Chapter 14
Indoor Air Quality

The greatest impact of air pollution on our daily life is not outdoor, but rather indoor because we spend most of our time in indoor environments or built environments. Air pollutants at the ground level atmosphere enter indoor environments through windows, doors, cracks, and mechanical systems.

Indoor air quality (IAQ) engineering becomes more and more important to modern society. And it is another relatively new topic related to air emissions and it cannot be missed in a book like this for completeness. This chapter starts with a brief introduction of indoor air quality (IAQ) and the sources and effects of indoor air pollution leading to the engineering approaches to the reduction of indoor air pollution. The approaches include source control, exhaust by hood, dilution by fresh air (ventilation and/or in-duct air cleaning), and indoor air cleaning by air recirculation.

14.1 Introduction

Indoor air quality (IAQ) is the quality of air in an indoor environment. The IAQ indicators include air temperature, air relative humidity, and concentrations of air pollutants. Temperature and relative humidity aim at primarily thermal comfort and the others mainly health.

Indoor air quality is important for various reasons. The first and most obvious one is that the majority of the people in a modern society spend most of their time in indoor environments. On average, people in the industrialized countries like USA spend 90 % or more of their lifetime indoors. Certain group of people, such as young children and seniors, may spend more time indoors than the regular working force. While the number may be lower in less developed nations, it could also be even higher in cold areas like Canada and Russia.

A few decades ago, however, few people realized that there are air pollutants in indoor environment, and that they have great negative impact on the health and performance of the occupants. Since the early 1970s, there has been a constant

increase in the awareness of indoor air pollution with the advances of research and education in related field.

Increasing attention to indoor air quality was largely attributed to the awareness of poor health associated with the poor indoor environment. According to the studies sponsored by the US EPA, concentrations of indoor air pollutants may be 2–5 times, and sometimes, over 100 times higher than their outdoor counterparts, and indoor air pollution is one of the top five environmental risks to public health, comfort, and performance [1]. The situation is believed to be worsening with reduced ventilation rate for energy conservation and increased use of chemically formulated household products, and emissions from electronic office products.

Indoor air pollution has a profound impact on the quality of life and the economy. The National Institute for Occupational Safety and Health (NIOSH) ranked occupational lung dysfunctions (including lung cancer, pneumoconioses, and occupational asthma) as the top occupational diseases and injuries. Lung dysfunction is undoubtedly related to the indoor air quality that people are exposed to. In some extreme case, indoor air pollutant could cause death.

Illnesses related to indoor air pollution can be classified into two categories:

- Sick building syndrome (SBS)
- Building related illness (BRI)

SBS is defined as the discomfort or sickness associated with poor indoor air quality without clear identification of the source substances. These symptoms could be, but are not limited to, irritation to eyes, noses, or throat, fatigue, and nausea. BRI is defined as a recognized disease caused by known agents that can be clinically identified. Examples of SRI symptoms include asthma, legionella, hypersensitivity, and humidifier fever. Obviously, the difference between the SBS and BRI is whether the causes of the sickness can be diagnosed clinically. Most of the time, the general public do not differentiate them, and they both are often referred to as sick building syndrome. Approximately one million buildings in the United States are sick buildings with 70 million occupants [2].

It is challenging to list all the sources of indoor air pollutants. Nonetheless, they can be grouped into outdoor and indoor sources. Outdoor air contaminants can enter indoor environments through HVAC systems, building envelopes, or even windows and doors. Indoor sources include combustion sources, such as smoking and cooking, operation of equipment, such as printers and computers, and biological sources, such as plants, animals, and human beings.

An incomplete list of sources of indoor air pollutants (excluding those with outdoor origins) is shown in Table 14.1. The list cannot be complete because of the nearly infinite contaminants in the air and multiple sources of each pollutants. Therefore, this table shall be used for guidance only.

Asbestos is a set of six naturally occurring silicate minerals used commercially for their desirable physical properties. They all have in common their eponymous asbestiform habit: long (roughly 1:20 aspect ratio), thin fibrous crystals.

The prolonged inhalation of asbestos fibers can cause serious illnesses including malignant lung cancer, mesothelioma, and asbestosis. Asbestosis is most closely

Table 14.1 Incomplete list of sources of indoor air pollutants

Contamination (Examples)	Typical sources
Asbestos	• Insulation materials • Ceiling and floor tiles
Combustion related contaminants	• Open fire cooking • Heating • Tobacco smoking • Incent • Candle
Formaldehyde	• Engineered board: Dry wall, interior-grade plywood, cabinetry and furniture, foam insulation, fabrics • Building materials: Adhesives, glues, furniture finishing, sealants, paints, stains, varnishes, wood preservatives, new carpet dyes and fibers, plastics
Biological contaminants (Allergen, mold, dust mite)	• Indoor plants • Animals • Human beings • Bedding for animals • Wet or damp materials
Radon	• Soil • Rock • Basement • Some building materials
Nanoaerosol	• Cooking • Printer • Photocopy machine • Nanospray
None-combustion particulates	• Dust • Hair • Skin
Volatile organic compounds (VOCs)	• Daily consumable products • Building materials

associated with the surface area rather than the diameters of inhaled asbestos; Mesothelioma is most closely associated with numbers of asbestos that are longer than 5 μm and thinner than 0.1 μm or so; lung cancer is most closely associated with those longer than about 10 μm and thicker than about 0.15 μm [3]. This does not mean other asbestos fibers can be considered nonhazardous because all asbestos can induce pathological responses and may contribute to the development of asbestos-related diseases [4].

The trade and use of asbestos have been restricted or banned in many jurisdictions. However, asbestos is not a health concern until it becomes airborne and enters the respiratory system. Care must be executed when renovating asbestos based old buildings.

Formaldehyde has been produced by catalytic oxidation of methanol for over two centuries [5]. It is widely used for the production of resins. Formaldehyde-based resins are used as adhesives in the manufacturing of construction materials, such as plywood, particle-board, and moulding materials. They are also used for furniture and other wood products. It is also a raw material for surface coatings, leather, rubber, and cement industries. Other indoor sources include stonewool and glasswool mats in insulating materials [6].

It is not clear how many people are occupationally exposed to formaldehyde worldwide. However, there are three types of occupations that are of high risk. The first is those working in the production of aqueous solutions of formaldehyde and their downstream chemical industries such as the synthesis of resins. The second group is related to its release from formaldehyde-based resins during the manufacture of wood products, textiles, synthetic vitreous insulation products, and plastics. Last but not the least, people are exposed to the pyrolysis or combustion of organic matter, e.g., in engine exhaust gases.

Indoor volatile organic compounds (VOCs) are emitted by many indoor materials. They can be generally grouped into two, being building materials and daily consumable products. Building materials include adhesives, glues, furniture finishing, sealants, paints, stains, varnishes, wood preservatives, new carpet dyes and fibers, and plastics. The daily consumable products include air fresheners, perfumes, hairsprays, hair gel, cleaning solvents, shoes and fabrics, automotive products, and contaminated water in sewage and sink.

Indoor air quality is a comprehensive topic that requires multiple disciplines, including, almost all branches in modern science and engineering. In this chapter, we focus on the engineering basics and technologies for indoor air quality control.

14.2 Threshold Limit Values

Threshold limit values (TLVs) refer to the upper limit of the concentrations of indoor air pollutants under which it is believed to be safe for all working occupants without impacting their health. The TLVs are established for different substances mainly for protecting the occupants' health with some tolerance of the discomfort such as irritation, narcosis, nuisance, or some stress. Examples of the health impairments that the TLVs are set against include compromise physiological function, adversely affect reproduce developmental processes, and shorten life expectancy.

There are two categories of TLVs. One is issued by governmental regulatory agencies and enforced by law; the other is published as recommended guidelines by scientific communities. For example, in the US, the former is defined by the Environmental Protection Agency (EPA) and the Occupational Safety and Health Agency (OSHA) of the United States; while the later can be set by America Conference of Governmental and Industrial Hygienists (ACGIH), American

Society of Heating, Ventilating, and Air-conditioning Engineering (ASHRAE) or even individual researchers.

The recommended TLVs are not the fine lines between safe and dangerous concentrations, nor are they a relative index of toxicity. Serious adverse health effects do not necessarily take place as a result of exposure to the indoor air pollutants above their TLVs. It is the best practice to maintain concentrations of all indoor air pollutants as low as practical.

According to the exposure period, TLVs can also be classified into the following three categories,

(1) Time-Weighted Average Threshold Limit Value (TLV-TWA),
(2) Short-Term Exposure Limit Threshold Limit Value (TLV-STEL), and
(3) Threshold Limit Value—Ceiling (TLV-C).

TLV–TWA is the time-weighted average concentration based on 8 h workday and a 40 h workweek, when all workers may be repeatedly exposed, day after day. The second one, STEL is defined as a 15 min TWA exposure that should not be exceeded at any time during a workday even if the 8 h TWA is within the TLV-TWA. TLV-STEL is the concentration to which it is believed that workers can be exposed continuously for a short period of time without suffering from (1) irritation, (2) chronic or irreversible tissue damage, or (3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue, or materially reduce work efficiency. STELs are recommended only where toxic effects have been reported from high short-term exposures in either humans or animals. There should be at least 60 min between successive exposures in this range. An averaging period other than 15 min may be recommended when this is warranted by observed biological effects.

Example TLVs of typical indoor air pollutants are listed in Table 14.2. More data can be found in literature such as [7] guidelines for indoor air quality. American Conference of Governmental Industrial Hygienists (ACGIH) also publishes annual threshold limit values for chemical substances and physical agents and biological exposure indices. Note that many air pollutants do not have all the three TLVs. It is important to observe whether any one of these types of TLVs is exceeded, a potential hazard from that contaminant is presumed to exist.

14.2.1 Normalized Air Contaminant Concentration

In most indoor environments, more than one air pollutants exist simultaneously. For example, carbon dioxide and airborne particles are always present in a typical working environment. When multiple pollutants exist, the effects of some on human health may be independent of others. In this case, TLVs for individual contaminants can be used to determine the indoor air quality. In general, however, the combined effects of multiple air pollutants on the health and comfort are considered greater

than the summation of all individual effects. In order to quantify the combined effect, normalized concentration, C_N, should be used [2]. Mathematically, it is,

$$C_N = \sum \frac{C_i}{TLV_i} \tag{14.1}$$

where C_i and TLV_i are the concentration and threshold limit value of the ith air pollutant of concern, respectively. The equation shows that the normalized contaminant concentration is a dimensionless parameter as long as the units in the nominator and denominator match for each air pollutant counted.

When C_N is less than unity, the air quality is considered acceptable. Otherwise, the air quality needs improvement by reducing the concentrations of one or multiple air pollutants. In reality, however, it is very challenging to enforce the normalized concentration, because there is always a chance that it is greater than unity, provided the list of the pollutants is long enough.

Example 14.1: Threshold limit value
In a welding shop, the measured concentrations of CO, CO_2 and welding fumes are 10, 1,500 ppmv and 3.5 mg/m^3, respectively, all below the recommended TLV-TWA. Is this working environment safe to the workers daily based on normalized concentration?

Solution
TLV-TWA can be found in Table 14.2. And they are listed as follows

Table 14.2 Threshold values of typical indoor air pollutants in work places

Particulate pollutant		TWA (mg/m^3, except for asbestos)	
Asbestos		0.1 fiber/ml	
Coal dust, anthracite		0.4	
Coal dust, bituminous		0.9	
Grain dust (Oat, wheat, barley)		4.0	
Graphite (non fiber)		2.0	
Iron oxide particles and fume, inhalable		5.0	
Lead		0.05	
Welding fumes		5.0	
Gases	Formula	TWA (ppmv)	STEL (ppmv)
Ammonia	NH$_3$	25	35
Carbon dioxide	CO$_2$	5,000	30,000
Carbon monoxide	CO	25	
Formaldehyde	HCHO	–	0.3
Hydrogen sulfide	H$_2$S	10	15
Methanol	CH$_3$OH	200	250
Ozone	O$_3$	0.05–0.2	–

Sources ACGIH [11], WHO [7]

Pollutant	TLV-TWA	Measured concentration	C_i/TLV_i
CO	25	10	0.40
CO_2	5,000	1500	0.30
Welding fumes	5	3.5	0.70

Then the normalized concentration can be calculated as follows

$$C_N = \sum \frac{C_i}{TLV_i} = 0.40 + 0.30 + 0.70 = 1.4 > 1.0$$

Since the $C_N > 1$, it is not safe for the workers to be there daily (8 h).

14.2.2 Clean Room

Clean room is a special indoor environment where the number of airborne particles is controlled to avoid contamination of the products. The cleanness of the clean room is specified by the International Standard Organization (ISO) Standard ISO 146441-1. The upper limit of particle number concentration (number/m^3) is defined as,

$$c_p^* = 10^N \left(\frac{0.1}{d_p^*}\right)^{2.08} \tag{14.2}$$

where c_p^* = upper limit of particle number concentration, number/m^3
N = the clean room class number (1, 2,..., 9)
d_p^* = threshold particle diameter in μm, and they are 0.1, 0.2, 0.3, 0.5, 1 and 5 μm.

According to ISO 146441-1, in a class N cleanroom, the number concentration of particles greater than d_p^* cannot exceed c_p^*. To help appreciate the cleanness of a cleanroom, one can compare it with a typical room in an office building, which is close to a Class 9 clean room [2].

Example 14.2: Cleanroom class calculation
An ISO 146441-1 Class 2 cleanroom is 3 m high with a total floor area of 100 m^2, what is the maximum amount of particles that are larger than 100 nm in diameter?

Solution Substitute

$$d_p^* = 100 \text{ nm} = 0.1 \text{ μm}; \quad N = 2$$

into Eq. (14.2), we get

$$c_p^* = 10^N \left(\frac{0.1}{d_p^*}\right)^{2.08} = 10^2 \left(\frac{0.1}{0.1}\right)^{2.08} = 100/m^3$$

Since the volume of the room is 300 m^3, the total number of particles larger than 100 nm in diameter cannot exceed 30,000 in total. That is an extremely clean room!

For the ease of practice, the cleanroom classes and their corresponding maximum particle number concentrations are computed using Eq. (14.2) and they are summarized in Table 14.3. In this table, the values are the maximum concentrations for the particles size or greater. The greater the class number, the higher allowable particle concentration can be.

For a given class, all limits for all particles sizes must be satisfied. For a Class 1 clean room, the concentration of particles greater than 0.2 μm should be 2 or less particle/m^3. Meanwhile, the particles $\geq$0.1 μm should not exceed 10 #/m^3.

Cleanroom is important to the quality of many industries, such as medical, manufacturing, and packaging. Cleanrooms were first developed for aerospace applications to manufacture and assemble satellites, missiles, and aerospace electronics. Most applications involve clean airspaces of large volumes with cleanliness levels of ISO Class 9 or cleaner. Recent advances in electronics industries continue to drive the design of cleanrooms. Most recently designed semiconductor clean rooms are ISO Class 5 or cleaner. In addition, preparation of pharmaceutical, biological, and medical products all require clean airspaces to control airborne bacteria and viruses to prevent contamination. Furthermore, some operating rooms in hospital may be classified as cleanrooms, but their primary function is to limit particular types of contamination rather than the quantity of particles.

Table 14.3 Cleanroom classes

ISO class number (N)	Maximum particle number concentration (#/m^3) for particle size $c_p^* = 10^N \left(\frac{0.1}{d_p}\right)^{2.08}$					
	0.1 μm	0.2 μm	0.3 μm	0.5 μm	1 μm	5 μm
ISO Class 1	10	2				
ISO Class 2	100	24	10	4		
ISO Class 3	1,000	237	102	35	8	
ISO Class 4	10,000	2,370	1,020	352	83	
ISO Class 5	100,000	23,700	10,200	3,520	832	29
ISO Class 6	1,000,000	237,000	102,000	35,200	8,320	293
ISO Class 7				352,000	83,200	2,930
ISO Class 8				3,520,000	832,000	29,300
ISO Class 9				35,200,000	8,320,000	293,000

14.3   IAQ Control by Ventilation/Dilution

Indoor air quality (IAQ) can be effectively controlled by HVAC systems. The acronym HVAC stands for heating, ventilation and air conditioning. A HVAC system provides treated outdoor air to the indoor environment and deliver it to the point of interest through ducts. As shown in Fig. 14.1, outdoor air enters the system through the air intake followed immediately the air cleaning devices, most likely a filter. As needed, air can be heated or cooled depending on the weather condition. Moisture can be added or removed as well. The air after filtration and conditioning is then distributed to multiple points in the building through supply air duct. After mixing within the rooms, air pollutants will be taken out of the room and become return air. Meanwhile, the temperature and humidity of the indoor air are adjusted to a comfort level. A portion of the return air, after treatment, is merged with the intake air in order to save energy. The rest will be discharged to the atmosphere through the exhaust.

14.3.1   Minimum Ventilation Rate

Ventilation controls the indoor air quality by bringing fresh air into an indoor environment to supply or reduce the heat and moisture and to dilute gaseous and
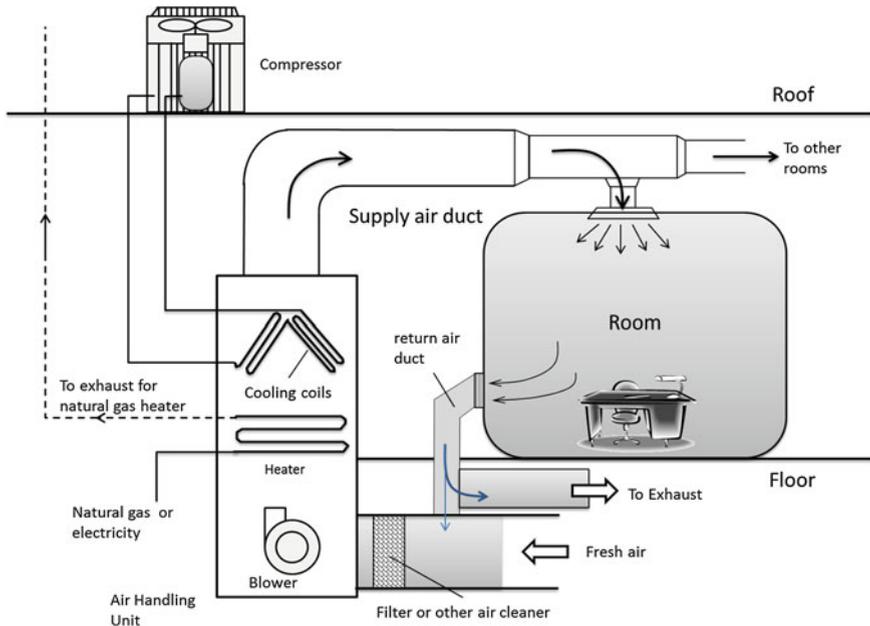

Fig. 14.1   HVAC system with internal air circulation and cleaning

particulate pollutants. In general, three types of variables are of concern, and can be controlled by ventilation system for an indoor environment:

- Temperature,
- Relative humidity, and
- Air pollutants.

Ideally a minimum ventilation rate must be maintained in order to control all these parameters at desired levels for an indoor environment with minimum energy consumption. However, practically the minimum ventilation rates of many buildings are based on the temperature control to reduce energy consumption. In some special buildings such as an animal holding room in a cold climate, ventilation may be based on relative humidity control. Air pollution levels are controlled by ventilation in very few indoor environments such as a welding workshop, which may be near the working station.

As a starting point of the analysis, consider a control volume, where temperature, relative humidity, and air pollutant levels are uniform. This assumption is acceptable if the control volume is small enough or the error is acceptable. This control volume could be an entire room or a zone within. When the control volume is a room, the air within is assumed completely mixed. Admittedly, this is a bold assumption, but it has been widely used in guiding the HVAC industry.

As shown in Fig. 14.2, intake supply air enters the room at a volumetric flow rate of air Q_s. The volume of the pace is V. The total enthalpy, moisture content, and pollutant concentration are denoted as h_s, w_s, and c_s, respectively. In a real HVAC system there is also recirculating air that contains the air within the space of concern. It is herein considered part of the supply air, the property of which can be calculated. Air exits the room at a volumetric flow rate of air, Q_e, and the total enthalpy, moisture content, and pollutant concentration are h_e, w_e, and c_e, respectively. Within the room, the total sensible heat transfer rate is $\dot{q}$, the moisture

Fig. 14.2 Simplified heat and mass transfer model for a ventilated space
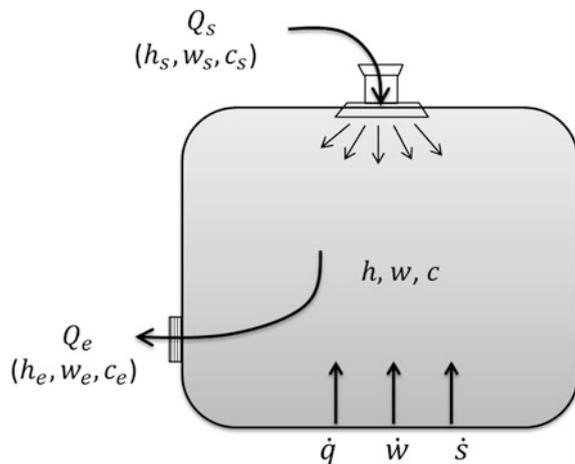
production rate is $\dot{w}$, and the pollutant production rate is $\dot{s}$. The densities of the air at the intake, indoor space, and the exit are denoted as ρ_s, ρ, and ρ_e, respectively. Since it is assumed that indoor air is completely mixed, the properties of the exhaust air are the same as those of the room air. For example,

$$v = v_e$$

$$h = h_e \qquad (14.3)$$

$$c = c_e$$

Then, mass balance for dry air leads to,

$$\frac{d}{dt}\left(\frac{V}{v}\right) = \frac{Q_s}{v_s} - \frac{Q_e}{v_e} \qquad (14.4)$$

where v is specific volume of moist air, which is defined herein as the volume of the moist air (dry air plus the water vapor) containing one unit of mass of "dry air" (m^3 air/kg dry air). As such the unit of both sides of the equation is kg dry air/s and that of Q's is m^3 air/s.

Equation (14.4) shows that the difference between the mass flow rates of the supply dry air and the mass flow rate of exhaust dry air equals the change of mass of dry air within the airspace. In this equation, *we use specific volume* of the air instead of the density because specific volume the of the air defines the volume of the mixture (dry air plus water vapor) containing one unit of mass of "dry air". The SI unit of specific volume of air is (m^3 air per kilogram of dry air). Note that it is different from the inverse of air density.

$$\frac{1}{v} \neq \rho \qquad (14.5)$$

The unit of air density is kg of air/m^3 air. Similarly, we can describe the energy balance based on the sensible heat as follows

$$\frac{d}{dt}\left(\frac{Vh}{v}\right) = \dot{q} + \frac{Q_s}{v_s}h_s - \frac{Q_e}{v_e}h_e \qquad (14.6)$$

where h = sensible heat for supply air and exhaust air (kJ/kg of *dry* air). It implies that the difference between the sensible heat of the supply air and that of the exhaust air equals is the total sensible heat production plus the change of sensible heat in the room air.

Similarly, the moisture mass balance and a specific pollutant mass balance can be described using the following two equations, respectively,

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{Vw}{v}\right) = \dot{w} + \frac{Q_s}{v_s}w_s - \frac{Q_e}{v_e}w_e. \tag{14.7}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(Vc) = \dot{s} + Q_s c_s - Q_e c_e. \tag{14.8}$$

where w is humidity ratio (kg of water vapor per kg of *dry* air), $\dot{w}$ is the water vapor production rate in kg/s, c is the pollutant concentration in air (kg of pollutant per m^3 of air), $\dot{s}$ is the mass production rate of the particulate pollutant in *kg/s*, Subscripts 's' and 'e' stand for supply and exhaust air, respectively.

If the unit of air pollutant concentration c is in ppmv, the unit conversion is necessary for accurate calculation of ventilation rate with a unit of $(\mathrm{m^3 air/s})$.

The total sensible heat transfer rate, $\dot{q}$ in Eq. (14.6), of the ventilated airspace is the sum of all heat loss or gain within the airspace, including the sensible heat production rate by occupants and indoor equipment (e.g. stove, lights), and the heat transfer through building envelope. $\dot{q}$ can be positive or negative, which indicates heating load or cooling load. Moisture production rate $\dot{w}$ in Eq. (14.7) depends on the status of the indoor sources, for example, exhale of human beings or the capacity of a working humidifier. For the occupants (human or animals) related data can be found in handbooks and/or standards such as those published by ASHRAE [8].

It is relatively challenging to determine the pollutant production rate, $\dot{s}$ in Eq. (14.8), which varies dramatically for different pollutants and sources. Among all the typical air pollutants in indoor environments, carbon dioxide can often be determined indirectly from the load of the occupants because the increase of CO_2 level in an indoor environment is mainly a metabolic product. From large scale statistical analyses, it has been determined that the carbon dioxide production rate of average human and animals is *1 m^3 of CO_2 per 24,600 kJ* of total heat production (THP) under normal indoor condition [8]. Converting to the mass production rate of carbon dioxide in kg/s leads to

$$\dot{s}_{CO_2} = \rho_{CO_2}\frac{THP}{24,600}. \tag{14.9}$$

where $\dot{s}_{CO_2}$ = the mass production rate of CO_2 (kg/s), ρ_{CO_2} = the density of carbon dioxide (1.83 kg/m^3 at 20 °C and 1 atm), *THP* = the total heat production of occupants (kJ/s). Note that the total heat includes the sensible heat and latent heat, whereas the heat production $\dot{q}$ in Eq. (14.6) only includes the sensible heat.

For steady state operation, the rate of mass of dry air entering (Q_s/v_s) equals to that exiting (Q_e/v_e) the room. Energywise, the total sensible heat contained in the supply air plus the net sensible heat transfer rate, must be equal to the total sensible

heat removed by the exhaust air. With this minimum requirement, the d/dt terms are zeros and aforementioned equations become, respectively,

$$\frac{d}{dt} = 0 \tag{14.10}$$

$$\frac{Q_s}{v_s} = \frac{Q_e}{v_e}. \tag{14.11}$$

$$\dot{q} + \frac{Q_s}{v_s} h_s = \frac{Q_e}{v_e} h_e. \tag{14.12}$$

$$\dot{w} + \frac{Q_s}{v_s} w_s = \frac{Q_e}{v_e} w_e. \tag{14.13}$$

$$\dot{s} + Q_s c_s = Q_e c_e. \tag{14.14}$$

Solving these equations leads to the relationship between volumetric ventilation rates and sensible heat balance (or temperature balance) control at steady state

$$\frac{\dot{q}}{h_e - h_s} = \frac{Q_s}{v_s} = \frac{Q_e}{v_e}. \tag{14.15}$$

By similar approaches, we can get the moisture balance ventilation requirement at steady state. Combination of the conservation of mass equation and the conservation of moisture equation gives volumetric ventilation rates for moisture (or relative humidity) balance control at steady state

$$\frac{\dot{w}}{w_e - w_s} = \frac{Q_s}{v_s} = \frac{Q_e}{v_e}. \tag{14.16}$$

Applying the mass balance to pollutant balance one can get the pollutant balance ventilation requirement. At steady state,

$$\dot{s} = Q_e c_e \left(1 - \frac{v_s c_s}{v_e c_e} \right) = Q_s c_s \left(\frac{v_e c_e}{v_s c_s} - 1 \right). \tag{14.17}$$

The analysis above defines different ventilation rates for the control of temperature, moisture, and a specific air pollutant.

There is a minimum ventilation rate that is required to maintain an acceptable indoor environmental condition (temperature, humidity, and a specific pollutant concentration). This minimum value must be the *greatest value* of the *six* ventilation rates for balances of sensible heat, moisture, and the given pollutant defined by Eqs. (14.15) to (14.17). Otherwise, at least one of the requirements cannot be met. In reality, the HVAC equipment of a building has an upper limit in capacity and there is a maximum ventilation rate. Therefore, we have to be careful in selecting the right HVAC equipment.

14.3.2 Psychrometric Chart

In order to calculate the ventilation rates above, we can no longer assume that air is always dry because moisture is a major concern in ventilation. The physical and thermodynamic properties of the moist air at sea level can be found in psychrometric chart. The ASHRAE-style psychrometric chart, shown Figure A.2, was pioneered by Willis Carrier in 1904 [9]. It depicts the parameters that are needed for our calculation above such as dry bulb temperature (T), humidity ratio (w), relative humidity (ϕ), specific sensible enthalpy (h), specific volume(v).

Example 14.3: Ventilation rate calculation
There are 20 people in a dinning room, each produces 200 W total heat. The carbon dioxide concentration in the supply air is 500 ppmv. Assume the supply air temperature is 15 °C and relative humidity 50 %. The room air is to be maintained at 22 °C and 60 % relative humidity. If the required maximum CO_2 concentration in the room is 1000 ppmv, estimate the minimum ventilation rate based on the CO_2 concentration.

Solution
Based on the supply air temperature of 15 °C and 50 % relative humidity we can get the specific volume of supply air using a psychrometric chart,

$$v_s = 0.822 \, \text{m}^3/\text{kg dry air}$$

The specific volume of exhaust air at 22 °C and 60 % relative humidity is

$$v_e = 0.855 \, \text{m}^3/\text{kg dry air}$$

The total heat production rate by 20 people in the dining room is,

$$THP = 20 \times 200 \, \text{W} = 4000 \, \text{W} \, or \, 4 \, \text{kJ/s}.$$

Then the mass production rate of CO_2 is estimated using Eq. (14.9)

$$\dot{s}_{CO_2} = \rho_{CO_2} \frac{THP}{24{,}600} = 1.83 \times \frac{4}{24{,}600} = 2.98 \times 10^{-4} (\text{kg/s})$$

Then the minimum ventilation rate fan is determined using Eq. (14.17)

$$\dot{s}_{CO_2} = Q_e c_e \left(1 - \frac{v_s c_s}{v_e c_e}\right) = Q_s c_s \left(\frac{v_e c_e}{v_s c_s} - 1\right)$$

Since $v_s < v_e$, the minimum ventilation rate should be calculated based on the exhaust air. However, we need to convert the unit of concentration c from ppmv to kg CO_2/m^3 air.

$$c_e = \frac{1{,}000\,\text{m}^3\,\text{CO}_2 \times 1.83\,\text{kg CO}_2/\text{m}^3\,\text{CO}_2}{10^6\,\text{m}^3\,\text{air}} = 1.83 \times 10^{-3}\,\text{kgCO}_2/\text{m}^3\text{air}$$

The exhaust ventilation rate is

$$Q_e = \frac{\dot{s}_{\text{CO}_2}}{c_e\left(1 - \frac{v_s c_s}{v_e c_e}\right)}$$

$$= \frac{2.98 \times 10^{-4}\,\text{kg CO}_2/\text{s}}{\left(\frac{1000\,\text{m}^3\,\text{CO}_2 \times 1.83\,\text{kg CO}_2/\text{m}^3\text{CO}_2}{10^6\,\text{m}^3\,\text{air}}\right)\left(1 - \frac{0.822}{0.855} \times \frac{500}{1000}\right)}$$

$$= 0.31\,\text{m}^3\,\text{air}/\text{s}$$

14.4 Indoor Air Cleaning Model

Similar to the air dispersion models for ambient air pollutants, we can develop models for indoor air dispersion. The simplest is box model as introduced in Sect. 11.1. We consider an indoor space of concern as a box, which seems to be more reasonable than being treated for an ambient environment. Most models assume the indoor air is uniform for the ease of analysis [10]. This is called compete mixing model. Zonal models are available too, but we will not discuss them in this book. Instead, we will introduce an indoor air cleaning model as follows [10].
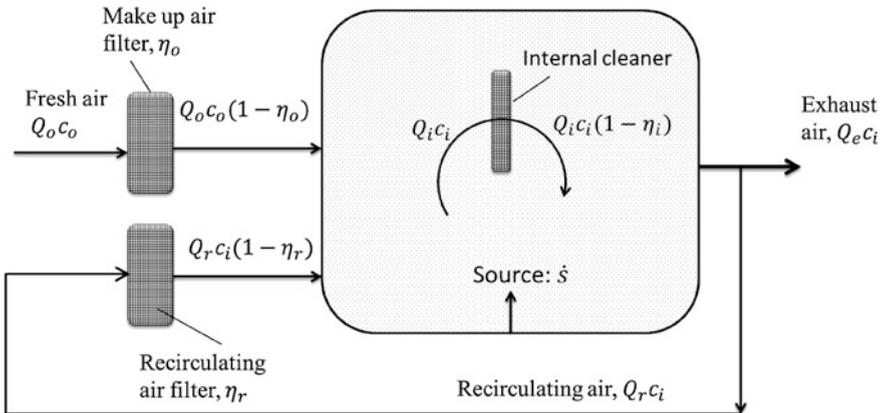

Fig. 14.3 Schematic diagram for the ventilation model with indoor air cleaning

Consider the schematic diagram in Fig. 14.3, where air flow through the building envelop is ignored. There is also an internal air cleaner to help clean the air. The mass balance of an air pollutant leads to

$$V\frac{dc_i}{dt} = [Q_oc_o(1 - \eta_o) + Q_rc_i(1 - \eta_r) + \dot{s}] - (Q_ec_i + Q_ic_i\eta_i) \tag{14.18}$$

where Q_o, Q_r, Q_i, and Q_e are the volumetric flow rates of fresh air, recirculating air, internal air cleaning, and exhaust air, respectively. V is the volume of the space of concern, and the total area within the space is A. The internal source rate with respect to the air pollutant is $\dot{s}$. At any moment the indoor air concentration is c_i and that in the fresh air is c_o. The last term $(Q_ec_i + Q_ic_i\eta_i)$ stands for the removal rate of the pollutant from the room air.

Since air pollutant is the main concern in this analysis, the change of moisture level in the air can be ignored; then the mass balance of air leads to

$$Q_o = Q_e \tag{14.19}$$

Then Eq. (14.18) becomes,

$$-V\frac{dc_i}{dt} = [Q_o - Q_r(1 - \eta_r) + Q_i\eta_i]c_i - [Q_oc_o(1 - \eta_o) + \dot{s}]. \tag{14.20}$$

If we assume only c_i and t are variables, then integration leads to

$$c_i = \left[c_{i0} - \frac{Q_oc_o(1 - \eta_o) + \dot{s}}{Q_o - Q_r(1 - \eta_r) + Q_i\eta_i}\right]\exp\left[-\frac{Q_o - Q_r(1 - \eta_r) + Q_i\eta_i}{V}t\right] \\ + \frac{Q_oc_o(1 - \eta_o) + \dot{s}}{Q_o - Q_r(1 - \eta_r) + Q_i\eta_i}. \tag{14.21}$$

It can be presented in a simple form as

$$c_i(t) = (c_{i0} - c_{i\infty})\exp\left(-\frac{t}{\tau}\right) + c_{i\infty} \tag{14.22}$$

where $C_i = C_{i0}$ at $t = 0$

$$c_{i\infty} = \frac{Q_oc_o(1 - \eta_o) + \dot{s}}{Q_o - Q_r(1 - \eta_r) + Q_i\eta_i} \tag{14.23}$$

$$\tau = \frac{V}{Q_o - Q_r(1 - \eta_r) + Q_i\eta_i} \tag{14.24}$$

In the above equation, $c_{i\infty}$ is the steady state concentration in the indoor space when $t \to \infty$, and τ can be considered as a time constant that is used to characterize the transient concentration in the space.

Example 14.4: Transient indoor air pollutant concentration

Consider a commercial kitchen with a volume of 80 m^3 where natural gas is used as a cooking fuel. Assume that after cooking the indoor fume concentration is 1,000 μg/m^3. The HVAC system works with a fresh air flow rate of 10 m^3/s and an internal recirculating air flow rate of 1/3 of the fresh air flow rate. Ignore the outdoor and indoor source other than cooking. The intake and recirculating filter efficiencies are both 90 % and the internal air cleaner has a flow rate of 1 m^3/s and an efficiency of 95 %. Plot the indoor fume concentration over time.

Solution

The problem is simplified by ignoring the outdoor and indoor sources other than cooking. After cooking, $\dot{s} = 0$, and $c_0 = 0$ in Eq. (14.23). This simplification leads to

$$c_{i\infty} = \frac{Q_o c_o (1 - \eta_o) + \dot{s}}{Q_o - Q_r (1 - \eta_r) + Q_i \eta_i} = 0$$

Then, Eq. (14.22) becomes
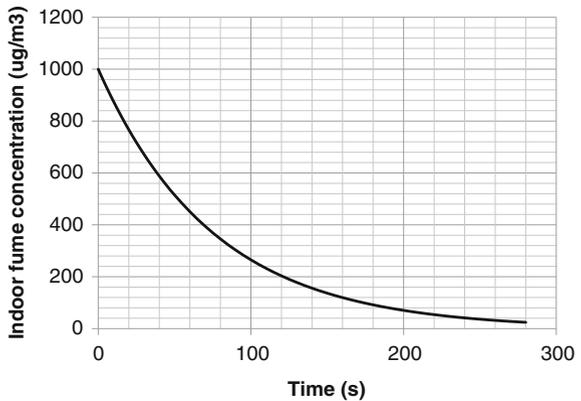
$$c_i(t) = c_{i0} \exp\left(-\frac{t}{\tau}\right)$$

where the time constant is calculated using Eq. (14.24):

$$\tau = \frac{V}{Q_o - Q_r(1 - \eta_r) + Q_i \eta_i} = \frac{800}{10 - \frac{10}{3}(1 - 0.9) + 1 \times 0.95} = 75.35(s)$$

Then we have

$$c_i(t) = 1000 \exp\left(-\frac{t}{75.35}\right) (\mu m/m^3)$$

Fig. 14.4 Calculated indoor air pollutant concentration over time

The plot over time is shown in Fig. 14.4.

In addition to the analytical models above, there are a variety of computation fluid dynamics (CFD) models that can be employed for the predication of indoor air quality and indoor air pollutant concentrations. Readers are recommended to learn these specialized models from other publications including those listed in the Reference section [10–20].

14.5 Practice Problems

1. Minimum ventilation requirement is the _____ value of the ventilation requirements based on sensible heat balance, moisture balance, and pollutant balance.

   a. maximum
   b. minimum
   c. average
   d. arbitrary

2. While you were cooking using gas burners in your kitchen, the measured concentrations of CO and CO_2 were 10 and 3500 ppmv, respectively. Is the air quality in your cooking environment acceptable based on these two pollutants only? (Given: the TLV's for CO and CO_2 are 25 and 5000 ppmv, respectively).

   a. Yes, because the CO concentration is below the corresponding TLV.
   b. No, because the CO_2 concentration is below the corresponding TLV.
   c. Yes, because the normalized TLV is below unit.
   d. No, because the normalized TLV is above unit.

3. In a Class 1 clean room, the measured total particle concentration is 9 particles/m^3 for particles larger than 0.1 μm and 3 particle/m^3 for particles larger than 0.2 μm. Does this cleanroom meet the Class 1 criteria?

4. In a large auditorium with a ventilation rate of 6 m^3/s, the carbon dioxide concentrations in the exhaust air and supply air are 800 and 400 ppmv, respectively. The specific volume of exhaust and supply air are 0.82 and 0.78 m^3/kg dry air, respectively. The building has an air volume of 8,000 m^3, and the air inside is assumed to be completely mixed. In a power failure, all exhaust fans are stopped, and there are 1000 people inside, each generates a heat of 200 W. Assume there is no air exchange between the inside and outside of the auditorium. How long it will take the CO_2 to reach the ceiling threshold value of 5,000 ppmv after the power failure.

5. There are 30 students in a classroom, each student produce 120 W of sensible heat and 100 g of water vapour per hour (or 70 W latent heat). The room air temperature is 20 °C and the specific volume and a relative humidity of 50 %.

The carbon dioxide concentration of the supply air is 400 ppmv. Supply air has a temperature of 10 °C a relative humidity of 70 %. Heat loss through the building shelter is 2 kW and heat gain from equipment and lights are 1.5 kW. It is desired to maintain an indoor carbon dioxide concentration of less than 800 ppmv, relative humidity of less than 50, and room temperature of 20 °C, what should the minimum ventilation be for the air?

6. Consider a tire center with a volume of 1,000 m^3 where tire continuously emit VOC at a rate of 100 μg/s. Assume at time zero, indoor VOC concentration is 1,000 μg/m^3. The HVAC system works at a fresh air flow rate of 100 m^3/min and an internal recirculating flow rate of 1/3 of that of the intake fresh air. An internal air cleaner has a flow rate of 0.1 m^3/s; ignore the outdoor source of VOC. The fresh air is free of VOC and recirculating activated carbon filter efficiency is the same as that of the internal air cleaner, which is 90 %. Plot the indoor VOC concentration over time.

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