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 $c_a$.

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:**

\[
\nabla \frac{dc}{dt} = Q_s c_s + S - cQ_e - cA_k k_w
\]

\[
\begin{align*}
\text{Cons. of mass of species:} \\
\text{for the room } c(t)
\end{align*}
\]

\[
\begin{align*}
\text{know:} & \\
c_1 &= c(1-\eta_1) \\
c_2 &= c_a (1-\eta_2)
\end{align*}
\]
Conservation of mass of air + species  bulk flow @ tee

$$
\frac{\text{bottom tee:}}{C_1 Q_r + C_2 Q_m = C_s Q_s}
$$

Solve for \( C_s = \frac{C_1 Q_r + C_2 Q_m}{Q_s} \)

\( C_s = C_1 (1-f) + C_2 f \)

Plug in (2): \( C_s = C(1-n_1)(1-f) + C_n (1-n_2) f \)

A critical step → Plug into (1) and regroup all terms

With \( C \) in, all terms w/o \( C \) get into standard form:

\[ \frac{dc}{dt} = \beta - Ac \]

(1) \( \frac{dc}{dt} = S + Q_s C(1-n_1)(1-f) + Q_s C_n (1-n_2) f - Q_s C - A k w C \)

Regroup:

\[ \frac{dc}{dt} = \frac{S + Q_s C_n (1-n_2) f}{A} - \frac{Q_s + A k w - Q_s (1-n_1)(1-f)}{A} \]

\[ \frac{dc}{dt} = \beta - A C \]
To calculate $C_{sY}$ in the room,

$$C_{sY} = \frac{B}{A}$$

for constant $B$ i.e. $A$

$$C_{sY} = 43.6 \frac{mg}{m^3}$$

Now calculate time until people smell the alcohol.

- Odor threshold = $19 \frac{mg}{m^3}$
- $C_{sY} = 43.6 \frac{mg}{m^3}$

For $\frac{dC}{dt} = B - AC$ → recall,

$$t = \frac{-1}{A} \ln \left( \frac{C_{sY} - C}{C_{sY} - C_0} \right)$$

Set $C = 19 \frac{mg}{m^3}$ for any $C(t)$ in the room.

Solve for $t$

$$t = \frac{-1}{0.5 \frac{1}{min}} \ln \left( \frac{43.6 - 19}{43.6 - 3} \right) = 1.002 \text{ min}$$

$$t = 1 \text{ min}$$
Sec 5.7 - Partially mixed condition:

Introduce mixing factor, \( m \), to account for non-uniform mixing in the room.

\( 0 < m < 1 \)
\( m = 1 \rightarrow \text{well-mixed} \)
\( m < 1 \rightarrow \text{not well-mixed} \)

(See Text)

Sec 5.8 - How do we well-mixed model as an experimental tool:

- Measure wall loss coeff. (we did in example)
- Measure source strength, \( S \) (like a flux chamber)
- Efficiency of air cleaner (\( n \))

\[
\begin{array}{c}
Q_i \\
\hline
\ Q_o \end{array}
\]

\[
\begin{array}{c}
C(n) \\
\hline
n \end{array}
\]

\[
\begin{array}{c}
Q_e \end{array}
\]
Sec 5.9 Clean Rooms

- Designed to protect a product, rather than occupants
- Typically electronics, medical devices, ...
- Particle not gas

Various configurations have been designed

(large Q into room)

High efficiency filter

Clean room requirements are very strict:

- Temperature
- Humidity
- Static electricity
- Concentration of particles, some vapors

Filter terminology:

HEPA = High Efficiency Particulate Air Filter
ULPA = Ultra Low Penetration Air Filter
Clean Rooms [Section 5.9]:

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\text{m} )</th>
<th>( D_p \geq 0.2 , \mu\text{m} )</th>
<th>( D_p \geq 0.5 , \mu\text{m} )</th>
<th>( D_p \geq 5 , \mu\text{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>English</td>
<td>#/m(^3)</td>
<td>#/ft(^3)</td>
<td>#/m(^3)</td>
</tr>
<tr>
<td>M1</td>
<td>350</td>
<td>9.9</td>
<td>75.0</td>
<td>2.14</td>
</tr>
<tr>
<td>M1.5</td>
<td>1240</td>
<td>35</td>
<td>265</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>M2</strong></td>
<td>3500</td>
<td>99.1</td>
<td>757</td>
<td>21.4</td>
</tr>
<tr>
<td>M2.5</td>
<td>12400</td>
<td>350</td>
<td>2650</td>
<td>75.0</td>
</tr>
<tr>
<td><strong>M3</strong></td>
<td>35000</td>
<td>991</td>
<td>7570</td>
<td>214</td>
</tr>
<tr>
<td><strong>M3.5</strong></td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M4.5</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>M5</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M5.5</td>
<td>10000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>M6</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>M6.5</strong></td>
<td>100000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Both are based on particles of \( D_p \geq 0.5 \, \mu\text{m} \).

**In English:**

\[
\text{Class } \text{100} = 100 \, \text{#/ft}^3 = \text{number concentration of particles } \geq 0.5 \, \mu\text{m}
\]

**In metric units:**

\[
\text{SI} = \text{class } M2 = 10^2 \, \text{#/m}^3 \text{ of particle } \geq 0.5 \, \mu\text{m}
\]

**Conversion:**

\[
\frac{\text{m}^3}{\text{ft}^3} = \left(\frac{0.3048 \, \text{m}}{\text{ft}}\right)^3 = 0.02832 \, \frac{\text{m}^3}{\text{ft}^3}, \quad \frac{35.3 \, \text{ft}^3}{\text{m}^3}
\]
We plot the data of Table 5.2 below:

![Graph showing data points and lines for different classes.]

Figure 5.12 Class definitions for clean rooms in the US; class based on cubic feet – conversion: 1.00 particles/ft³ = 35.3 particles/m³.

To use: For a measured \( C_{\text{number}} \), a measured \( D_p \) → determine class of the clean room.

E.g. if \( C_{\text{number}} = 20 \text{ particles/ft}^3 \) and \( D_p \geq 2.0 \mu\text{m} \),

This is a Class 1000 clean room

[not clean enough to be Class 100]