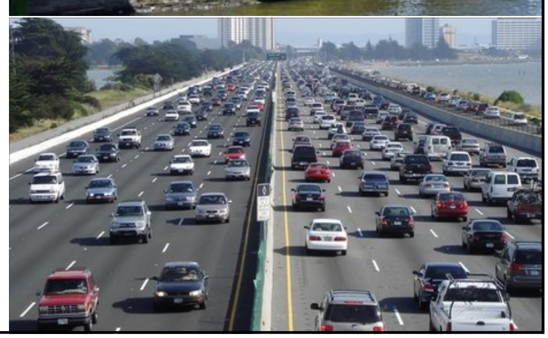
Chapter 14

Indoor Air Quality

Indoor Environment and Built Environment

- Buildings
- Transportations vehicles



Indoor Air Quality (IAQ)

Indoor air quality (IAQ) is the quality of air in an indoor environment.

- Thermal comfort
  - Temperature,
  - Relative Humidity
- Indoor Air Pollutant

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Why is IAQ Important?

- We spend over 90% of our time in indoor environments
- IAQ is much poorer than outdoor air
  - 2-100 times worse in USA/Canada
  - National Institute for Occupational Safety and Health (NIOSH) ranked Occupational lung dysfunctions (including lung cancer, pneumonoconioses, and occupational asthma) the top occupational diseases and injuries.
- 30% of newly constructed or remodeled facilities have IAQ problems. Illnesses related to indoor air pollution have been classified into two categories:
  - Sick building syndrome (SBS)
  - Building related illness (BRI)
- Indoor contaminants are responsible for half of all illnesses
- Liability issues

Illnesses related to indoor air pollution

- **SBS: Sick building syndrome**
  - SBS is defined as the discomfort or sickness associated with poor indoor air quality with clear identification of the source substances.
  - Examples: irritation to eyes, noses, or throat, fatigue, and nausea.
- **BRI: Building related illness**
  - BRI is defined as a recognized disease caused by known agents that can be clinically identified.
  - Examples: asthma, legionella, hypersensitivity, and humidifier fever.
- Approximately one million buildings in the United States are sick buildings with 70 million occupants.

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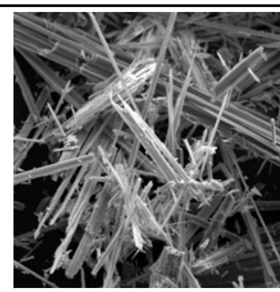
Indoor air pollutants

Asbestos



- Dust/Aerosol/PM
- Asbestos
- Combustion related contaminants
- Formaldehyde
- VOCs: Volatile Organic Compounds
- Bio-aerosol: Allergen, mold , dust mite
- Radon

Threshold Limit Values

- Threshold limit values (TLVs) refer to 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.
  1. Time-Weighted Average Threshold Limit Value (TLV-TWA)
     - Usually 8 hours 24 hours or Annual
  2. Short -Term Exposure Limit Threshold Limit Value - (TLV-STEL):
     - Say 15 minutes
  3. Threshold Limit Value - Ceiling (TLV-C):
     - At any instance

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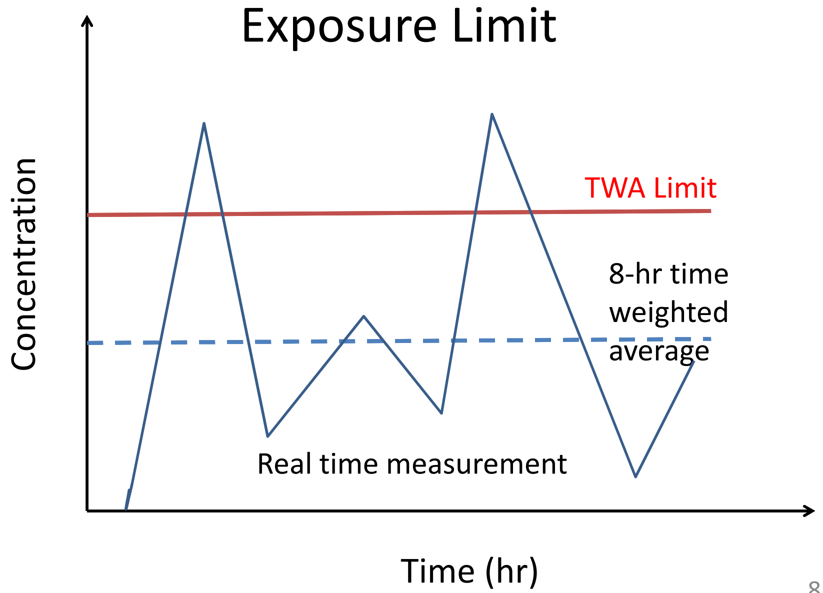
8-Hour Time-Weighted Average Exposure Limit



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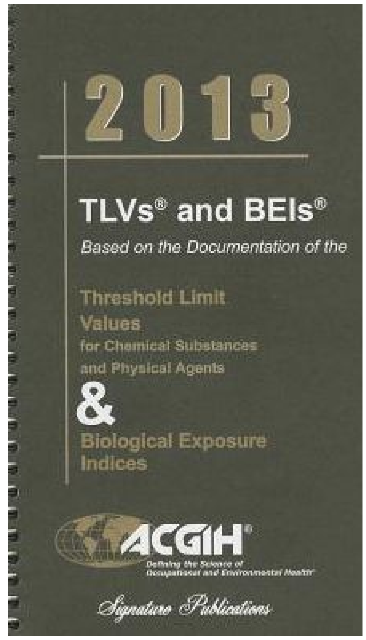
Exposure Limit Guidelines

- American Conference of Governmental Industrial Hygienists (ACGIH) also publishes
  - Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices.
  - Updated annually
- WHO (2010) guidelines for indoor air quality



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Threshold values of typical indoor air pollutants in work places

Pollutant	Formula	Odor	TWA	STEL
Gases (In ppmv unless stated otherwise)				
Ammonia	NH_3	Sharp pungent	25	35
Carbon dioxide	CO_2	None	5,000	30,000
Carbon monoxide	CO	None	25	
Formaldehyde	HCHO	Pungent	-	0.3
Hydrogen sulfide	H_2S	Rotten eggs nauseating	10	15
Methanol	CH_3OH	Alcohol	200	250
Ozone	O_3	Odorous	0.05-0.2	-
Particulates (Unit in mg/m^3 unless stated otherwise)				
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	

Normalized Air Contaminant Concentration

In order to quantify the effect of the combined effect, the normalized concentration

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

Measured concentrations (C_i)

Threshold limits (TLV_i)

C_N>1: Do something!

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Example 14.1

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

Solution

Air 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

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

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

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Clean room

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Clean room ISO 146441-1

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

- c_p^* =upper limit of particle number concentration, number/m^3
- N = the clean room class number
  - N=1, 2, ...9
- d_p^* = threshold particle diameter in μm,
  - d_p^* = 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^*.

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Example 14.2: Cleanroom class

- *An ISO 146441−1 Class 2 cleanroom is 3 meter heigh with a total area of 100 m², what is the maximum amount of particles that are greater than 100 nm?*
- *Solution:*

  Substitute $d_p^* = 100\ nm = 0.1\ \mu m; N = 2$

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

- *Since the volume of the room is 300 m³, the total number of particles larger than 100 nm in diameter cannot exceed 30,000 in total.*

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ISO Class Number (N)	Maximum particle number concentration (#/m³) for particle sizes					
	>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

IAQ Control

- **Source control**
  - Very important to IAQ
- **Ventilation**: Ventilation controls the indoor air quality by
  - bringing fresh air into an indoor environment
  - supply or reduce the heat and moisture and
  - dilute gaseous and particulate pollutants indoors.
- **IAQ control devices**
  - Indoor air cleaner
  - Indoor (de)humidifier

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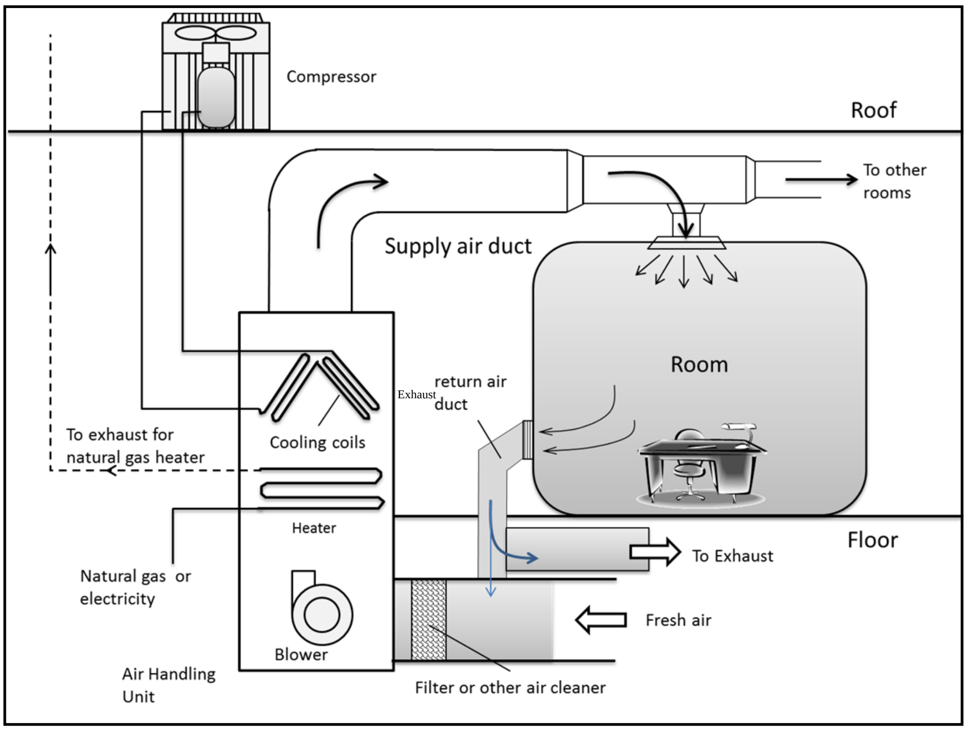
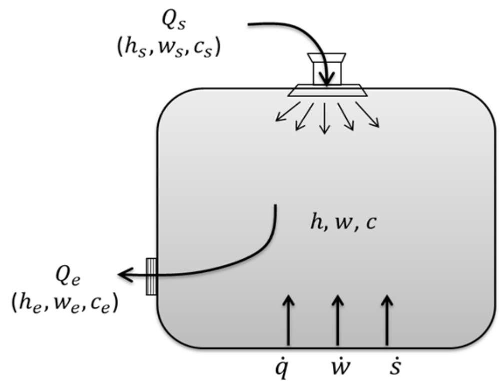


- In general, three types of variables are of concern and can be controlled by ventilation in an indoor environment:
  - temperature,
  - relative humidity, and
  - air pollutants.



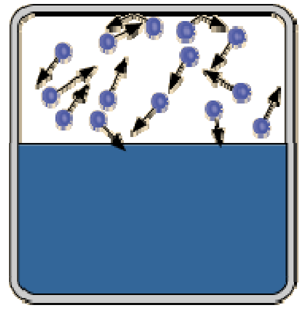
- Ideally a minimum ventilation rate must be maintained in order to control all these parameters at desired levels for an indoor environment.

- Practically many buildings minimum ventilation rates are based on the temperature control due to the energy concern.

Moist Air

- Moist Air=Dry air + Water vapor
- For air at certain pressure and temperature
- Water vapor pressure
  - Partial pressure of water vapor
- Saturated air

Dew Point



- The dew point is the temperature at which the water vapor in air (at constant pressure) condenses into liquid water at the same rate at which it evaporates.
- At temperatures below the dew point, water vapor condenses and leaves the air.
- The condensed water is called dew when it forms on a solid surface.

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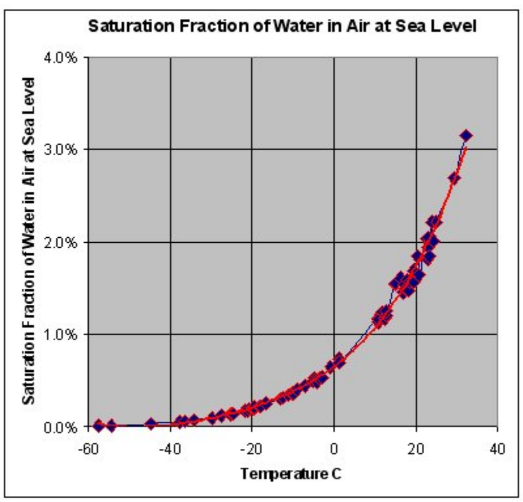

Saturated Fraction of Water Vapor by Mass

- The maximum saturation pressure of the water vapor in moist air varies with the temperature of the air vapor mixture

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Humidity

- **Absolute humidity:** the mass of water vapor per unit volume of moist air
  - Not useful for heat and mass transfer
- **Relative humidity** is the ratio of the partial pressure of water vapor in an air-water mixture to the saturated vapor pressure of water at a prescribed temperature.
  - The relative humidity of air depends on temperature and the pressure of the system of interest.

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How Relative Humidity Affects IAQ

- Too low, dry air, evaporation from surface (including your body)
  - Dry skin, dry eyes, dry throat…. Discomfort!
  - 50-60% most comfort
- Too high, condensation, mold

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Acceptable Temperature Ranges ASHRAE 62.1-2004

- Dry bulb at 30% relative humidity:
- Winter: 68.5 ºF – 76.0ºF (20.28 oC- 24.44 oC)
- Summer: 74.0ºF – 80.0ºF (23.33 oC-26.67 oC)

Minimum Ventilation Rate

- 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.

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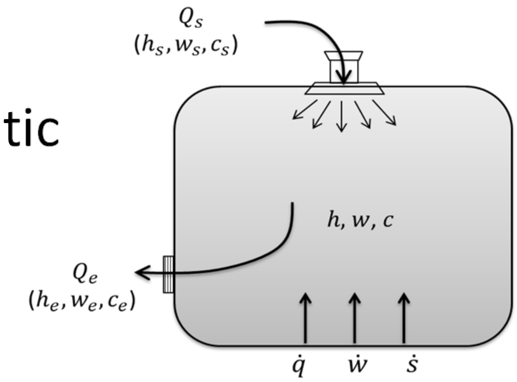
Model Schematic Diagram



Q= Volumetric flow rate; V= Volume of the pace
h =total enthalpy *w* =moisture content
c =pollutant concentration *s*= supply air *e*= exhaust air

- *dot* stands for generation rate
- Perfect mixing → the properties in the exhaust air are the same as in the room air. $v = v_e$; $h = h_e, c = c_e$

Mass balance for dry air

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

- 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".
- 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 the water vapor) containing one unit of mass of "dry air".

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the energy balance

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

- 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 to the total sensible heat production plus the change of sensible heat in the room air.
- The total sensible heat transfer rate, $\dot{q}$, of the ventilated airspace is the sum of all heat loss or gain through and 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. $\dot{q}$ cam be positive or negative, which are referred to as *heating load* or cooling load.

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Moisture mass balances

$$\frac{d}{dt}\left(\frac{Vw}{v}\right) = \dot{w} + \frac{Q_s}{v_s}w_s - \frac{Q_e}{v_e}w_e$$

where w = humidity ratio (kg of water vapor per kg of dry air, kg/kg).

Subscripts '*s*' and '*e*' stand for supply and exhaust air, respectively. $\dot{w}$ is the water vapor production rate in kg/s.

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Specific Pollutant Mass Balance

$$\frac{d}{dt}(Vc) = \dot{s} + Q_s c_s - Q_e c_e$$

- $\dot{s}$ is the mass production rate of the particulate pollutant in kg/s. In these two equations, the units of pollutant concentration should be (kg/m^3 air).
- In most engineering practice, the unit of gases is in ppmv Therefore, unit conversions are necessary for accurate calculation of ventilation rate with a unit of m^3 air/s
- $\dot{s}_{CO2} = \rho_{CO2} \frac{THP}{24{,}600}$

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CO_2 Production Rate

- From large scale statistical analyses, it has been determined that the carbon dioxide production rate of average human and animals is
- 1 liter of CO_2 ~24,600 J of total heat production (THP) under standard indoor conditions.
- Converting to the mass production rate of carbon dioxide in kg/s is

$$\dot{s}_{CO_2} = \rho_{CO_2} \frac{THP}{24600}$$

- ρ_{CO_2} =the density of carbon dioxide (1.83 kg/m^3 at 20 ^oC and 1 atm)
- THP = the total heat production of occupants (kJ/s)

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$$v = v_e; h = h_e ; c = c_e$$

- $\frac{d}{dt}\left(\frac{V}{v}\right) = \frac{Q_s}{v_s} - \frac{Q_e}{v_e}$
- $\frac{d}{dt}\left(\frac{Vh}{v}\right) = \dot{q} + \frac{Q_s}{v_s} h_s - \frac{Q_e}{v_e} h_e$
- $\frac{d}{dt}\left(\frac{Vw}{v}\right) = \dot{w} + \frac{Q_s}{v_s} w_s - \frac{Q_e}{v_e} w_e$
- $\frac{d}{dt}(Vc) = \dot{s} + \frac{Q_s}{v_s} c_s - \frac{Q_e}{v_e} c_e$

- $\frac{Q_s}{v_s} - \frac{Q_e}{v_e} = 0$
- $\frac{\dot{q}}{h_e - h_s} = \frac{Q_s}{v_s} = \frac{Q_e}{v_e}$
- $\frac{\dot{w}}{w_e - w_s} = \frac{Q_s}{v_s} = \frac{Q_e}{v_e}$
- $\dot{s} + Q_s c_s = Q_e c_e$

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

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Psychrometric chart

- http://www.uigi.com/UIGI_SI.PDF
- See handout

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Example 14.3: Ventilation rate calculation

- A dinning room have 20 people
- 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 50% relative humidity.
- The room air is 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.

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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,*

  ν_s=0.822 m^3/kg dry air
- *The specific volume of exhaust air at 22 ℃ and 60% relative humidity is*

  ν_e=0.855 m^3/kg dry air
- *The total heat production rate by 20 people in the dining room is,*

  THP=20×200 W=4000W or 4 kJ/s
- *Then the mass production rate of CO_2 is estimated using Equation (14-9)*

$$\dot{s}_{CO2} = \rho_{CO2}\frac{THP}{24600} = 1.83 \times \frac{4}{24600} = 2.98 \times 10^{-4}\,(kg/s)$$

- *Then the minimum ventilation rate fan is determined using Equation (14-6)*

$$\dot{s}_{CO2} = Q_e c_e\left(1 - \frac{\nu_s c_s}{\nu_e c_e}\right) = Q_s c_s\left(\frac{\nu_e c_e}{\nu_s c_s} - 1\right)$$

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Solution (continued)

$$\dot{s}_{CO2} = Q_e c_e \left(1 - \frac{\nu_s c_s}{\nu_e c_e}\right) = Q_s c_s \left(\frac{\nu_e c_e}{\nu_s c_s} - 1\right)$$

- *Since ν_s<ν_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.*

$$c_e = \frac{1000\ m^3 CO_2 \times 1.83 kg\ CO_2/m^3\ CO_2}{10^6\ m^3\ air}$$
$$= 1.83 \times 10^{-3}\ kg\ CO_2/m^3\ air$$

- *The exhaust ventilation rate is*

$$Q_e = \frac{\dot{s}_{CO2}}{c_e\left(1 - \frac{\nu_s c_s}{\nu_e c_e}\right)}$$
$$= \frac{2.98 \times 10^{-4}\ kg\ CO_2/s}{\left(\frac{1000\ m^3 CO_2 \times 1.83\ kg\ CO_2/m^3\ CO_2}{10^6\ m^3\ air}\right)\left(1 - \frac{0.822}{0.855} \times \frac{500}{1000}\right)}$$
$$= 0.31\ m^3\ dry\ air/s$$

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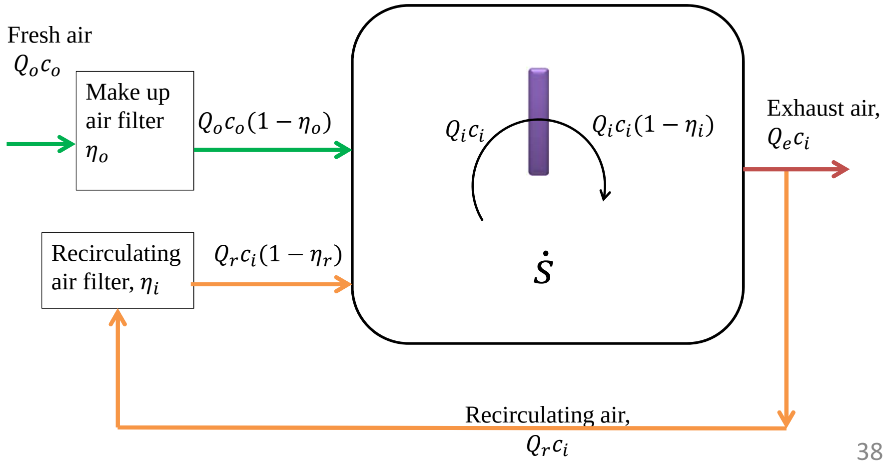
Indoor Air Cleaning Modeling

Space volume V; Source: $\dot{s}$;
Indoor concentration c_i ; Outdoor concentration c_o



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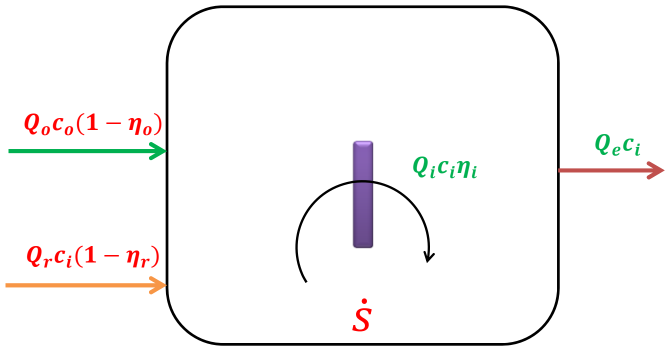
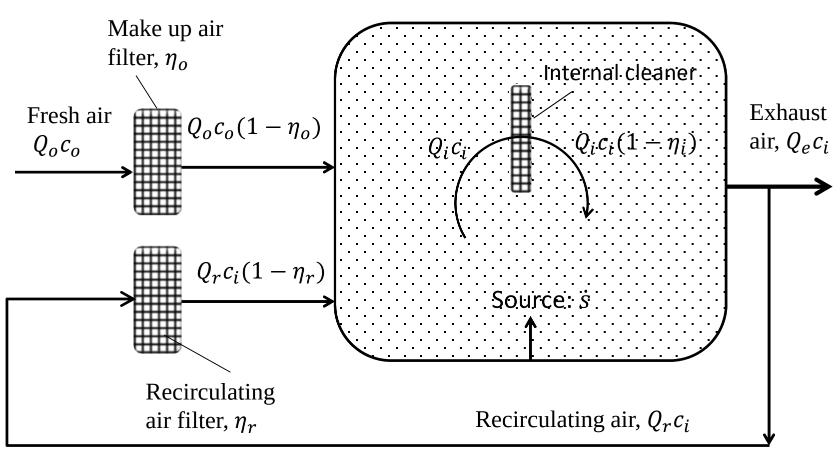


$$V\frac{dc_i}{dt} = [Q_o c_o(1-\eta_o) + Q_r c_i(1-\eta_r) + \dot{s}] - (Q_e c_i + Q_i c_i \eta_i)$$

Accumulation rate | Into the control volume | Removal rate

$Q_o = Q_e$



$$Q_o = Q_e$$

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

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

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

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

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

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

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

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Example 14.4

- *Consider a kitchen with a volume of 80 m^3*
- *where natural gas is used as a cooking fuel*
- *Assume after cooking the indoor fume concentration is 1000 µg/m^3.*
- *The HVAC system works at a fresh flow rate of 1 m^3/s*
- *a recirculating flow rate 1/3 of that of the fresh air.*
- *An internal air cleaner has a flow rate of 0.1 m^3/s;*
- *Ignore the outdoor and indoor source.*
- *The intake and recirculating filter efficiencies are the same as 90%*
- *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.*

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Solution

- $\dot{s}$=0, and $c_o = 0$
- $c_{i\infty} = \frac{Q_o c_o(1-\eta_o)+\dot{s}}{Q_o - Q_r(1-\eta_r)+Q_i\eta_i} = 0$
- $= \frac{V}{Q_o - Q_r(1-\eta_r)+Q_i\eta_i}$
- $\tau = \frac{800}{10-\frac{10}{3}(1-0.9)+1\times 0.95} = 75.35\ (s)$
- $c_i(t) = 1000\exp\left(-\frac{t}{75.35}\right)$

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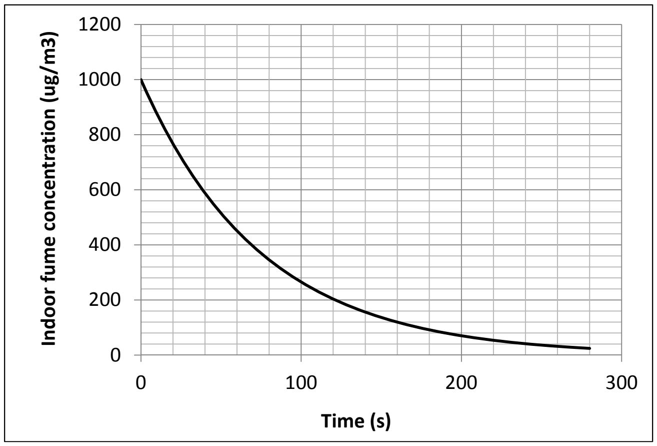

Figure 14-4. Calculated indoor air pollutant concentration over time