Today, we will:

• Discuss **Ventilation Effectiveness** [Section 5.12]
• Discuss **Make-up Air Operating Costs** [Section 5.13] and do an example problem

- Last time, we talked about **mean age** in ventilation efficiency
- A related quantity is **Room Mean Age**, $t_{room, avg}$

$$Q = Q_{out} + (E)_{exh}$$

**We E at our measurement location rather than a single point P in room**

**Multiple paths for the air to go from inlet to exhaust**

$$t_{room, avg} = \text{room age averaged over the whole room}$$

(a global rather than local property)

- To measure $t_{room, avg}$ - we use **“step-up tracer experiment”**

  - Start with clean air, ventilation on, steady state
  - At $t=0$, we inject a tracer gas into supply air
  - Monitor $C_{E}(t)$ - mill conc. at the exhaust opening

**Typical tracer gas is SF$_6$ (sulfur hexafluoride)**
Define $t_{\text{room,avg}} = \text{Room mean age}$

$$t_{\text{room,avg}} = \frac{\int_0^\infty t \left( 1 - \frac{C_E}{C_E(\infty)} \right) dt}{\int_0^\infty \left( 1 - \frac{C_E}{C_E(\infty)} \right) dt}$$

$e_{\text{room}} = \frac{\text{Room (ventilation) effectiveness coefficient}}{t_{\text{room,avg}}}$

(Where $t_N = \frac{1}{N} = \frac{A}{Q}$)
Example: Room with ideal displacement ventilation

To do: Calculate $e_{\text{room}}$

Solution:

$$e_{\text{room}} = \frac{t_N}{t_{\text{room, av}}}$$

$$t_N = \frac{1}{n} = \frac{4}{Q}$$

$$t_{\text{room, av}} = \frac{\int_{t_0}^{t_\infty} t \left(1 - \frac{C_E}{C_E(\infty)}\right) \, dt}{t_\infty - t_0}$$

At $t_N$, the "purge" reaches the exhaust

In time $t_N$ we displace all the air in the room

The area $t_0 \rightarrow t_N$ is

$$\int_{t_0}^{t_N} C_E \, dt = t_N$$
\[ \text{Numexhr} \rightarrow \int_{t=0}^{\infty} t \left( 1 - \frac{C_E}{C_E(\infty)} \right) \, dt \]

For \( t > t_N \), \( C_E = C_E(\infty) \), \( \therefore \int_{t=0}^{t_N} t \, dt = \frac{t_N^2}{2} \)

For \( 0 < t < t_N \), \( C_E = 0 \), \( \therefore 1 - \frac{C_E}{C_E(\infty)} = 1 \)

\[ \therefore t_{room, av} = \frac{t_N^2/2}{t_N} = \frac{t_N}{2} \Rightarrow e_{room} = \frac{t_N}{t_{room, av}} = \frac{t_N}{t_N/2} = 2 \]

\[ e_{room} = 2 \text{ for ideal displacement reaction} \]

For well-mixed room \( e_{room} = 1 \)

Summary: \[ 0 < e_{room} < 2 \]

- \( 0 < e_{room} < 1 \) → not well mixed (slow response time)
- \( e_{room} = 1 \) → perfectly well-mixed
- \( 1 < e_{room} < 2 \) → between well-mixed dilution & displacement
- \( e_{room} = 2 \) → ideal displacement reaction
Sec. 5.13 Make-up air operating costs

- IAQ — we want lots of make-up (fresh) air
- Make-up air costs & to heat or cool, dehumidify, humidify

HVAC engineers use

Heating Degree Days = DD\text{h} or HDD
Cooling ... = DD\text{c} or CDD

For a given city, for one day, calculate average outdoor temperature

\[ T_{\text{outdoor}} \]

E.g., \[ T_{\text{outdoor}} \approx 55^\circ F \]

Define \( T_{\text{bol}} \) = balance point temperature

If \( T_{\text{outdoor}} < T_{\text{bol}} \) → need heat

If \( T_{\text{outdoor}} > T_{\text{bol}} \) → need A/C (cooling)

Standard for \( T_{\text{bol}} \) is 65°F (Somewhere 60°F)

In one typical full day, \[ T_{\text{bol}} - T_{\text{outdoor}} = 65^\circ F - 55^\circ F = 10^\circ F \]

This is 10 heating degree days for this one day
For the whole year,

\[ \text{HDD} = DD_h = (1 \text{ day}) \leq (T_{\text{bul}} - T_{\text{outdoor}})^+ \]

Heat cost ($) \propto DD_h

Cooling \quad \text{very similar}

\[ \text{CDD} = DD_c = \text{cooling degree days} \]

\[ DD_c = (1 \text{ day}) \leq (T_{\text{outdoor}} - T_{\text{bul}})^+ \]

Cooling cost ($) \propto DD_c

"Heating season" \quad \text{July 1 to June 30}

"Cooling season" \quad \text{Jan 1 to Dec 31}

See weather-data-depot.com

Typical \quad \text{State College} \quad \begin{cases} \text{DD}_h = 6000 \text{ oF-days} \\ \text{DD}_c = 700 \text{ oF-days} \end{cases}
Eq. for the cost of heating or cooling

(Eq 5-70)

Assume \( T_{int,dc} = 70°F \) year round

\[
\$_{heating} = 0.154 \frac{DD_h \cdot t_{operating} \cdot C_{fu}}{Q_{fu}}
\]

"Engineering Eq" — must we proper specific units:

\( DD_h \) (°F heating days) \( \oplus \) \( T_{bol} = 65°F \)

\( t_{operating} = \% \) of week operation (typically 24x7 = 168 \( \frac{h}{wk} \))

\( C_{fu} = \) unit fuel cost = \( \$ \)

\( Q = \) make-up air \( [ACFM] \) \( (\frac{ft^3}{min}) \)

\( Q_{fu} = \) unit fuel energy = available energy per unit of fuel

\( \frac{BTU}{\text{unit of fuel}} \)

\( \frac{BTU}{\text{gallon}} \), \( \frac{BTU}{\text{SCF}} \)
Table 5.5  Heating degree days for several cities in the United States (abstracted from ASHRAE Fundamentals Handbook, 1997). *Note:* Newer, year-by-year data are available at [http://weatherdatadepot.com](http://weatherdatadepot.com).

<table>
<thead>
<tr>
<th>city</th>
<th>$DD_h$ ($^\circ$F days)</th>
<th>$DD_h$ (K days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles, CA</td>
<td>1245</td>
<td>692</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>6016</td>
<td>3342</td>
</tr>
<tr>
<td>Miami, FL</td>
<td>206</td>
<td>114</td>
</tr>
<tr>
<td>Chicago, IL</td>
<td>6127</td>
<td>3404</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td>4292</td>
<td>2384</td>
</tr>
<tr>
<td>New York City, NY</td>
<td>4909</td>
<td>2727</td>
</tr>
<tr>
<td>Bismarck, ND</td>
<td>9044</td>
<td>5024</td>
</tr>
<tr>
<td>Nashville, TN</td>
<td>3696</td>
<td>2053</td>
</tr>
<tr>
<td>Dallas/Ft. Worth, TX</td>
<td>2290</td>
<td>1272</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>4727</td>
<td>2626</td>
</tr>
</tbody>
</table>

Table 5.6  Available energy per unit of fuel for several heating options.

<table>
<thead>
<tr>
<th>fuel</th>
<th>efficiency</th>
<th>$q_{fu}$ (BTU/lbm)</th>
<th>$q_{fu}$ (BTU/gal)</th>
<th>$q_{fu}$ (BTU/ft$^3$)</th>
<th>$q_{fu}$ (BTU/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal</td>
<td>50%</td>
<td>6,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>oil</td>
<td>75%</td>
<td>106,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>natural gas (heat exchanger)</td>
<td>80%</td>
<td>800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>natural gas (direct-fired)</td>
<td>90%</td>
<td>900</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electricity (resistance heating)</td>
<td>100%</td>
<td>3,415</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>