air quantity for an equivalent single-duct system. All the humidity control, and also some



5.12 Dual-duct installation in a false ceiling and detail of the mixing box.

of the heating and cooling for the building, is achieved by conditioning the fresh air intake in the plant room.

Primary fresh air is injected through nozzles into the induction unit in each room. These units may be in the floor, in the ceiling void or under the windowsill. Because of the high-velocity jets, the local atmospheric pressure within the unit is lowered and air is induced into it from the room. The induced air may enter at three or four times the volume flow rate of primary air, and it flows through a finned pipe bank and dust filter before mixing with primary air and being supplied to the room.

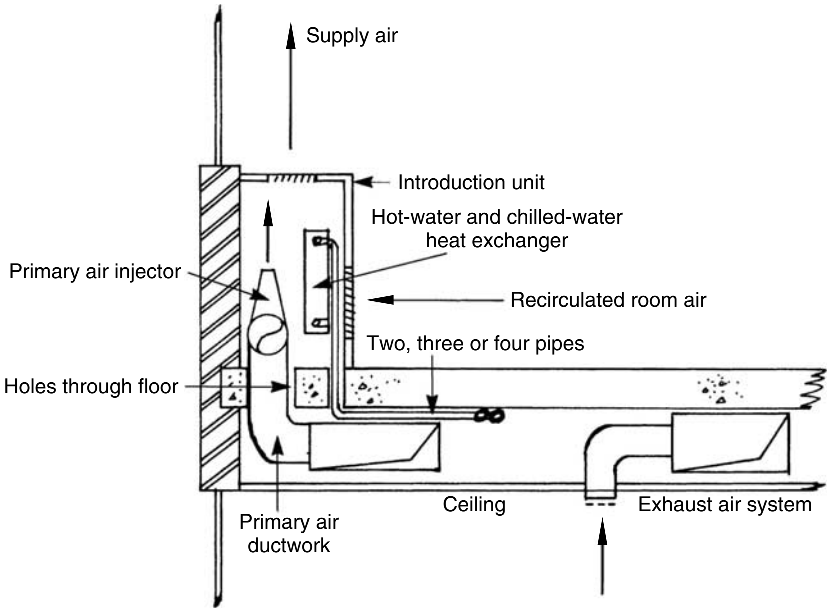
The secondary air flow rate can be manually adjusted using a damper. Either hot or chilled water is passed through the room coil depending upon demand. A two-, three- or four-pipe distribution system will be used. The two-pipe system requires a change-over date from heating to cooling plant operation, but a three-way valve can blend hot and chilled water from the three-pipe arrangement. The third alternative has separate hot- and chilled-water pipe coils and pipework.

The extract ductwork and fan removes 90% of the primary air supply and exhausts it to the atmosphere. All recirculation is kept within the room and this greatly reduces duct costs and service duct space requirements. Figure 5.13 shows a typical installation in an office.

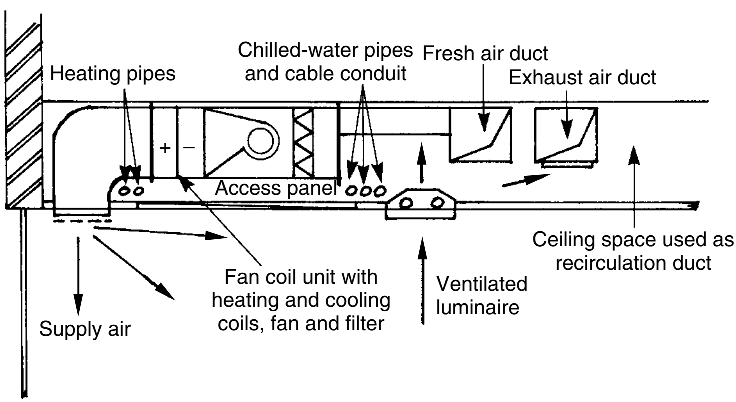
Fan coil units

Heating and cooling loads that prove to be too great for induction units can be dealt with by separate fan and coil units fitted into the false ceiling of each room or building module. Better air filtration can be achieved than with the induction unit. A removable access hatch below the unit is required to facilitate motor and filter maintenance.

Care is taken to match the fan-generated noise to the required acoustic environment. As with the other systems, the extracted air can be taken through ventilated luminaires to remove the lighting heat output at source and avoid overheating the room. The supply and extract



5.13 Induction unit installation in a multi-storey building.

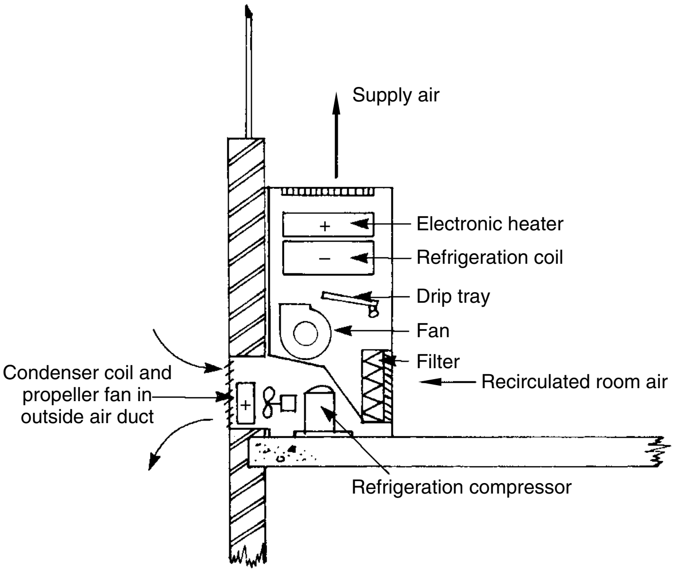


5.14 Fan coil unit installation in a false ceiling.

ducts only carry the fresh air. All recirculation is confined to the room. A typical layout is shown in Fig. 5.14.

Packaged unit

A packaged unit is a self-contained air-conditioning unit comprising a hermetically sealed refrigeration compressor, a refrigerant evaporator coil to cool room air, a hot-water or electric resistance heater battery, a filter, a water- or air-cooled refrigerant condenser and automatic controls. Packaged units can either be completely self-contained, needing only a supply of electricity, or piped to central heating and condenser cooling-water plant. Small units are fitted into an external wall



5.15 Packaged air-conditioning unit.

and have a change-over valve to reverse the refrigerant flow direction. This enables the unit to cool the internal air in summer and the external air in winter.

Heat rejected from the condenser is used to heat the internal environment in winter. In this mode of operation it is called a heat pump. A separate ventilation system may be needed. Compressor and fan noise levels are compared with the acceptable background acoustic environment. Maintenance requirements are filter cleaning, bearing lubrication and replacement of the compressor when it becomes too noisy or breaks down.

Split system units have a separate condenser installed outside the building. Two refrigerant pipes of small diameter connect the internal and external equipment boxes. This allows greater flexibility in siting the noise-producing compressor. Ducted models provide conditioning and ventilation and are often sited on flat roofs. Figure 5.15 shows a typical through-the-wall installation.

Vapour-compression refrigeration

The electrically driven vapour-compression refrigeration system is the principal type used. Its rival, the absorption cycle, burns gas to produce cooling but has a coefficient of performance of around 1, whereas vapour compression has a coefficient of performance in the range 2–5, and so it is cheaper to operate. Compressor types are as follows.

1. Single- or multi-cylinder reciprocating piston compressor with spring-loaded valves: domestic refrigerators and small air conditioners have hermetically sealed motor–compressor units which are sealed for their service period, that is, about 10 years.

   A condensing unit comprises a sealed compressor, a refrigerant condenser, a liquid receiver, pipework and controls. Refrigerant pipework is installed on site from this unit to a finned pipe forced-draught air-cooling coil in the air-conditioning system.

Large air-cooling plant comprises a multi-cylinder in-line or V-formation compressor, a shell and tube refrigerant to a water evaporator producing chilled water, and a shell and tube refrigerant to a water condenser where the refrigerant vapour is condensed into liquid and the heat given out is carried away by a water circuit to a cooling tower on the roof.

2. The centrifugal compressor is used in large chilled-water plants where the noise and vibration produced by the reciprocating type would be unacceptable. A centrifugal impeller of small diameter is driven through a step-up gearbox from a three-phase electric motor. The lack of vibration and compactness of the very high-speed compressor makes siting the plant easier.
3. The screw compressor has two meshed gears, which compress the refrigerant in the spaces between the helical screws. One gear is driven by an electric motor through a step-up gearbox. The compressor operates at high speed and has very low noise and vibration levels.

The operation of a vapour-compression refrigeration plant is shown in Fig. 5.16.

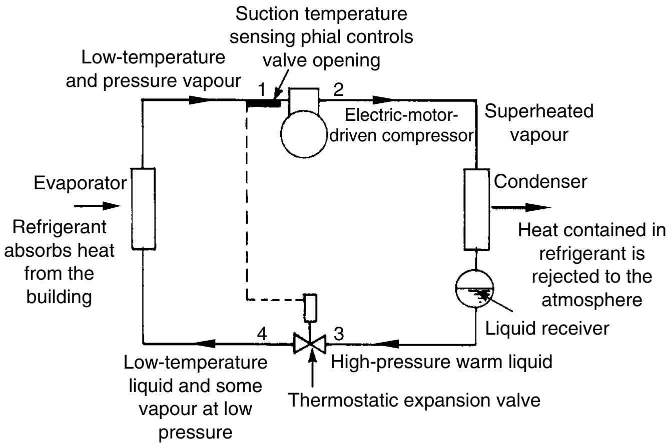
Refrigerants commonly used are non-toxic fluids with high latent heat. Refrigeration plant with a capacity of up to about 175 kW, and motor cars, uses refrigerant HFA134A (replaced R12, which is CCl_2F_2), which boils at −29.8°C in the atmosphere. In a typical system it will be evaporated at 5°C under a pressure of 3.6 bar and condensed at 40°C at 9.6 bar. Larger plant uses fluorinated hydrocarbon R22 ($CHClF_2$), which has a greater refrigerating effect per kilogram but is more expensive.

The coefficient of performance (COP) is an expression of cycle efficiency and is found from

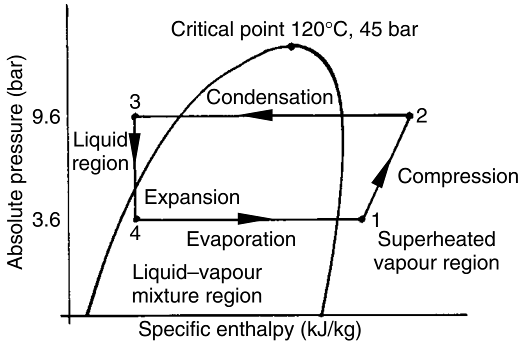
$$\text{COP} = \frac{\text{heat absorbed by refrigerant in the evaporator W}}{\text{power consumption by the compressor W}}$$

The vapour-compression cycle can be represented on a pressure–enthalpy diagram for the refrigerant as shown in Fig. 5.17. Referring to Figs 5.16 and 5.17, compression 1–2 raises the temperature of the refrigerant dry superheated vapour from about 20°C to 60°C, where it can then be cooled and condensed at a sufficiently high temperature to reject the excess heat from the building to the hot external environment.

It condenses at 40°C and collects in the liquid receiver. This warm high-pressure liquid passes through an uninsulated pipe so that it is subcooled to below its saturation temperature (about 20°C) at the expansion valve located alongside the evaporator.



5.16 Vapour-compression refrigeration system.



5.17 Pressure–enthalpy diagram for a refrigerant showing the vapour-compression cycle.

The pressure rise produced through the compressor is dissipated in friction through the fine orifice in the valve. Such a sudden pressure drop is almost an adiabatic thermodynamic process. This is represented by the vertical line 3–4 on the pressure–enthalpy diagram. Some heat loss from the valve body takes place so that 3–4 will be slightly curved. Condition 4 is at the lower pressure of the evaporation process, where the refrigerant temperature has dropped to 5°C. Some of the refrigerant liquid has flashed into vapour.

The liquid and flash vapour mixture flows through the evaporator, where it is completely boiled into vapour and is then given a small degree of superheat (path 4–1). It then enters the compressor as dry low-pressure superheated vapour at 20°C. A suction temperature-sensing phial controls the refrigerant flow rate by means of a liquid-filled bellows on the thermostatic expansion valve. This matches refrigerant flow to the refrigerating effect required by the air-conditioning system and ensures that liquid droplets are not carried into the compressor, where they could cause damage.

Large plant has refrigerant pressure controllers, which reduce compressor performance by unloading some cylinders. Lubricating oil contaminates the refrigerant leaving the compressor. This is separated gravitationally and returned to the crankcase.

The pressure–enthalpy diagram depicts the reverse Carnot cycle. In the other direction, the cycle is for an internal combustion engine. The theoretical ideal coefficient of performance is given by,

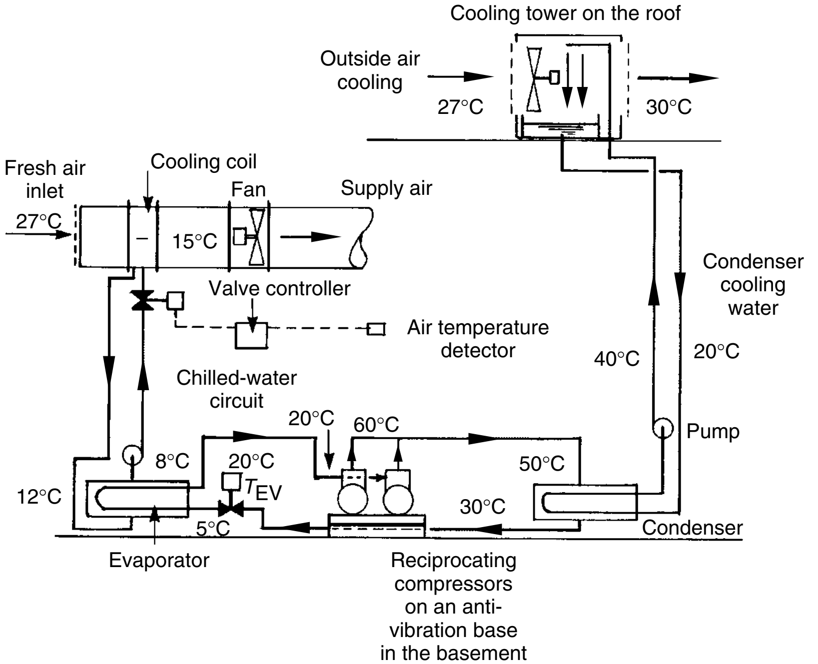
$$\text{Ideal COP} = \frac{T_1}{T_2 - T_1}$$

where T_1 is the evaporation absolute temperature (K) and T_2 is the condensation absolute temperature (K). With the temperatures previously used,

$$\text{Ideal COP} = \frac{273 + 5}{(273 + 40) - (273 + 5)}$$

$$= 7.94$$

Friction losses from fluid turbulence, heat transfers to the surroundings, and mechanical and electrical losses in the compressor all reduce this value to 2–4 in commercial equipment. The electricity consumption of fans and pumps adds to the running costs.



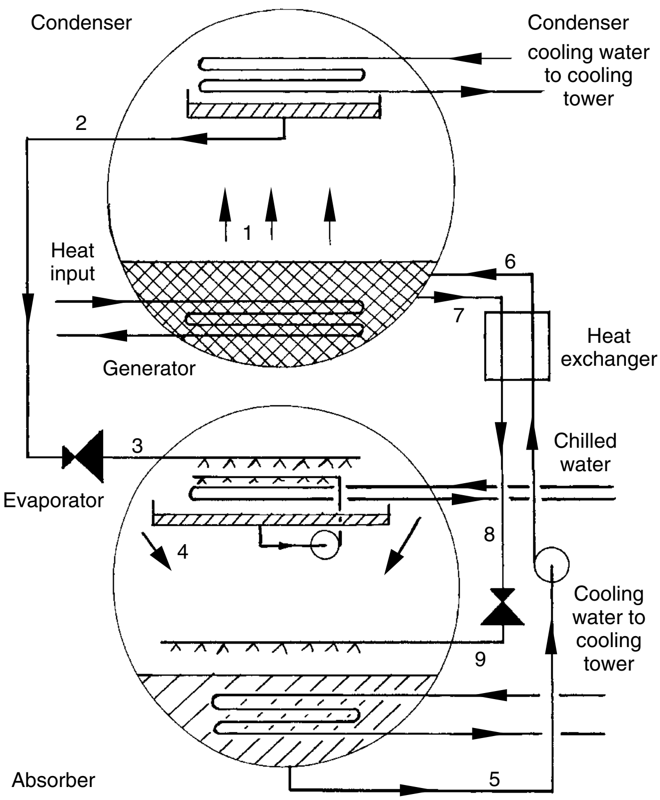
5.18 Refrigeration plant serving an air-conditioning system, showing typical fluid temperatures.

Figure 5.18 shows the installation of a chilled-water refrigeration plant serving one of the cooling coils in an air-conditioning system in a large building. Each air-handling system has filters, heaters, humidifiers and recirculation ducts appropriate to the design. There are several separate air-handling plants, each serving its own zone. Zones are decided by the similarity of demand for conditioning. The south-facing orientation has a cyclic requirement for cooling that is distinct from that of the other sides of a building. Internal areas require cooling throughout the year. These differing needs are often met by having separate zones for each area.

Absorption refrigeration cycle

An example of a two-drum absorption refrigeration cycle is shown in Fig. 5.19. The input heat source may be gas, steam or hot water from a district heating scheme, or rejected heat from a gas-turbine electricity-generating set.

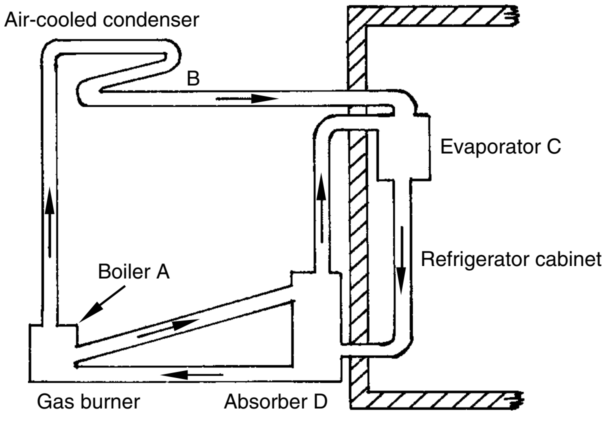
The generator (1) contains a concentrated solution of lithium bromide salt in water. Pure water is boiled off this solution and condenses on the cooling-water pipes, which are connected to an external cooling tower. The generator drum pressure is sub-atmospheric at 0.07 bar, with boiling and condensation taking place at 38°C. Water leaves the condenser (2), and then passes through an expansion valve (3), where its pressure and temperature are lowered to 0.01 bar and 7°C. It then completely evaporates while being sprayed over water pipes in the evaporator. These pipes are the chilled-water circuit at 6–10°C, which supplies the refrigeration for the air-conditioning cooling coils. Water vapour in the evaporator drum (4) is sucked into a weak lithium bromide solution by the salt's affinity for water. Latent heat given up by the water vapour as it condenses into the solution is removed from the cooling tower by cooling-water pipes. The weak solution (5)



5.19 Two-drum absorption refrigeration cycle.

is pumped back into the higher-pressure generator drum to complete the cycle. This pump is the only moving part of some systems. Concentrated salt solution (6) is passed down to the absorber via a heat exchanger and pressure-reducing valve to replace the salt removed. The production of chilled water is equivalent to about half the heat input to the generator.

The gas domestic refrigerator works on an absorption system using liquid evaporation to provide the cooling effect. Figure 5.20 shows the features of modern equipment. A solution of ammonia in water is heated in the boiler (A) by a small gas flame. This is the only energy input. Ammonia gas is driven off the solution and then condensed to a liquid in the air-cooled condenser (B) outside the refrigerator cabinet. The liquid ammonia then passes, with some hydrogen, into the evaporator (C) inside the refrigerator cabinet. This is the ice box. The ammonia completely evaporates while absorbing the heat from the cabinet. The two gases are then led into the absorber (D), where the ammonia is absorbed by a weak solution trickling down the absorber. The strong ammonia solution produced is then driven back into the boiler, while the hydrogen gas, which is not absorbed, passes to the evaporator. The weak solution trickling down the absorber is provided from the boiler. Both types of absorption refrigerator provide cooling from a source of heat, they have few or no moving parts and they only require low-power pumps. This makes the cycle suitable for solar power input. The equipment is vibrationless and very quiet in operation.



5.20 Gas-fired domestic absorption refrigeration system.

Ventilation rate measurement

Measurement of room ventilation rate may be required for research into the energy consumption of heated buildings or to carry out commissioning tests on warm-air heating, ventilation or air-conditioning systems. Three basic methods are available.

Smoke

Provided that smoke detectors and alarms are deactivated and suitable warning is given, the room can be filled with smoke and the ventilation system switched on. The time to clear the smoke is used to calculate the air change rate and volume flow rate. Smoke candles or an oil-burning generator are used.

Anemometer

The air velocity through each ventilation grille and any obvious gaps around doors and windows is measured using a suitable anemometer: a rotating vane for large grilles, and a thermistor, mini-vane or pitot-static tube for small airways. The air flow rates into and out of the room are calculated from the airway areas and the average air velocities through them.

Tracer gas

A non-toxic tracer gas (nitrous oxide or helium) is released into the room and thoroughly mixed with portable fans to fill the complete volume. Samples of room air are taken at intervals and passed through an analyser, which measures the concentration of tracer gas. The room air change rate is calculated from two known concentrations and the time interval between them. This technique can be used for naturally ventilated buildings and produces accurate results.

The katharometer measures air electrical conductivity and gives an output of percentage concentration of tracer in air. An infrared analyser uses a source of infrared radiation and passes it down two tubes to receiving photocells. One tube contains a reference gas and the other the sample of room air. The different gases absorb different amounts of radiation, and the variation in the signals from the photocells is calibrated as the percentage of tracer gas in the air.

Consider the injection of tracer gas into a room such that its concentration is C_r%. A stirring fan is used. Ventilation of the room is at the rate of N air changes per hour. The tracer gas concentration falls to C_τ% during time interval τ. The room air change rate can be found as follows:

$$N = \frac{1}{\tau} \ln\left(\frac{C_r}{C_\tau}\right)$$

so that,

$$N\tau = \ln\left(\frac{C_r}{C_\tau}\right)$$

and hence,

$$e^{N\tau} = C_r/C_\tau$$

Thus the concentration C_τ at time τ is given by:

$$C_\tau = C_r \times e^{-N\tau}$$

EXAMPLE 5.10

Nitrous oxide tracer gas is admitted into a building and mixed with the internal air to achieve a 8% concentration. After 45 min, the tracer gas concentration has fallen to 1.5%. Calculate the air change rate per hour.

$$N\,\frac{\text{air changes}}{\text{h}} = \frac{1}{\tau\ \text{h}} \times \ln\left(\frac{C_r}{C_\tau}\right)$$

Now,

$$\tau = 45\ \text{min} = 0.75\ \text{h}$$

$$C_r = 8\%$$

and,

$$C_\tau = 1.5\%$$

Hence,

$$N = \frac{1}{0.75} \ln\left(\frac{8}{1.5}\right)$$

$$= 1.33 \ln 5.33$$

$$= 2.23\ \text{air changes/h}$$

Materials for ventilation ductwork

The materials used for ventilation ductwork are listed in Table 5.3. Thin-gauge galvanized mild steel sheet ducts are the most popular because of their low cost. Prefabricated ducts and fittings allow rapid site erection. Circular, rectangular, flat or spirally wound circular ducts are generally used. Joints are pop-riveted and sealed with waterproof adhesive tape, hard-setting butyl bandage or heat-shrunk plastic sleeves. Large ducts have bolted angle-iron flanges, which also act as support brackets. Stiffening steel strips or tented sheets are used to reduce the drumming effect on flat duct sides caused by air turbulence. Bare metal is painted with metal oxide or zinc chromate paint. Ducts are thermally insulated with resin-bonded glass fibre boards or expanded polystyrene.

An air pressure consisting of the design operational pressure plus 250 pascal (Pa) (1 Pa = N/m^2) is applied after installation for test purposes. The maximum allowed leakage rate is 1% of the system design air flow rate and leaks must not be audible.

Chlorofluorocarbons

Chlorofluorocarbons (CFC) are numbered to represent the chemical combination. Those in common use are listed in Table 5.4.

When CFCs are released into the atmosphere as a result of leakage from refrigeration systems, the production of expanded foam, venting to the atmosphere during maintenance of refrigeration compressors, the use of aerosols, chemical cleaning or the destruction of refrigerators, they find their way to the upper atmosphere, where they are broken down by the action of ultraviolet solar radiation and chlorine is released. This degradation will continue for many years. Atmospheric ozone is destroyed by the chlorine, and it is reported that the resulting increase in the levels of ultraviolet radiation reaching the earth's surface will cause ecological damage as well as an increase in skin cancer.

Table 5.3 Ventilation ductwork materials.

Material	*Application*	*Jointing technique*
Galvanized mild steel sheet	All ductwork	Riveted slip joints, machine-formed snap-lock, flanged, butyl cement bandage, heat-shrunk sleeve
UPVC and polypropylene	Prefabricated systems for housing and toilet extract	Flanged, socket and spigot
Resin-bonded glass fibre	Low-velocity and domestic warm-air heating	Butt, sleeved, socket and spigot
Asbestos cement	Prefabricated circular and rectangular for flues and chemical exhausts	Socket and spigot
Flexible glass fibre, proofed fabric reinforced with galvanized spring wire helix	Short connections from a duct to a terminal unit	Jubilee clip, waterproof tape
Aluminium, copper, wired glass, stainless steel	Kitchen extract hoods, ornamental use	Flanges
Brick, concrete, timber, fibre- or plasterboard	Recirculation airways within suspended ceilings and floors, surfaces sealed against dust release	As appropriate

Table 5.4 Chlorinated fluorocarbons in common use.

Number	*Use*	*Ozone depletion potential*
R11	Foam insulation and furniture	1.0
R12	Refrigeration systems of all size	1.0
R22	Larger refrigeration plant	0.05
R113	Solvent cleaner	1.0
R502	Refrigeration	0.33
Halon	Fire extinguishers	1.0

In 1986, 100 000 tonnes of CFCs were manufactured, and the 1987 Montréal Protocol agreement was signed by most countries with the target of reducing production to zero by the year 2000. In the immediate time-scale, R22 has a sufficiently low ozone depletion potential (ODP) to be used until a suitable replacement is found. Current use of R12, which is the most common refrigerant fluid, particularly in small refrigeration plants and domestic refrigerators and freezers, is replaced by hydrogen fluorine alkaline HFA134A. CFC refrigerants are miscible with the mineral lubricating oil used in the compressor, but HFA134A is not and requires synthetic polyglycol alkaline (PGA) lubricant.

Good practice in the use of CFCs involves the following:

1. avoid leakage by correct use of pipe materials, engineering design, testing and maintenance procedures;
2. recover fluid from the system by using a vacuum pump;
3. return CFCs to the manufacturer;
4. employ reliable contractors;
5. use alternative chemicals.

R12 returned to the manufacturer is either cleaned and recycled with new R12 by bulk mixing or pyrolysed at 2500 K in a furnace, where it is completely destroyed and the flue gas is filtered as necessary.

Any replacement for commonly used CFCs must have the following properties:

1. no chlorine content;
2. ODP = 0;
3. non-flammable;
4. low toxicity;
5. similar boiling temperature and vapour pressure to R12;
6. miscible with compressor lubricant and easily separated;
7. thermodynamic and fluid flow properties compatible with currently installed refrigeration systems;
8. cost-effective;
9. no new environmental risks.

Sick building syndrome

Indoor environments may be made artificially close to the warm spring day that most people would like to inhabit, but it is not the genuine atmosphere and will be polluted with synthetic particles and vapours plus other contributory factors:

- tobacco smoke
- body odour
- deodorants
- vapours from cleaning fluids, photocopiers, paints and furnishings
- dust
- bacteria
- noise
- flickering lamps
- glare from artificial illumination and the sun
- carpets
- polyvinyl chloride (PVC)
- paper
- formaldehyde
- volatile chemicals
- bacteria grown in stagnant water in humidifiers
- treated water aerosols distributed from showers, washing facilities or fountains
- open-plan office
- too many people.

The air temperature, humidity and air movement, which will seem either stagnant or too draughty, can rarely please more than 95% of the occupants and frequently please a lot fewer. The total environmental loading upon the occupants may rise to an unacceptable level, which can be low for those who are hypersensitive, that is, physically and psychologically unable to fight off such a bombardment of additional foreign agents to the body.

Sick building syndrome, SBS, is epitomized by the occupants' exhibiting a pattern of lethargy, headaches, dry eyes, eye strain, aching muscles, upper respiratory infections, catarrh and aggravated breathing problems such as asthma, upon returning to their workplace after the weekend. Apparent causes are sealed windows, air conditioning, recirculated air, recirculating water humidifiers, high-density occupation, low negative ion content, smoking, air-ductwork corrosion, airborne micro-organisms, dust, and excrement from dust mites in carpets. SBS can be defined as a combination of health malfunctions that noticeably affect more than 5% of the building's population.

This means that there should be sick house syndrome as well. Perhaps there is, or perhaps we are more tolerant at home. Cases of formaldehyde vapour irritation after cavity insulation have been noted. The pattern of house occupation is different, and variation of climatic controls is easily achieved.

Relief can be gained by operating windows, temperature control, sun blinds, air grilles, by a brisk walk or by going outdoors to stimulate the body to sweat toxins out.

It has been easy to blame air conditioning for SBS, but the cause is more complex and has much to do with the standards we demand of our buildings, the psychological influence of having to go into the workplace at all and the total internal environment created. Naturally ventilated buildings often have a higher bacteria and dust count than air-conditioned buildings, which use filters and have sealed windows.

Outbreaks of Legionella diseases have been attributed to the growth of bacteria in stagnant water in wet cooling towers. These bacteria are distributed on air currents and breathed in by those susceptible to infection, sometimes with fatal results. Dry heat exchangers are preferred for discharging surplus building heat gains back into the external atmosphere but they are rather large. Adequate cleanliness and biocide dosing of recirculated cooling-tower water is mandatory.

The cure for SBS requires the following actions:

1. measure pollutants to identify causes;
2. remove recirculating water humidifiers from air-conditioning plant and replace only with direct steam or water injection;
3. allow individuals to have control over local air movement, direction and temperature;
4. clean recirculating water systems such as wet cooling towers and remaining humidifiers and treat them with biocides;
5. ensure that fresh air ventilation ductwork, filters, heating and cooling coils and grilles are internally and externally clean and fully functional;
6. inspect and clean air-conditioning systems and potential dust-traps regularly;
7. appraise the lighting system to maximize natural illumination and reduce glare.

Air temperature profile

The recommended upper limit for the room environmental temperature for normally occupied buildings is 27°C (CIBSE, 1986, Section A8). The external design air temperature for comfort in offices in London (CIBSE, 1986, Table A2.22) may be chosen as 29°C d.b., 20°C w.b. Higher outdoor air temperatures occur. The indoor limit of 27°C will be exceeded in naturally ventilated buildings in the UK and in warmer locations (Chadderton, 1997a, chapter 3). The elevation of indoor temperature above that of the outdoor air is caused by a combination of the infiltration of external air, solar radiation and indoor heat gains. In parts of the world where high solar radiation intensity and continuously higher external temperatures are common, for example, Sydney with 35°C d.b. and 24°C w.b., the necessity for controlled air circulation and refrigeration can be recognized.

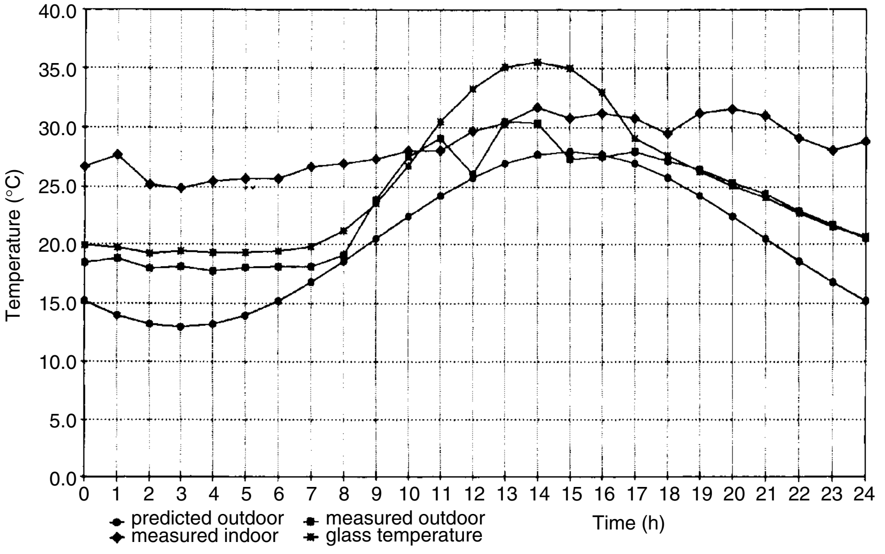
Environmental temperature is a combination of mean radiant and air temperatures (Chapter 1). Intense solar radiation through glazing during the summer can lead to the mean radiant temperature being higher than the air temperature. The temperature of the air in an office, factory or residence may need to be kept to an upper limit of, say, 26°C d.b. in order to limit the environmental temperature to 27°C. Such conditions are tolerable, but not comfortable, for sedentary work. Considerable discomfort is experienced when strenuous physical activity is conducted.

The indoor air temperature fluctuates through each 24-h period owing to the position of the sun relative to the building. South-facing rooms that have a large area of glazing are likely to be exposed to the greatest indoor air temperatures. Figure 5.21 shows the variation of outdoor air, indoor air, window glass and predicted outdoor air temperatures for a south-facing office in Southampton on Sunday 27 June 1993. The windows and doors remained closed throughout the weekend. The office had only natural ventilation, no mechanical cooling, open light grey slatted venetian blinds, and had been used normally for the preceding week. The exterior wall had a 70% glazed area.

The general profile of the outdoor air temperature t_{ao} that is expected can be calculated from a sine wave (Jones, 1985, p. 113):

$$t_{ao} = t_{max} - \frac{t_{max} - t_{min}}{2} \times \left[1 - \sin\frac{\theta\pi - 9\pi}{12}\right]$$

The 24-h clock time is θ hours: that is, a time between 0 and 24 h. The predicted outdoor air temperature curve has been calculated for maximum and minimum values, t_{max} and t_{min}, of 28°C d.b. and 13°C d.b. on an hourly basis for 24 h. This corresponds to the conditions after a week of warm sunny weather in June 1993 in Southampton. This has been a common occurrence since 1990. A thermocouple temperature logger, similar to that in Figure 1.3, measured the



5.21 Temperature profiles: south-facing office, Sunday 27 June 1993.

outdoor air, indoor air and the internal surface temperature of the outer pane of the double-glazed window, hourly. Figure 5.21 shows that the measured outdoor air temperature follows the general shape of the predicted sine wave. The thermocouple that was adhering to the glass showed a combination of two factors: first, that the air temperature in the cavity between the panes of double glazing rose to 35°C; second, that the glass absorbed some of the incident solar radiation and was raised in temperature. The internal room air temperature was measured in a shaded location at just above desk height. The room air temperature remained between 25°C d.b. and 31°C d.b. During normal use, the same office produced an internal air temperature of 25°C d.b. when the outdoor air temperature peaked at 27°C d.b.

While such an example does not prove conclusively that all south-facing rooms in the UK need to be air conditioned for human thermal comfort, it does give some evidence to strengthen the argument in favour of mechanical cooling. Working in air temperatures that move above 24°C d.b. in naturally ventilated spaces that have significant solar radiation can be noticeably uncomfortable. Whether the performance of human productivity or effectiveness becomes impaired is arguable. Low-cost cooling systems can be designed that make use of cool parts of a building to lower the temperature of the areas that are exposed to solar radiation. Heat pump systems, mechanical ventilation and evaporative water-cooling towers can be used to limit room air temperatures, without the need to involve high-cost refrigeration equipment.

EXAMPLE 5.11

A south-facing office in Basingstoke has natural ventilation and a large area of glazing. The maximum and minimum outdoor air temperatures are expected to be 26°C d.b. and 12°C d.b. on a summer day. Calculate the outdoor air temperature that is expected at 1600 h. Find the indoor air temperature that will be generated if solar radiation heat gains raise the indoor air by 1.5°C from that of the outdoor air. Comment upon the thermal comfort conditions that are provided for the office and make recommendations.

$\theta = 16$ h for the time of 1600 h

$$t_{ao} = t_{max} - \frac{t_{max} - t_{min}}{2} \times \left(1 - \sin\frac{\theta\pi - 9\pi}{12}\right)$$

$$= 26 - \frac{26 - 12}{2} \times \left(1 - \sin\frac{16\pi - 9\pi}{12}\right)$$

$$= 26 - 7 \times (1 - \sin 1.833)$$

The 1.833 is in radians and not degrees. Switch on the radians mode of the calculator then press the SIN X key to find the answer of sin 1.833 = 0.966. Alternatively, in degree mode, multiply 1.833 by 360 and then divide the answer by (2π). This produces an angle of 105°. Press the SIN key and find:

$\sin 105 = 0.966.$

There are 2π radians in 360°.

$$t_{ao} = 26 - 7 \times (1 - 0.966)$$

$$= 25.8°\text{C d.b.}$$

$$\text{indoor air temperature } t_{ai} = 25.8 + 1.5°\text{C d.b.}$$

$$= 27.3°\text{C d.b.}$$

The calculated indoor air temperature exceeds that recommended. While this may prove be acceptable for reasonable thermal comfort, there is solar radiation and possible glare during the afternoon in summer. External solar shading or interior blinds are recommended if seating cannot be relocated away from direct solar glare. Sedentary office workers would benefit from measures to increase the throughput of cooler air from the north side of the building or by means of a mechanical cooling system.

Questions

1. A banking ball is cooled in summer by an air-conditioning system that provides an air flow rate of 5 m^3/s to remove sensible heat gains of 50 kW. Room air temperature is maintained at 23°C. Derive the formula for calculating the supply air temperature and find its value.
2. A room has a sensible heat gain of 10 kW and a supply air temperature of 10°C d.b. Find the supply air rate required to keep the room air down to 20°C d.b.
3. Figure 5.22 shows a west-facing window in a warm climate at a latitude of 35° south around midday. Explain how solar control is being achieved here and how and if it may be applied to commercial buildings in other latitudes.
4. Ten people occupy an office and each produces 50 W of latent heat. The supply air flow rate is 0.5 m^3/s and its temperature is 12°C d.b. If the room is to be maintained at 21°C d.b. and 50% saturation, calculate the supply air moisture content.
5. The cooling coil of a packaged air conditioner in a hotel bedroom has refrigerant in it at a temperature of 16°C. Room air enters the coil at 31°C d.b. and 40% saturation and leaves at 20°C d.b. at a rate of 0.5 m^3/s.

   (a) Is the room air dehumidified by the conditioner?
   (b) Find the room air wet-bulb temperature and specific volume.
   (c) Calculate the total cooling load in the room.

5.22 Shaded window.

6. A department store has 340 people in an area of 35 m × 25 m that is 4 m high. Smoking is permitted.
   (a) Calculate the fresh air quantity required to provide 12.5 l/s per person.
   If the air change rate is not to be less than 5 changes/h, find the following.
   (b) supply air quantity;
   (c) percentage fresh air in the supply duct;
   (d) extract air quantity if 85% of the supply air is to be mechanically withdrawn;
   (e) recirculated air quantity;
   (f) ducted exhaust air quantity.
7. Air enters an office through a 250 mm × 200 mm duct at a velocity of 5 m/s. The room dimensions are 5 m × 3 m × 3 m. Calculate the room air change rate.
8. Show two methods of allowing fresh air to enter a room where extract ventilation is by mechanical means and the incoming air is not to cause any draughts.
9. Discuss the relative merits of centrifugal and axial flow fans used in ventilation systems for occupied buildings.
10. Sketch and describe the arrangements for natural and mechanical ventilation of buildings. State two applications for each system.
11. Describe the operating principles of four different systems of air conditioning. State a suitable application for each.
12. State, with reasons, the appropriate combinations of natural and mechanical ventilation for the following: residence, city office block, basement boiler room, industrial kitchen, internal toilet accommodation, hospital operating theatre, entertainment theatre.
13. Explain, with the aid of sketches, how the external wind environment affects the internal thermal environment of a building.

14. A four-storey commercial building is to be mechanically ventilated. Air-handling plant is to be sited on the roof. Each floor has dimensions 20 m × 10 m × 3 m and is to have 6 air changes/h. Of the air supplied, 10% is allowed to exfiltrate naturally and the remainder is extracted to roof level. The supply and extract air ducts run vertically within a concrete service shaft and the limiting air velocity is 10 m/s. Estimate the dimensions required for the service shaft. Square ducts are to be used and there is to be at least 150 mm between the duct and any other surface.
15. List the procedure for the design of an air-conditioning system for an office block.
16. A lecture theatre has dimensions 15 m × 15 m × 4 m and at peak occupancy in summer has sensible heat gains of 30 kW and latent heat gains of 3 kW. Room and supply air temperatures are to be 23°C d.b. and 14°C d.b. respectively. Room air moisture content is to be maintained at 0.008 kg H_2O/kg air. Calculate the supply air volume flow rate, the room air change rate and the supply air moisture content.
17. To avoid draughts, a minimum supply air temperature of 30°C d.b. is needed for the heating and ventilation system serving a public room. The room has an air temperature of 21°C d.b. and a sensible heat loss of 18 kW. It is proposed to supply 2 m^3/s of air to the room. Calculate the supply air temperature that is required. If it is not suitable, recommend an alteration to meet the requirements.
18. Describe the operation of the vapour-compression refrigeration cycle and sketch a complete system employing chilled-water distribution to cooling coils in an air-conditioning system.
19. Discuss the uses of the absorption refrigeration cycle for refrigerators and air-conditioning systems.
20. Show how refrigeration systems can be used to pump heat from low-temperature sources, such as waste water, outdoor air arid solar collectors, to produce a usable heat transfer medium for heating or air-conditioning systems.
21. Measurements in a mechanically ventilated computer room showed that tracer gas concentration fell from 10% to 3% in 5 min. Calculate the air change rate.
22. A gymnasium of dimensions 20 m × 12 m × 4 m is to be mechanically ventilated. The maximum occupancy will be 100 people. The supply air for each person is to comprise 20 l/s of fresh air and 20 l/s of recirculated air. Allowing 10% natural exfiltration, calculate the room air change rate, the air flow rate in each duct and the dimensions of the square supply duct if the limiting air velocity is 8 m/s.
23. Where does sick building syndrome apply?

    1. Architectural design failures.
    2. Perception that exterior design of a building does not fit in successfully with existing local architecture.
    3. Interior of a building that looks to be designed by a sick mind.
    4. Polluted interior atmosphere.
    5. Poor quality external environment makes users of the building susceptible to airborne upper respiratory ailments and overall sickness.

24. Which is the reason to use ice thermal storage in a HVAC refrigeration system?

    1. Reduce water chiller plant room space requirement.
    2. Reduce number of water chillers needed.
    3. Reduce water chiller run time.
    4. Install smaller capacity refrigeration compressors.
    5. Reduce energy cost.

25. How can an off-peak ice-making chiller be more efficient to operate than a daytime water chiller?

    1. Greater temperature difference between evaporation and condensing temperatures.
    2. Lower outdoor night-time dry- and wet-bulb air temperatures.
    3. Reduced electrical tariff.
    4. Reduces peak hours electrical demand kW.
    5. It is not more energy-efficient.

26. Which of these can affect asthma sufferers?

    1. Excess of outside air ventilation.
    2. House dust mites and mould spores.
    3. Warm indoor air.
    4. Humid and warm indoor air.
    5. Matters other than those related to ventilation.

27. Which is the most efficient way of recovering energy from room air?

    1. Recirculation.
    2. Sensible heat recovery thermal wheel.
    3. Total heat recovery thermal wheel.
    4. Plate heat exchanger.
    5. Run-around pipe coils.

28. How does a run-around pipe coil system function?

    1. Closed pipe loop passes water by gravity circulation between heat source and sink locations.
    2. Outgoing air-duct water-cooled coil; closed cycle water pipework; warmed water pumped through incoming outdoor air-duct coil, recovering useful heat.
    3. Refrigerated evaporator coil in outgoing waste heat duct passes useful heat to condenser coil in the incoming air duct.
    4. Refrigeration system recovers waste heat in an outgoing air with a chilled-water coil in exhaust air duct.
    5. Cold-water feed pipe to domestic hot-water system preheated in an outdoor air coil in warm weather.

29. What does a chilled beam mean?

    1. Steel structural beam exposed in the occupied room and cooled by a supply air stream from a directional grille.
    2. Refrigerated pipe within a room.
    3. Chilled-water pipes alongside structural floor beams.
    4. Exposed steel beam at high level in a room having chilled-water pipes attached.
    5. Natural convector chilled-water finned pipe.

30. Which water temperature flows through a chilled beam?

    1. 6–12°C.
    2. 4–18°C.
    3. Below room air dew-point.
    4. Minimum of room air temperature minus 10°C.
    5. Above room air dew-point.

31. Why might an under floor air distribution system, UFAD, have benefits?

    1. Keeps feet cool.
    2. Quieter than ducts within ceiling.
    3. Supply air within the floor void cools concrete floor slab thermal mass.
    4. Keeps under floor power and communications cables cool.
    5. There are no benefits as it costs more.

32. How could a chilled-water cooling coil distribute bacteria into occupied air-conditioned rooms?

    1. It cannot, as air temperature remains too cool.
    2. It will not under normal operation.
    3. Condensate water trap between drain tray and sewer always maintains a water seal.
    4. Water seal in P-trap between drain tray and sewer may become dehydrated and allow sewer gases to pass into the air-handling unit and supply duct.
    5. It will not when adequately maintained in accordance with codes and standards.

33. How could a cooling-water tower become a health hazard?

    1. It cannot while adequately maintained.
    2. Very easily, bird droppings may create bacterial growth in cooling water immediately after monthly servicing work and inspection.
    3. Chemical dosing with biocide does not allow any cooling-tower water contamination.
    4. Cooling tower is outdoors and so is no more a health hazard than an ornamental fountain.
    5. Cooling-tower water is always too cool to support growth of bacteria, mould or algae.

34. What can be done to maintain the health and safety of the internal surfaces of ducted ventilation and air-conditioning systems?

    1. Replace aged air ducts.
    2. Increase air velocity to blow deposits out of ducts and terminal units outside of occupied hours.
    3. Change air filters regularly.
    4. Internal visual inspection, compressed air brushing, scraping and vacuum cleaning.
    5. Nothing more than maintaining air filters to keep air and ducts clean.

35. Where can sinusitis, asthma, pneumonia and skin dermatitis originate?

    1. Mould spores in warm humid uncleaned air and water building services systems.
    2. Contaminated outdoor air.
    3. Low air humidity.
    4. Contacting people with breathing infections.
    5. Warm humid air in crowded buildings or transportation.

36. When carbon dioxide level in occupied rooms is sensed for control of ventilation airflow, what is the maximum set point used, approximately, in parts per million, ppm.

    1. 100
    2. 700
    3. 250
    4. 1000
    5. 5000

37. When the coefficient of performance during heating, COP_H, of a vapour-compression refrigeration cycles is 3, which of these is the correct compressor power input to generate 750 kW of heating?

    1. 750 kW.
    2. 2250 kW.
    3. 100 kW.
    4. 250 kW.
    5. 75 kW.

38. When the coefficient of performance during cooling, COP_R, of a vapour-compression refrigeration cycles is 2.25, which of these is the correct compressor power input to generate 225 kW of cooling?

    1. 225 kW.
    2. 22.5 kW.
    3. 506 kW.
    4. 100 kW.
    5. 2.25 kW.

39. What does ventilating a building mean?

    1. Maintaining indoor air circulation.
    2. Exhausting room air to outdoors.
    3. Minimum provision of 4 air changes/h.
    4. Removal of moisture, odours and carbon dioxide from rooms.
    5. Provision of adequate outdoor air into each room.

40. How should conditioned supply air enter a room?

    1. Directed at the ceiling.
    2. Directed at walls.
    3. Should mix with room air outside the occupied room volume.
    4. Strike the floor in walkways and mix with room air.
    5. Diffuse imperceptibly with room air.

41. Which is a suitable design criterion for air conditioning?

    1. Some manual control over air movement preferred.
    2. Windows should always be openable.
    3. Manual adjustment of air-conditioning system must be avoided.
    4. Automatic comfort control essential for every occupant.
    5. Sealed windows avoided as they always generate discomfort.

42. Which is correct about air filters?

    1. Air filter air pressure drop reduces as dust load increases.
    2. Increasing dust load in a filter causes no reduction in air flow to the rooms.
    3. Air filtration at the air-handling unit completely stops atmospheric dust and dirt from entering the building.
    4. Increasing dust load in a filter reduces supply air flow rate.
    5. A dirty air filter has an air pressure drop of around ten times that of a clean filter.

43. Which is not correct for natural ventilation in the UK?

    1. Must generate at least 4 air changes/h.
    2. Often associated with low-energy buildings.
    3. Original means of ventilating pre-1950's traditional brick buildings.
    4. Always justifiable in this climate.
    5. Often only provides up to 3 air changes/h.

44. What is meant by hybrid ventilation?

    1. System has latest technology in computer control.
    2. Only works in tall buildings.
    3. Combines active control of natural ventilation with mechanical air movement systems.
    4. Unnatural combination of mechanical systems with manually operated ventilators.
    5. Combination of systems invented by Hyme Bridowski in 1935.

45. What drives the fan in a large air-handling unit?

    1. Diesel engine prime mover.
    2. Three-phase electric motor.
    3. Single-phase synchronous alternating current motor.
    4. 1000 V AC motor.
    5. 240 V AC motor.

46. Which is a small fan drive motor, such as in a FCU?

    1. DC variable-speed motor as they are lowest cost.
    2. 415 V AC motor if they require around 850 W power output.
    3. Three-phase for any size as this is the most energy-efficient type.
    4. 240 V, three-phase synchronous electric motor.
    5. 240 V, single-phase direct drive motor.

47. AHU chilled-water flow control is by:

    1. Modulating damper.
    2. Electronic control system.
    3. Modulating water flow valve.
    4. Manually set only once by the commissioning engineer.
    5. All valves remain fully open to maximize available cooling during hot weather.

48. An office 15.0 m × 7.0 m × 2.8 m has 11.0 air changes/h from air supplied through a duct where it flows at a velocity of 8.5 m/s. Which two answers are correct?

    1. Supply air flow rate is 1.20 m^3/s.
    2. Supply air flow rate is 750.0 l/s.
    3. Supply air flow rate is 0.9 m^3/s.
    4. Duct dimensions are 325 mm × 325 mm.
    5. Duct dimensions are 650 mm × 325 mm.

49. A retail shop 22.0 m × 6.5 m × 3.5 m has 7.5 air changes/h from air supplied through a duct where it flows at a velocity of 9.5 m/s. Which two answers are correct?

    1. Supply air flow rate is 0.085 m^3/s.
    2. Supply air flow rate is 1043 l/s.

3. Supply air flow rate is 10.4 m^3/s.
4. Duct dimensions are 335 mm × 335 mm.
5. Duct dimensions are 990 mm × 990 mm.

50. A conference hall 55.0 m × 27.0 m × 3.6 m has 15.0 air changes/h from air supplied through a duct where it flows at a velocity of 4.5 m/s. Which two answers are correct?

    1. Supply air flow rate is 22.275 m^3/s.
    2. Supply air flow rate is 5940 l/s.
    3. Supply air flow rate is 2.228 m^3/s.
    4. Duct dimensions are 1000 mm × 5000 mm.
    5. Duct dimensions are 2000 mm × 2475 mm.

51. Which of these statements on air-conditioning systems is correct? More than one answer is correct.

    1. Air-handling units are usually the largest item of plant.
    2. Air-handling units are always manufactured off-site and delivered in one piece to any building.
    3. Some air-handling units are large enough for a person to walk inside.
    4. Air-handling units are where the room supply air is conditioned.
    5. Air-handling units do not contain any moving parts.

52. Why are motorized dampers fitted into the outside air and return air intakes to the air-handling unit in a large air-conditioning system?

    1. Close of the air supply during a storm.
    2. Stop sucking dust into the building.
    3. Vary the winter and summer intake of outdoor air.
    4. Shut the air conditioning down at night.
    5. Fully open up during fire mode.

53. Identify which statement correctly describes the operation of the vapour-compression refrigeration cycle:

    1. A compressor pump drives liquid refrigerant around the system.
    2. Refrigerant condenses at 20°C to reject heat from the building.
    3. Refrigerant gas vaporizes at 30°C and at high pressure to absorb heat from the building.
    4. An expansion valve raises refrigerant gas pressure.
    5. Heat is absorbed from the building by vaporizing refrigerant at low pressure at around 5°C.

54. Which statement is correct?

    1. A cooling tower cannot be a source of infectious bacteria.
    2. The cooling tower rejects heat from the building to the outdoor atmosphere.
    3. Cooling towers are only operational during the summer.
    4. Cooling towers sprays mains water into the air.
    5. Cooling-tower water systems are occasionally dosed with biocide.

55. What does VRV mean?

    1. Variable refrigerant volume.
    2. Volume refrigerated valve.

3. Vacuum recycled vanadium.
4. Variable refrigeration value.
5. Valid refrigerant valence.

56. How is the coefficient of performance, COP, of a refrigeration system maximized?

    1. Discharging waste heat to the atmosphere at the highest temperature.
    2. Discharging waste heat to the atmosphere at the lowest temperature.
    3. Evaporating refrigerant at the lowest possible temperature.
    4. Evaporating refrigerant at the lowest possible temperature.
    5. Using the smallest possible temperature increase between evaporation and condensation of the refrigerant.

57. Which is correct about air pressurization of buildings?

    1. Supply and exhaust air quantities must be equal.
    2. Outdoor wind environment creates internal air pressurization.
    3. When exhaust air volume exceeds supply air quantity, building is pressurized.
    4. When exhaust air volume exceeds supply air quantity, building is depressurized.
    5. Supply air fans do not create building air pressurization.

58. Which are the two types of heat transfer taking place during ventilation of a building?

    1. Latent and radiant.
    2. Sensible and convection.
    3. Latent and conduction.
    4. Sensible and radiant.
    5. Sensible and latent.

59. Which does not correctly describe heat transfer?

    1. Sensible heat is removed from air when water droplets spray into warm air and vaporize.
    2. Latent heat transfer occurs when water is evaporated into steam vapour.
    3. Evaporative coolers and cooling towers rely on latent heat transfer to remove sensible heat from the water passing through.
    4. Evaporative coolers work less efficiently in warm humid climates.
    5. Cooling towers already have saturated air, so there is no latent heat transfer with the circulating water.

60. Why is a psychrometric chart used?

    1. Shows temperature profile through a wall.
    2. Calculates latent heat demand.
    3. Calculates sensible heat load on the building.
    4. Shows physical properties of humid air.
    5. Plots air dry-bulb temperature against atmospheric pressure.

61. Which is correct for sensible heating processes on a psychrometric chart?

    1. Curved line between two dry-bulb temperatures.
    2. Vertical straight line.
    3. Any line at 45° to the horizontal.
    4. Horizontal line.
    5. A line concentric with the dew-point curve.

62. Which of these is a sensible heating process line on a psychrometric chart?

    1. Straight line between two dry-bulb temperatures at constant specific enthalpy.
    2. Line between two dry-bulb temperatures at constant percentage saturation.
    3. Straight line between two dry-bulb temperatures at constant moisture content from right to left.
    4. Angled straight line between two dry-bulb temperatures from left to right.
    5. Straight line between two dry-bulb air temperatures at constant moisture content from left to right.

63. Which of these does not correctly describe a cooling process line on a psychrometric chart?

    1. Cannot be precisely drawn on the chart due to variation of air percentage saturation within the air spaces around a cooling and dehumidification coil.
    2. Only the end points of the line are known precisely.
    3. Line drawn represents overall picture of cooling process through the coil.
    4. Curved line downwards from right to left between two moisture contents.
    5. Straight line angled downwards between two pairs of coordinates from air dry-bulb temperature and moisture content.

64. Which of these describes the leaving air condition when warm humid air enters a chilled-water cooling coil?

    1. Higher moisture content.
    2. Higher specific enthalpy.
    3. Same moisture content.
    4. Lower dry-bulb air temperature and around 90% saturation.
    5. 100% saturated air at same moisture content.

65. Which correctly describes cooling processes on a psychrometric chart?

    1. Reduces percentage saturation.
    2. Reduces air wet-bulb temperature.
    3. Maintains air at constant specific enthalpy.
    4. Maintains constant air wet-bulb temperature.
    5. Does not change air specific volume.

66. Which does not correctly describe humidification processes on a psychrometric chart?

    1. Water sprays onto a chilled-water cooling coil.
    2. Steam injection provides better air cleanliness.
    3. Straight line moving away from 100% saturation curve.
    4. Straight line moving towards the 100% saturation curve.
    5. Adiabatic saturation line.

67. Which is correct about a VAV air-conditioning system?

    1. Setting a minimum supply air flow rate at each terminal unit avoids dumping cool air onto occupants.
    2. Always requires terminal reheat coil.
    3. Stands for vortices-activated valve.
    4. Stands for volume-activated variable flow system.
    5. One terminal unit serves two zone orientations.

68. Which is a correct description of the dual-duct air-conditioning system?

    1. Duplicated supply and return air ducts.
    2. A reduced cost design.
    3. Simultaneous heating and cooling to adjacent rooms.
    4. Not used in commercial office buildings.
    5. Appropriate for low-energy new buildings.

69. Which is a correct description of the induction unit air-conditioning system?

    1. Each room terminal unit has a secondary air circulation fan.
    2. Recirculation air is induced away from the air discharged to atmosphere by suction from the supply air fan.
    3. Recirculated room air is neither heated nor cooled.
    4. Each terminal induction unit has a 2-, 3- or 4-pipe heating and chilled-water distribution.
    5. Recirculated room air does not need filtration.

70. What does FCU air-conditioning system stand for?

    1. Full conditioning unit.
    2. Face console unit.
    3. Full compressor unit.
    4. Fan coil unit.
    5. Failed compressor unit.

71. Which is a correct description of the fan coil unit air-conditioning system?

    1. Terminal unit used in an induction system.
    2. An FCU is a small AHU.
    3. Anything having a fan.
    4. Room air conditioner with a fan.
    5. Electric heating coil with a supply air fan.

72. Which is appropriate for an FCU?

    1. Can be around the size of a suitcase.
    2. Does not always contain a fan.
    3. The unit that takes heated and cooled streams of air from different ducts, mixes them and supplies conditioned air into the zone.
    4. Potential direct replacement for an induction unit.
    5. Always large enough to walk around inside it.

73. Which of these applies to packaged room air-conditioning units?

    1. Always connected to a ducted air system.
    2. Always connected to a central chilled-water plant system.
    3. Each unit has a refrigeration compressor.
    4. Always very quiet operation.
    5. Power demand not exceeding 250 W.

74. Which is not correct for packaged room air-conditioning units?

    1. Small applications such as home single office and motel room.
    2. Stand-alone unit used for large computer server rooms.
    3. Silent and have no servicing requirement.

4. May be connected to the BMS.
5. Built-in controls.

75. Which applies to vapour-compression refrigeration?

    1. Refrigerant gas compressor may be multi-cylinder reciprocating piston or volute scroll.
    2. Refrigerant always remains as a gas.
    3. Refrigerant R12 is ozone friendly.
    4. Refrigerant R22 is in domestic refrigerators.
    5. Ammonia is not suitable as a refrigerant.

76. Which applies to vapour-compression refrigeration?

    1. Compressed air.
    2. Refrigerant vaporizes in the compressor.
    3. Screw compressor.
    4. Linear compressor.
    5. Refrigerant condenses at low pressure and temperature.

77. Which applies to the vapour-compression refrigeration cycle?

    1. Refrigerant liquid is pressurized by a centrifugal compressor.
    2. Refrigerant liquid warms the inside of the building.
    3. Reciprocating compressor increases refrigerant gas pressure.
    4. Refrigerant thermostatic expansion valve stops and starts the flow of refrigerant to the compressor.
    5. Refrigerant liquid evaporates fully at 25°C and 4 bar pressure in the evaporator.

78. What does COP of a refrigeration cooling system mean?

    1. Convective operated pressure system.
    2. Compressor operated performance.
    3. Ratio of heat absorbed by refrigerant divided by power consumption of the compressor.
    4. Number is always less than 1.0.
    5. Ratio of the heat discharged in the condenser to the input power to the compressor.

79. Which applies to the lubrication of refrigeration compressors?

    1. Reciprocating compressors produce oil carry-over into the refrigerant pipes.
    2. Reciprocating compressors do not require lubrication.
    3. Compressor lubricating oil never leaves the crankcase.
    4. Piston rings do not let crankcase oil pass.
    5. Refrigerant lubricates the compressor bearings.

80. What are refrigerants?

    1. Combustible hydrocarbons.
    2. Water.
    3. Hydrocarbon oil.
    4. Toxic.
    5. Fluorinated hydrocarbons.

81. Which correctly describes the refrigeration cycle?

    1. Thermostatic expansion valve regulates the rate of refrigerant flow into the evaporator to ensure superheated vapour enters the compressor.

2. Thermostatic expansion valve allows refrigerant liquid to expand.
3. Opening of the thermostatic expansion valve is controlled from a temperature sensor on the compressor discharge pipe.
4. Thermostatic expansion valve stops and starts the flow of refrigerant from a digital controller.
5. TEV is an evaporator isolating valve.

82. Which of these correctly describes a water-cooled refrigeration system?

    1. Cold vapour leaves the compressor and enters a finned tube heat exchanger with axial flow cooling fans.
    2. Low-pressure warm vapour condenses and rejects latent heat to the outside environment through a shell and tube heat exchanger.
    3. Refrigerant vapour condenses at 40°C in an air-cooled heat exchanger.
    4. Water-cooled condenser pump circulates water to a cooling tower.
    5. Refrigerant evaporator is a direct expansion cooling coil in an air-handling unit.

83. Which does a cooling tower do?

    1. Always remains completely clean as it is continuously washed with water circulation.
    2. Never polluted with airborne contamination.
    3. Operates without any energy input.
    4. Collects atmospheric dust, debris and bird droppings.
    5. Filters the condenser cooling water.

84. Which is a primary characteristic of a cooling tower?

    1. Quiet operation.
    2. Uses almost no water.
    3. Potential source of water-based Legionella bacteria for outdoor air.
    4. Compact unit usually installed within a chiller plant room.
    5. Functions equally well in any outdoor climate.

85. Which is a primary characteristic for absorption refrigeration?

    1. Absorbs heat from within the building whereas a vapour-compression system cools a water circulation system.
    2. Has an absorption compressor.
    3. Uses gas pressure to generate cooling.
    4. Requires a source of primary heat energy.
    5. Uses no electrical energy.

86. How is room ventilation rate measured?

    1. Impossible to measure something that cannot be seen.
    2. Can only be calculated from duct air flow rate measurement.
    3. Found from releasing a non-toxic tracer gas into the room and measuring its rate of decay with a katharometer.
    4. Measured quantity of tracer gas concentration in room remains constant when mechanical ventilation is switched off and measured with a thermo anemometer.
    5. Tracer gas concentration measured with a carbon dioxide sensor and falls in a straight line graph when mechanical ventilation is switched off.

87. Which is correct about commissioning air-duct systems?
    1. Air-duct systems do not need to be inspected during commissioning.
    2. All air ducts must be internally cleaned prior to commissioning.
    3. All air ducts must be internally inspected with remote-controlled lamps and cameras before use.
    4. Rough internal projections, rivets and metal cuttings are removed by the commissioning technician.
    5. Air-duct systems are sealed in sections and pressure tested for an air-tightness standard compliance.

88. Which is correct about noise in air-conditioning ducts?
    1. Ducts are mounted on springs to isolate vibration from the building structure.
    2. Fan and motor are solidly bolted to a concrete plant base to isolate noise and vibration.
    3. Noise from sources within the building cannot enter air ducts and transfer elsewhere.
    4. Fans have a flexible air-tight fabric connection with air-conditioning ducts to stop transmission of vibration.
    5. Noise created in one room cannot travel through an air conditioning-duct and enter another room.

89. Which is not correct about chlorinated fluorocarbons?
    1. R22 commonly used in large refrigeration systems such as chilled-water plant.
    2. Contained within sealed refrigeration systems at below atmospheric pressure so never leaks into atmosphere.
    3. Used in halon fire extinguishing fluid.
    4. Non-toxic.
    5. Only exists at atmospheric pressure in gaseous form.

90. What happens to chlorinated fluorocarbons when released into the atmosphere?
    1. Dissolved by nearby water and rain.
    2. Harmlessly coexist in the atmosphere.
    3. Vaporized and dispersed by wind and rain.
    4. Degraded by ultraviolet solar radiation releasing chlorine into upper atmosphere that remains there for many years.
    5. Degraded by infrared solar radiation in the upper atmosphere releasing harmless oxides of chlorine, carbon and fluorine.

91. Which factor is included in SBS assessment?
    1. Poorly maintained mechanical equipment.
    2. Time of day.
    3. Shift work times.
    4. Overbearing management style over workforce.
    5. Illegal medication.

92. Which factor is not included in SBS assessment?
    1. Inadequately clean working environment.
    2. Staff not taking work breaks.
    3. Dust in workspace.
    4. Lighting glare.
    5. Tiredness.

93. Which symptoms manifest with sick building syndrome?

    1. Upper respiratory infections.
    2. High staff turnover not attributable to commercial factors.
    3. Dry eyes.
    4. Inability to retain staff in the building.
    5. Inability to retain tenants in the building.