Today, we will:

- Do an example problem of room ventilation with recirculation
- Briefly discuss Partially Mixed Conditions [Section 5.7]
- Briefly discuss The Well-Mixed Model as an Experimental Tool [Section 5.8]
- Discuss Clean Rooms [Section 5.9] and, if time, do an example problem

Example – Room ventilation with two filters and recirculation

Given: A hospital operating room with the ventilation system shown. Ethyl alcohol is accidentally entering the room through the make-up air duct at concentration $c_a$.

![Diagram of ventilation system]

Here are the parameters:

- $A_s = 85.0 \text{ m}^2$ (total surface area of the room)
- $c(0) = 3.0 \text{ mg/m}^3$ (initial alcohol concentration in the room)
- $c_a = 100. \text{ mg/m}^3$ (alcohol concentration in the ambient make-up air)
- $f = 0.90$ (fresh make-up air fraction)
- $k_w = 0.10 \text{ cm/s} = 0.060 \text{ m/min}$ (wall loss coefficient)
- $Q = Q_e = Q_s = 20. \text{ m}^3/\text{min}$ (supply ventilation rate into the clean room)
- $S = 1000 \text{ mg/min}$ (source strength of ethyl alcohol inside the room)
- $V = 50 \text{ m}^3$ (volume of the room)
- $\eta_1 = 95.\%$, $\eta_2 = 95.\%$ (air cleaner efficiencies)

To do: Calculate the steady-state concentration of the ethyl alcohol in the operating room. Calculate how long it will take for people in the room to smell the alcohol. Use an odor threshold of 10 PPM (19 mg/m$^3$).

Solution:

\[ \frac{dA}{dt} = Q_s c_s + S - c Q_e - c A_s k_w \]
Equation: \[ C_i = (1-n_i)c \quad \text{clear 1} \]
\[ C_2 = (1-n_2)c_a \quad \text{clear 2} \]

Bottom tee: \[ C_i Q_r + C_2 Q_m = C_s Q_s \]
\[ C_f = \frac{C_i Q_r + C_2 Q_m}{Q_s} \]

But, we know:
\[ Q_m = f Q_s \]
\[ Q_r = (1-f) Q_s \]

First critical step:
Second """" to split term in (1) into 2 parts:
1) term with C
2) """" without C

Plug (2) into (1): split:
\[ \frac{dA}{dt} = S + Q_s C_a (1-n_1)f - \left[ Q_s + A_{kw} - Q_s (1-n_1)(1-f) \right]c \]

Critical step (?) - find A : B
In standard form, 1st-order ODE: \( \frac{dc}{dt} = B - Ac \)

\[ B = S + Q_s A_{(1-n_s)} \]
\[ A = Q_s + A_s k_w - Q_s (1-n_s)(1-f) \]

Calc \( C_{sf} \) →
\[ C_{sf} = \frac{B}{A} \] when \( A \neq B \cdot constant \)

\[ C_{sf} = 43.6 \ \frac{mg}{m^3} \]

Calc \( t \) when people smell the alcohol

- Odor threshold = 19 \( \frac{mg}{m^3} \)
- \( C_s = 43.6 \ \frac{mg}{m^3} \)

Recall, 1st-order ODE: \( t = \frac{-1}{A} \ln \left( \frac{C_{sf} - C}{C_{sf} - C(0)} \right) \)

\[ t = 1.002 \ \text{min} \quad \text{or} \quad t = 1.0 \ \text{min} \]
Sec. 5.7 → Partially Mixed Conduction

\[ M = \text{mixing factor} \] used in HVAC literature

\[ 0 \leq m < 1 \]

\[ m = 1 \rightarrow \text{well mixed (all our examples so far)} \]
\[ m < 1 \rightarrow \text{not perfectly well mixed} \]

Sec. 5.8 → Using the well-mixed model as an experimental tool

- can measure: \[ S = \text{solar strength} \]
  (same analysis as flux density)

- \[ k_w = \text{wall loss coeff} \] (see previous lecture)

- efficiency of an air cleaner \( \eta \)

Clean Rooms → Designed to protect a product

whereas general ventilation design is to protect people

Very strict requirements → temperature, humidity, conc. of vapors, parasites
Figure 5.11 Clean rooms: (a) vertical laminar-flow, (b) horizontal laminar-flow, (c) tunnel laminar-flow, (d) tabletop tunnel laminar-flow, (e) island laminar-flow, and (f) unitary work station (miniature) (from Canon Communications, 1987).
Table 5.2 Clean room class limits; maximum permissible $c_{\text{number}}$ in English and SI units; **bold** $c_{\text{number}}$ indicates number concentration on which the corresponding **bold** class name is based (abstracted from ASHRAE HVAC Applications Handbook, 1999.)

<table>
<thead>
<tr>
<th>Class name</th>
<th>$D_p \geq 0.1 \mu m$</th>
<th>$D_p \geq 0.2 \mu m$</th>
<th>$D_p \geq 0.5 \mu m$</th>
<th>$D_p \geq 5 \mu m$</th>
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</thead>
<tbody>
<tr>
<td>SI</td>
<td>English</td>
<td>#/m³</td>
<td>#/ft³</td>
<td>#/m³</td>
</tr>
<tr>
<td>M1</td>
<td>350</td>
<td>9.9</td>
<td>75.0</td>
<td>2.14</td>
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<td>M1.5</td>
<td>1240</td>
<td>35</td>
<td>265</td>
<td>7.5</td>
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<td>M2</td>
<td>3500</td>
<td>99.1</td>
<td>757</td>
<td>21.4</td>
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<tr>
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<td>991</td>
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<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<td>10000</td>
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</tr>
<tr>
<td>M7</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>

- Original standards are in English units ($#/ft^3$)
  - Class 1 = $1 \ #/ft^3$ for particles with $D_p \geq 0.5 \mu m$
  - Smaller class is better

- Metric classes are based on exponent of $#/m³$ at $D_p \geq 0.5 \mu m$
  - Example: Class M2 = $10^2 \ #/m³$ for $D_p \geq 0.5 \mu m$

- Intermediate SI cases correspond to old English classes

- Convert $\frac{m³}{ft^3} = \left(\frac{0.3048 m}{ft}\right)^3 = 0.02832 \frac{m³}{ft^3}$

- $\frac{ft^3}{m³} = 35.31 \frac{ft^3}{m³}$
We plot the data of Table 5.2 below:

Figure 5.12 Class definitions for clean rooms in the US; class based on cubic feet – conversion: 1.00 particles/ft\(^3\) = 35.3 particles/m\(^3\).

How to use: e.g. \(C_{\text{number}} = 20 \, \text{part/ft}^3\) of \(D_p \geq 2.0\, \mu\text{m}\) particles.

What class of clean room is this?

Any \(\Rightarrow \text{This is a class 1000 clean room.}\)

(not clean enough to be a class 100)
Example (Example 5.10 in text – Time to Achieve Clean Room Conditions)

Given: A clean room with the ventilation system shown,

\[ \begin{align*}
Q_s &= Q \\
Q_r &= (1-f)Q \\
Q_m &= fQ
\end{align*} \]

and with the following specifications:
- \( \eta_1 = 98\% \), \( \eta_2 = 98\% \) (air cleaner efficiencies)
- \( f = 0.050 \) (fresh make-up air fraction)
- \( c_a = 10^3 \) particles/m³ (particle concentration in the ambient make-up air)
- \( D_p = 1.0 \) µm (particle size of concern)
- \( Q_s = 20. \) m³/min (supply ventilation rate into the clean room)
- \( S = 300 \) particles/min (particle emission rate within the clean room)
- \( V = 300 \) m³ (volume of the clean room)
- \( A_s = 320 \) m² (total surface area of the clean room)
- \( k_w = 0.030 \) m/min (wall loss coefficient)
- \( c(0) = 10^5 \) particles/m³ (initial particle concentration within the clean room)

To do: What class of clean room is this? Calculate how long it will take to achieve class 10,000, 1,000, 100, 10, and 1.

Solution:

\[ C_{sj} = \text{steady state \# concentration} \]

\[ C_{sj} = \frac{B}{A} = \frac{S + Q_j c_a f (1-n_2)}{Q_j + k_w A_j + Q_j (-f)(1-n_1)} \]

\[ C_{sj} = 10.67 \frac{\text{#}}{m^3} = 10.67 \frac{\text{#}}{m^3} \]

or \[ C_{sj} = 0.302 \frac{\text{#}}{ft^3} \]