Lecture 8: October 28, 2013
Ventilation and infiltration
Heating loads
Fluid flow

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Last time

- Exam solutions
- Ventilation and indoor air quality
- Fluid flow in buildings
  - Didn’t get to this
Scheduling

• HW #4 due today

• HW #5 will be assigned today

• Graduate students: Final projects
  – Maximum 8 page paper due November 25\textsuperscript{th}
  – 10 minute oral presentation in class on November 25\textsuperscript{th}
    • All students attend
    • Strict on timelines
Today’s objectives

• Finish IAQ/ventilation

• Heating load calculations

• Fluid flows in buildings (if there’s time)
Review from last time

• Indoor air quality: we spend most of our time indoors

• Outdoor air ventilation can both dilute indoor sources of pollutants and bring in pollutants from outdoors

• Key topics:
  – Mass balances
  – Unit conversions
  – Air exchange rate
  – Ventilation rates
  – Filtration
  – CADR
VENTILATION AND INFILTRATION
Finishing up IAQ

• Last class we measured CO₂ concentrations in the room
  – Along with T and RH

Let’s estimate the ventilation rate in the classroom
Air exchange: Ventilation and infiltration

Air exchange of outdoor air with air already in a building can be divided into two broad classifications:

Ventilation

Intentional introduction of outdoor air into a building

Subdivided into:

– *Mechanical (forced) ventilation*: The intentional movement of air into and out of a building using fans, intake vents, and exhaust vents

– *Natural ventilation*: The flow of air through open windows, doors, grilles, and other planned envelope penetrations, driven largely by natural or artificially induced pressure differences

Infiltration

Flow of outdoor air into a building through cracks, leaks, and other unintentional openings in the envelope (includes normal use of exterior doors) … i.e., *leakage*
Dealing with ventilation vs. infiltration

• Mechanical ventilation is straightforward
  – Fans move air through known openings
  – Flow rates typically known or at least measurable

• Natural ventilation is conceptually straightforward but physically complex
  – Known openings but highly varying wind speeds and directions

• Infiltration is complex
  – Typically unknown openings and multiple driving forces

• Need to know airflows through each of these in order to quantify IAQ and energy impacts
General models for air flows through leaks

• Given an opening:

\[ \dot{V} = A C \Delta P^n \]

- \( A \) = area of opening, ft\(^2\) (m\(^2\))
- \( \Delta P \) = pressure difference between inside and outside, in WG (Pa)
- \( C \) = flow coefficient, ft/(min inWG\(^n\)) [m/(s Pa\(^n\))]
- \( n \) = exponent, between 0.4 and 1.0 (usually 0.65 for buildings)

• For a combination of \( i \) openings:

\[ \dot{V} = \sum_{i} A_i C_i \Delta P_i^{n_i} \]
Driving forces of ventilation and infiltration: $\Delta P$

- Three primary mechanisms generate pressure differences (driving forces)
  - Stack effect (natural buoyancy)
    - Caused by the weight of a column of air located inside or outside a building
    - Depends on air density and height above a neutral reference level
      - Density is also a function of temperature
  - Wind
    - Caused by wind impinging on a building, creating a distribution of pressures on the exterior surface
    - Depends on wind direction, wind speed, air density, surface orientation, and surrounding conditions
  - Mechanical air handling equipment (fans)
    - Fans are used to supply, recirculate, exhaust, and otherwise balance pressures and flows in buildings

\[ \Delta P = \Delta P_{\text{wind}} + \Delta P_{\text{stack}} + \Delta P_{\text{vent}} \] (+ when causing flow to interior)
Stack effect

• **In wintertime**
  – Air within a building acts like a bubble of **hot** air in a sea of **cold** air
  – **Rises** to the top
  – Draws **outdoor air in from** cracks/gaps/openings in the **bottom**
  – Indoor air out through top

• **In summertime**
  – Air within a building acts like a bubble of **cold** air in a sea of **hot** air
  – **Falls** to the bottom
  – Drives **indoor air out through** cracks/gaps/openings in **bottom**
  – Outdoor air in through top
  
  • Temperature differences usually lower in the summer time so the amount of flow is smaller

\[
\Delta P_{stack} = \rho_{in} C_d \left(\frac{T_{out} - T_{in}}{T_{in}}\right) g (H_{NPL} - H)
\]
Stack effect: winter vs. summer
Wind pressures

- From velocity component of Bernoulli Equation:

\[ P_{velocity} = \frac{1}{2} \rho_{air} U_h^2 \]

where \( P_{velocity} \) = wind velocity pressure; \( U_h \) = air velocity at building height, \( h \); \( \rho_{air} \) = air density

- To convert velocity pressure to the difference between surface pressure and local atmospheric pressure:
  - Multiply by local wind pressure coefficient, \( C_p \)

\[ P_{surface} = \Delta P = C_p P_{velocity} = \frac{1}{2} C_p \rho U_h^2 \]

  - Get \( C_p \) from measurements or from ASHRAE Fundamentals Chapter 16 (2005 HOF)
Wind pressure coefficients ($C_p$) vary around buildings
Typical air leakage sites in buildings
What are typical values of $\lambda$ (AER)?

- Distribution of AERs in ~2800 homes in the U.S.
  - Measured using PFT (perfluorocarbon tracer) in the early 1990s
  - Nearly all infiltration

- What do you think this curve looks like now?

Murray and Burmaster, 1995 *Risk Analysis*
What are typical values of $\lambda$ (AER)?

- Distribution of AERs U.S. homes: infiltration
  - Early 1990s and revisited in 2010 (Persily et al. 2010)

<table>
<thead>
<tr>
<th>% less than</th>
<th>1990s median $\sim$0.5/hr</th>
<th>2010 median $\sim$0.4/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>0.4</td>
<td>1.0</td>
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</tr>
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<td>1.0</td>
</tr>
<tr>
<td>0.8</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

- 20% reduction in 20 years

Murray and Burmaster, 1995 *Risk Analysis*; Persily et al. 2010 *Indoor Air*
What are typical values of $\lambda$ (AER)?

- Distribution of AERs U.S. homes: infiltration
  - Addition of 106 new homes (Offermann et al., 2009)

- Not uncommon for new homes to have AER = 0.05-0.20 per hour

1990s median ~0.5/hr
2010 median ~0.4/hr
2009 new home median ~0.26/hr

Offermann et al. 2009 CEC PIER Report
Steady state mass balance and real AERs

- Assume $V = 200 \, \text{m}^3$ and $E = 1 \, \mu\text{g/hr}$
- Lower AER $\rightarrow$ higher $C_{\text{ss}}$

<table>
<thead>
<tr>
<th>Indoor concentration ($\mu\text{g/m}^3$)</th>
<th>0.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>E = 1 $\mu\text{g/ hr}$</td>
<td></td>
</tr>
<tr>
<td>C = 0.19 $\mu\text{g/m}^3$ @ median new CA home AER of 0.26/hr</td>
<td></td>
</tr>
<tr>
<td>C = 0.13 $\mu\text{g/m}^3$ @ median 2010 AER of 0.4/hr</td>
<td></td>
</tr>
<tr>
<td>C = 0.10 $\mu\text{g/m}^3$ @ median 1990 AER of 0.5/hr</td>
<td></td>
</tr>
</tbody>
</table>
Modeling air leakage (infiltration only)

- There are several models for estimating infiltration rates in buildings.
- One common model is the LBL Model for Air Leakage, also known as the Sherman-Grimsrud Model:

\[ \dot{V}_{\text{inf}} = A_{\text{leak}} \sqrt{a_s \Delta T + a_w v_w^2} \] [L/s]

- \( A_{\text{leak}} \) = building equivalent leakage area [cm²]
- \( \Delta T \) = interior-outdoor temp difference [K]
- \( a_s \) = stack effect coefficient [\( \frac{(L/s)^2}{cm^4K} \)]
- \( a_w \) = wind coefficient [\( \frac{(L/s)^2}{cm^4(m/s)^2} \)]
- \( v_w \) = wind speed [m/s]
**LBL Air Leakage Model**

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Basic Model Stack Coefficient $C_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>House Height (Stories)</td>
</tr>
<tr>
<td></td>
<td>One</td>
</tr>
<tr>
<td>Stack coefficient</td>
<td>0.000 145</td>
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</table>

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Local Shelter Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelter Class</td>
<td>Description</td>
</tr>
<tr>
<td>1</td>
<td>No obstructions or local shielding</td>
</tr>
<tr>
<td>2</td>
<td>Typical shelter for an isolated rural house</td>
</tr>
<tr>
<td>3</td>
<td>Typical shelter caused by other buildings across the street from the building under study</td>
</tr>
<tr>
<td>4</td>
<td>Typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away</td>
</tr>
<tr>
<td>5</td>
<td>Typical shelter produced by buildings or other structures that are immediately adjacent (closer than one house height): e.g., neighboring houses on the same side of the street, trees, bushes, etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Basic Model Wind Coefficient $C_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>House Height (Stories)</td>
</tr>
<tr>
<td></td>
<td>One</td>
</tr>
<tr>
<td>Shelter Class</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.000 319</td>
</tr>
<tr>
<td>2</td>
<td>0.000 246</td>
</tr>
<tr>
<td>3</td>
<td>0.000 174</td>
</tr>
<tr>
<td>4</td>
<td>0.000 104</td>
</tr>
<tr>
<td>5</td>
<td>0.000 032</td>
</tr>
</tbody>
</table>
LBL model example problem

• You measure an effective leakage area of 449 cm² in a single story wood-frame building in a suburban neighborhood
  – Floor area of 120 m² and ceiling height of 3 m

• Estimate the air exchange rate of the building when it is 68°F inside and 32°F outside and a wind speed of 15 mph

• What if the outdoor temperature drops to 0°F?

• What if wind speed doubles to 30 mph (13.4 m/s)?
Variation in infiltration AER

- Air exchange rates differ both between buildings and within buildings
  - Differences vary by driving forces and building characteristics
- Example research: “Continuous measurements of air change rates in an occupied house for 1 year: the effect of temperature, wind, fans, and windows”
  - 4600 AERs measured by automated SF$_6$ system in one house for 2 years!
Variation in infiltration AER

AERs in individual buildings can vary by season
- Driving forces: temperature, wind speed

AERs can vary by I/O temperature within seasons

Wallace et al. 2002 *J Expo Anal Environ Epidem*
Measured air exchange rates: Commercial buildings

- Recent study of ~40 commercial buildings in CA
  - Combination of infiltration and mechanical ventilation

Bennett et al. (2011) CEC Report
1. PURPOSE

1.1 The purpose of this standard is to specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects.

1.2 This standard is intended for regulatory application to new buildings, additions to existing buildings, and those changes to existing buildings that are identified in the body of the standard.

1.3 This standard is intended to be used to guide the improvement of indoor air quality in existing buildings.

2. SCOPE

2.1 This standard applies to all spaces intended for human occupancy except those within single-family houses, multifamily structures of three stories or fewer above grade, vehicles, and aircraft.

2.2 This standard defines requirements for ventilation and air-cleaning system design, installation, commissioning, and operation and maintenance.
Ventilation rate procedure

6.2.2.1 Breathing Zone Outdoor Airflow. The outdoor airflow required in the breathing zone of the occupiable space or spaces in a ventilation zone, i.e., the breathing zone outdoor airflow ($V_{bz}$), shall be no less than the value determined in accordance with Equation 6-1.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z$$  (6-1)

where

$A_z$ = zone floor area: the net occupiable floor area of the ventilation zone ft² (m²)

$P_z$ = zone population: the number of people in the ventilation zone during typical usage.

$R_p$ = outdoor airflow rate required per person as determined from Table 6-1

Note: These values are based on adapted occupants.

$R_a$ = outdoor airflow rate required per unit area as determined from Table 6-1
### TABLE 6-1  MINIMUM VENTILATION RATES IN BREATHING ZONE
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

<table>
<thead>
<tr>
<th>Occupancy Category</th>
<th>People Outdoor Air Rate $R_p$</th>
<th>Area Outdoor Air Rate $R_a$</th>
<th>Default Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>People Outdoor Air Rate</td>
<td>Area Outdoor Air Rate</td>
<td>Occupant Density (see Note 4)</td>
</tr>
<tr>
<td></td>
<td>$R_p$</td>
<td>$R_a$</td>
<td>#/1000 ft$^2$ or #/100 m$^2$</td>
</tr>
<tr>
<td>Correctional Facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell</td>
<td>5</td>
<td>0.12</td>
<td>25</td>
</tr>
<tr>
<td>Dayroom</td>
<td>5</td>
<td>0.06</td>
<td>30</td>
</tr>
<tr>
<td>Guard stations</td>
<td>5</td>
<td>0.06</td>
<td>15</td>
</tr>
<tr>
<td>Booking/waiting</td>
<td>7.5</td>
<td>0.06</td>
<td>50</td>
</tr>
<tr>
<td>Educational Facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daycare (through age 4)</td>
<td>10</td>
<td>0.18</td>
<td>25</td>
</tr>
<tr>
<td>Daycare sickroom</td>
<td>10</td>
<td>0.18</td>
<td>25</td>
</tr>
<tr>
<td>Classrooms (ages 5–8)</td>
<td>10</td>
<td>0.12</td>
<td>25</td>
</tr>
<tr>
<td>Classrooms (age 9 plus)</td>
<td>10</td>
<td>0.12</td>
<td>35</td>
</tr>
<tr>
<td>Lecture classroom</td>
<td>7.5</td>
<td>0.06</td>
<td>65</td>
</tr>
<tr>
<td>Lecture hall (fixed seats)</td>
<td>7.5</td>
<td>0.06</td>
<td>150</td>
</tr>
<tr>
<td>Art classroom</td>
<td>10</td>
<td>0.18</td>
<td>20</td>
</tr>
<tr>
<td>Science laboratories</td>
<td>10</td>
<td>0.18</td>
<td>25</td>
</tr>
<tr>
<td>University/college laboratories</td>
<td>10</td>
<td>0.18</td>
<td>25</td>
</tr>
<tr>
<td>Wood/metal shop</td>
<td>10</td>
<td>0.18</td>
<td>20</td>
</tr>
<tr>
<td>Computer lab</td>
<td>10</td>
<td>0.12</td>
<td>25</td>
</tr>
</tbody>
</table>
## TABLE 6-1  MINIMUM VENTILATION RATES IN BREATHING ZONE (Continued)
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

<table>
<thead>
<tr>
<th>Occupancy Category</th>
<th>People Outdoor Air Rate $R_p$</th>
<th>Area Outdoor Air Rate $R_a$</th>
<th>Default Values</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>People/Outdoor Air Rate $R_p$</td>
<td>Area/Outdoor Air Rate $R_a$</td>
<td>Occupant Density (see Note 4)</td>
<td>Combined Outdoor Air Rate (see Note 5)</td>
</tr>
<tr>
<td></td>
<td>cfm/person</td>
<td>L/s-person</td>
<td>cfm/ft²</td>
<td>L/s·m²</td>
</tr>
<tr>
<td>Office Buildings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breakrooms</td>
<td>5</td>
<td>2.5</td>
<td>0.12</td>
<td>0.6</td>
</tr>
<tr>
<td>Main entry lobbies</td>
<td>5</td>
<td>2.5</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Occupiable storage rooms for dry materials</td>
<td>5</td>
<td>2.5</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Office space</td>
<td>5</td>
<td>2.5</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Reception areas</td>
<td>5</td>
<td>2.5</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Telephone/data entry</td>
<td>5</td>
<td>2.5</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Miscellaneous Spaces</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bank vaults/safe deposit</td>
<td>5</td>
<td>2.5</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Banks or bank lobbies</td>
<td>7.5</td>
<td>3.8</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Computer (not printing)</td>
<td>5</td>
<td>2.5</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>General manufacturing (excludes heavy industrial and processes using chemicals)</td>
<td>10</td>
<td>5.0</td>
<td>0.18</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Air Class

- 1
- 2
- 3
<table>
<thead>
<tr>
<th>Occupancy Category</th>
<th>Exhaust Rate, cfm/unit</th>
<th>Exhaust Rate, cfm/ft²</th>
<th>Notes</th>
<th>Exhaust Rate, L/s/unit</th>
<th>Exhaust Rate, L/s-m²</th>
<th>Air Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arenas</td>
<td>–</td>
<td>0.50</td>
<td>B</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>Art classrooms</td>
<td>–</td>
<td>0.70</td>
<td></td>
<td>–</td>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>Auto repair rooms</td>
<td>–</td>
<td>1.50</td>
<td>A</td>
<td>–</td>
<td>7.5</td>
<td>2</td>
</tr>
<tr>
<td>Barber shops</td>
<td>–</td>
<td>0.50</td>
<td></td>
<td>–</td>
<td>2.5</td>
<td>2</td>
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<tr>
<td>Beauty and nail salons</td>
<td>–</td>
<td>0.60</td>
<td></td>
<td>–</td>
<td>3.0</td>
<td>2</td>
</tr>
<tr>
<td>Cells with toilet</td>
<td>–</td>
<td>1.00</td>
<td></td>
<td>–</td>
<td>5.0</td>
<td>2</td>
</tr>
<tr>
<td>Copy, printing rooms</td>
<td>–</td>
<td>0.50</td>
<td></td>
<td>–</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>Darkrooms</td>
<td>–</td>
<td>1.00</td>
<td></td>
<td>–</td>
<td>5.0</td>
<td>2</td>
</tr>
<tr>
<td>Educational science laboratories</td>
<td>–</td>
<td>1.00</td>
<td></td>
<td>–</td>
<td>5.0</td>
<td>2</td>
</tr>
<tr>
<td>Janitor closets, trash rooms, recycling</td>
<td>–</td>
<td>1.00</td>
<td></td>
<td>–</td>
<td>5.0</td>
<td>3</td>
</tr>
<tr>
<td>Kitchenettes</td>
<td>–</td>
<td>0.30</td>
<td></td>
<td>–</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Kitchens—commercial</td>
<td>–</td>
<td>0.70</td>
<td></td>
<td>–</td>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>Locker/dressing rooms</td>
<td>–</td>
<td>0.25</td>
<td></td>
<td>–</td>
<td>1.25</td>
<td>2</td>
</tr>
<tr>
<td>Locker rooms</td>
<td>–</td>
<td>0.50</td>
<td></td>
<td>–</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>Paint spray booths</td>
<td>–</td>
<td>–</td>
<td>F</td>
<td>–</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>Parking garages</td>
<td>–</td>
<td>0.75</td>
<td>C</td>
<td>–</td>
<td>3.7</td>
<td>2</td>
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<tr>
<td>Pet shops (animal areas)</td>
<td>–</td>
<td>0.90</td>
<td></td>
<td>–</td>
<td>4.5</td>
<td>2</td>
</tr>
<tr>
<td>Refrigerating machinery rooms</td>
<td>–</td>
<td>–</td>
<td>F</td>
<td>–</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>Residential kitchens</td>
<td>50/100</td>
<td>–</td>
<td>G</td>
<td>25/50</td>
<td>–</td>
<td>2</td>
</tr>
<tr>
<td>Soiled laundry storage rooms</td>
<td>–</td>
<td>1.00</td>
<td>F</td>
<td>–</td>
<td>5.0</td>
<td>3</td>
</tr>
<tr>
<td>Storage rooms, chemical</td>
<td>–</td>
<td>1.50</td>
<td>F</td>
<td>–</td>
<td>7.5</td>
<td>4</td>
</tr>
</tbody>
</table>
1. PURPOSE

This standard defines the roles of and minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable indoor air quality (IAQ) in low-rise residential buildings.

2. SCOPE

This standard applies to spaces intended for human occupancy within single-family houses and multifamily structures of three stories or fewer above grade, including manufactured and modular houses. This standard does not apply to transient housing such as hotels, motels, nursing homes, dormitories, or jails.

2.1 This standard considers chemical, physical, and biological contaminants that can affect air quality. Thermal comfort requirements are not included in this standard (see ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy).

2.2 While acceptable indoor air quality is the goal of this standard, it will not necessarily be achieved even if all requirements are met.
4. WHOLE-BUILDING VENTILATION

4.1 Ventilation Rate. A mechanical exhaust system, supply system, or combination thereof shall be installed for each dwelling unit to provide whole-building ventilation with outdoor air each hour at no less than the rate specified in Tables 4.1a and 4.1b or, equivalently, Equations 4.1a and 4.1b, based on the floor area of the conditioned space and number of bedrooms.

\[
Q_{\text{fan}} = 0.01 A_{\text{floor}} + 7.5 (N_{\text{br}} + 1) \quad (4.1a)
\]

where
- \( Q_{\text{fan}} \) = fan flow rate, cfm
- \( A_{\text{floor}} \) = floor area, \( \text{ft}^2 \)
- \( N_{\text{br}} \) = number of bedrooms; not to be less than one

\[
Q_{\text{fan}} = 0.05 A_{\text{floor}} + 3.5 (N_{\text{br}} + 1) \quad (4.1b)
\]

where
- \( Q_{\text{fan}} \) = fan flow rate, L/s
- \( A_{\text{floor}} \) = floor area, \( \text{m}^2 \)
- \( N_{\text{br}} \) = number of bedrooms; not to be less than one

<table>
<thead>
<tr>
<th>Floor Area (\text{ft}^2)</th>
<th>0–1</th>
<th>2–3</th>
<th>4–5</th>
<th>6–7</th>
<th>&gt;7</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1500</td>
<td>30</td>
<td>45</td>
<td>60</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td>1501–3000</td>
<td>45</td>
<td>60</td>
<td>75</td>
<td>90</td>
<td>105</td>
</tr>
<tr>
<td>3001–4500</td>
<td>60</td>
<td>75</td>
<td>90</td>
<td>105</td>
<td>120</td>
</tr>
<tr>
<td>4501–6000</td>
<td>75</td>
<td>90</td>
<td>105</td>
<td>120</td>
<td>135</td>
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<tr>
<td>6001–7500</td>
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<td>105</td>
<td>120</td>
<td>135</td>
<td>150</td>
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<tr>
<td>&gt;7500</td>
<td>105</td>
<td>120</td>
<td>135</td>
<td>150</td>
<td>165</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Floor Area (\text{m}^2)</th>
<th>0–1</th>
<th>2–3</th>
<th>4–5</th>
<th>6–7</th>
<th>&gt;7</th>
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<tbody>
<tr>
<td>&lt;139</td>
<td>14</td>
<td>21</td>
<td>28</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td>139.1–279</td>
<td>21</td>
<td>28</td>
<td>35</td>
<td>42</td>
<td>50</td>
</tr>
<tr>
<td>279.1–418</td>
<td>28</td>
<td>35</td>
<td>42</td>
<td>50</td>
<td>57</td>
</tr>
<tr>
<td>418.1–557</td>
<td>35</td>
<td>42</td>
<td>50</td>
<td>57</td>
<td>64</td>
</tr>
<tr>
<td>557.1–697</td>
<td>42</td>
<td>50</td>
<td>57</td>
<td>64</td>
<td>71</td>
</tr>
<tr>
<td>&gt;697</td>
<td>50</td>
<td>57</td>
<td>64</td>
<td>71</td>
<td>78</td>
</tr>
</tbody>
</table>
HEATING AND COOLING LOADS
Introducing heating and cooling loads

• We need to know how all of the heat gains and losses in a building add up to affect thermal comfort

• When we use HVAC systems to maintain comfortable indoor conditions, we need to know what the “peak” loads for both heating and cooling are in order to design/select equipment
  – Load calculations

• How do we combine what we know about individual modes of heat transfer to estimate heating and cooling requirements?
  – And how can we use that same information to estimate energy use requirements?
Heat balance

- For either heating or cooling loads, we can describe a “heat balance” on a building.
Sensible heat losses and gains

Conduction through envelope

\[ Q_{\text{cond}} = (UA)_{\text{cond}} (T_{\text{in}} - T_{\text{out}}) \]

Conduction through floor

\[ Q_{\text{cond, floor}} = (UA)_{\text{floor}} (T_{\text{in}} - T_{\text{ground}}) \]

Air exchange

\[ Q_{\text{air}} = \dot{V} \rho C_p (T_{\text{in}} - T_{\text{out}}) \]

Heat gains (sun, lights, equipment, and occupants)

\[ Q_{\text{gains}} = Q_{\text{solar}} + Q_{\text{light}} + Q_{\text{equip}} + Q_{\text{occ}} \]
Sensible heat balance: Total sensible load

\[ Q_{\text{sensible}} = Q_{\text{cond}} + Q_{\text{air}} + Q_{\text{floor}} - Q_{\text{gains}} \pm Q_{\text{storage}} \]

- \( Q_{\text{storage}} \) accounts for thermal mass or thermal inertia of a building
  - Static analysis neglects the storage term

- \( Q \) is positive when there is a heating load (cold outside)
  - Negative when there is a cooling load (hot outside)
Latent heat gains

- Mainly due to:
  - Air exchange
  - Equipment (kitchen/bathroom)
  - Occupants

\[ Q_{\text{latent}} = Q_{\text{latent,air}} + Q_{\text{latent,occ}} + Q_{\text{latent,equip}} \]

- Latent gain from air exchange is usually negative in winter
Building envelope heat transmission coefficient

\[ Q_{\text{sensible}} = Q_{\text{cond}} + Q_{\text{air}} + Q_{\text{floor}} - Q_{\text{gains}} \pm Q_{\text{storage}} \]

\[ Q_{\text{cond}} = (UA)_{\text{cond}} (T_{\text{in}} - T_{\text{out}}) \]

We’ve already defined a whole-building envelope heat transmission coefficient:

\[ (UA)_{\text{cond}} = (UA)_{\text{windows}} + (UA)_{\text{walls}} + (UA)_{\text{roof}} \]
Total heat transmission coefficient: Envelope + air exchange

- We can also lump conduction and air exchange together to define a total building heat transfer coefficient:

\[
(UA)_{total} = (UA)_{cond} + \rho C_p \dot{V} = K_{total}
\]
Heat gains

\[ Q_{\text{gains}} = Q_{\text{solar}} + Q_{\text{light}} + Q_{\text{equip}} + Q_{\text{occ}} \]

- Internal heat gains are heat sources on the inside of the building
- These are all always positive meaning they always add heat to the interior of the building
  - Affect both heating and cooling loads

Typical gains:
- Solar gains through windows
- Heat gains from occupants, lights, and equipment
  - Motors, copiers, computers, appliances, etc.
- We need to know their scheduling (when they are off and on) as well as their magnitude
Heat gains from people

- Representative heat gains for people in different activities are listed in the ASHRAE Handbook of Fundamentals
- Keep the latent load separate from the sensible load

### Table 1: Representative Rates at Which Heat and Moisture Are Given Off by Human Beings in Different States of Activity

<table>
<thead>
<tr>
<th>Degree of Activity</th>
<th>Total Heat, W</th>
<th>Sensible Heat, W</th>
<th>Latent Heat, W</th>
<th>% Sensible Heat that is Radiant&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adult Male</td>
<td>Adjusted, M/F&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Low V</td>
<td>High V</td>
</tr>
<tr>
<td>Seated at theater</td>
<td>115</td>
<td>95</td>
<td>65</td>
<td>30</td>
</tr>
<tr>
<td>Seated at theater, night</td>
<td>115</td>
<td>105</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>Seated, very light work</td>
<td>130</td>
<td>115</td>
<td>70</td>
<td>45</td>
</tr>
<tr>
<td>Moderately active office work</td>
<td>140</td>
<td>130</td>
<td>75</td>
<td>55</td>
</tr>
<tr>
<td>Standing, light work; walking</td>
<td>160</td>
<td>130</td>
<td>75</td>
<td>55</td>
</tr>
<tr>
<td>Walking, standing</td>
<td>160</td>
<td>145</td>
<td>75</td>
<td>70</td>
</tr>
<tr>
<td>Sedentary work</td>
<td>145</td>
<td>160</td>
<td>80</td>
<td>80</td>
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<tr>
<td>Light bench work</td>
<td>235</td>
<td>220</td>
<td>80</td>
<td>140</td>
</tr>
<tr>
<td>Moderate dancing</td>
<td>265</td>
<td>250</td>
<td>90</td>
<td>160</td>
</tr>
<tr>
<td>Walking 4.8 km/h; light machine work</td>
<td>295</td>
<td>295</td>
<td>110</td>
<td>185</td>
</tr>
<tr>
<td>Bowling&lt;sup&gt;d&lt;/sup&gt;</td>
<td>440</td>
<td>425</td>
<td>170</td>
<td>255</td>
</tr>
<tr>
<td>Heavy work</td>
<td>440</td>
<td>425</td>
<td>170</td>
<td>255</td>
</tr>
<tr>
<td>Heavy machine work; lifting</td>
<td>470</td>
<td>470</td>
<td>185</td>
<td>285</td>
</tr>
<tr>
<td>Athletics</td>
<td>585</td>
<td>525</td>
<td>210</td>
<td>315</td>
</tr>
</tbody>
</table>
Heat gains from lighting

- Lights are often a major internal heat load component
  - This is changing as lighting efficiency increases
- Lights contribute to heat gain through convection and radiation
  - Function of total wattage and how much they are used

<table>
<thead>
<tr>
<th>Description</th>
<th>Ballast</th>
<th>Watts/Lamp</th>
<th>Lamps/Fixture</th>
<th>Lamp Watts</th>
<th>Fixture Watts</th>
<th>Special Allowance Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compact Fluorescent Fixtures</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twin, (1) 5 W lamp</td>
<td>Mag-Std</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>1.80</td>
</tr>
<tr>
<td>Twin, (1) 7 W lamp</td>
<td>Mag-Std</td>
<td>7</td>
<td>1</td>
<td>7</td>
<td>10</td>
<td>1.43</td>
</tr>
<tr>
<td>Twin, (1) 9 W lamp</td>
<td>Mag-Std</td>
<td>9</td>
<td>1</td>
<td>9</td>
<td>11</td>
<td>1.22</td>
</tr>
<tr>
<td>Quad, (1) 13 W lamp</td>
<td>Mag-Std</td>
<td>13</td>
<td>1</td>
<td>13</td>
<td>17</td>
<td>1.31</td>
</tr>
<tr>
<td>Quad, (2) 18 W lamp</td>
<td>Mag-Std</td>
<td>18</td>
<td>2</td>
<td>36</td>
<td>45</td>
<td>1.25</td>
</tr>
<tr>
<td>Quad, (2) 22 W lamp</td>
<td>Mag-Std</td>
<td>22</td>
<td>2</td>
<td>44</td>
<td>48</td>
<td>1.09</td>
</tr>
<tr>
<td>Quad, (2) 26 W lamp</td>
<td>Mag-Std</td>
<td>26</td>
<td>2</td>
<td>52</td>
<td>66</td>
<td>1.27</td>
</tr>
<tr>
<td><strong>Fluorescent Fixtures</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) 450 mm, T8 lamp</td>
<td>Mag-Std</td>
<td>15</td>
<td>1</td>
<td>15</td>
<td>19</td>
<td>1.27</td>
</tr>
<tr>
<td>(1) 450 mm, T12 lamp</td>
<td>Mag-Std</td>
<td>15</td>
<td>1</td>
<td>15</td>
<td>19</td>
<td>1.27</td>
</tr>
<tr>
<td>(2) 450 mm, T8 lamp</td>
<td>Mag-Std</td>
<td>15</td>
<td>2</td>
<td>30</td>
<td>36</td>
<td>1.20</td>
</tr>
<tr>
<td>(4) 1200 mm, T8 lamp</td>
<td>Electronic</td>
<td>32</td>
<td>4</td>
<td>128</td>
<td>120</td>
<td>0.94</td>
</tr>
<tr>
<td>(1) 1500 mm, T12 lamp</td>
<td>Mag-Std</td>
<td>50</td>
<td>1</td>
<td>50</td>
<td>63</td>
<td>1.26</td>
</tr>
<tr>
<td>(2) 1500 mm, T12 lamp</td>
<td>Mag-Std</td>
<td>50</td>
<td>2</td>
<td>100</td>
<td>128</td>
<td>1.28</td>
</tr>
</tbody>
</table>
Heat gains from electric motors

• For an electric motor used inside a conditioned space:

\[ Q_{\text{motor}} = \frac{P}{E_m} F_l F_u \]

- \( P \) = motor power rating [W]
- \( \eta_m \) = motor efficiency \((0 < \eta_m < 1)\)
- \( F_u \) = motor use factor (fraction of time on)
- \( F_l \) = motor load factor = fraction of load delivered during the conditions for the load estimate

Typical motor efficiencies range from 20 to 80%
Load calculations

- Heating load calculations are based on steady state, instantaneous loads
  - Highest heating load is in late night or early mornings

- For cooling load calculations things are more difficult
  - Peak cooling loads will be during the day when solar radiation is present
  - Solar radiation varies during the day and building thermal mass affects radiative heating and cooling so calculations must be dynamic
  - People and equipment are usually present and these too can be variable

- Both utilize a concept of “design conditions”
Design conditions

• When sizing a system to provide a heating or cooling load we need to size it for worst case conditions (or nearly worst case conditions)
  – If equipment is too large it may run at very low efficiency

• We choose extreme (or nearly extreme) design conditions on which to base heating and cooling load calculations
  – Based on different levels of probability of occurrence

• Indoor design conditions are typically in the middle of the ASHRAE comfort zone
  – 70°F (21°C) and 30% RH

• Outdoor design conditions are not usually the coldest and/or warmest conditions ever measured, but are usually related to statistical measures obtained from long term (10+ years) measurements of temperature, humidity, and wind
Outdoor design conditions: Winter

- ASHRAE has compiled decades of weather data for many cities
  - Available in the ASHRAE Fundamentals Handbook

- ASHRAE lists the 99% and 99.6% cold temperatures
  - Also mean wind speed and prevailing direction

- Summer design conditions: Top 2%, 1%, or 0.4% in DBT

- The idea is that the air temperature is colder than the 99% value for about 88 hours per year and colder than the 99.6% for about 35 hours per year
  - For Chicago, the winter 99% dry bulb temperature is 0.8°F and the 99.6% DB temp is -5.0°F
  - Annual extreme is -11.5°F (with 7.5°F standard deviation), 5 year extreme is -16.5°F, 50 year extreme is -30.9°F
### ASHRAE Chicago O’Hare design conditions

- Design conditions are somewhat subjective (which percentile?)

---

#### Annual Heating and Humidification Design Conditions

<table>
<thead>
<tr>
<th>Coldest Month</th>
<th>Heating DB</th>
<th>Humidification DP/MCDB and HR</th>
<th>Coldest month WS/MCDB</th>
<th>MCWS/PCWD to 99.6% DB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4%</td>
<td>1%</td>
<td>0.4%</td>
<td>1%</td>
</tr>
<tr>
<td>99.6%</td>
<td>DP</td>
<td>HR</td>
<td>WS</td>
<td>MCWS</td>
</tr>
<tr>
<td>99%</td>
<td>MCDB</td>
<td></td>
<td>MCDB</td>
<td>PCWD</td>
</tr>
</tbody>
</table>

- **Lat:** 41.99N  **Long:** 87.91W  **Elev:** 673  **StdP:** 14.34  **Time Zone:** -6.00 (NAC)  **Period:** 82-06  **WBAN:** 94846

#### Annual Cooling, Dehumidification, and Enthalpy Design Conditions

<table>
<thead>
<tr>
<th>Hottest Month</th>
<th>Hottest Month DB Range</th>
<th>Cooling DB/MCWB</th>
<th>Evaporation WB/MCDB</th>
<th>MCWS/PCWD to 0.4% DB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4%</td>
<td>1%</td>
<td>0.4%</td>
<td>1%</td>
</tr>
<tr>
<td>9%</td>
<td>DP</td>
<td>HR</td>
<td>WS</td>
<td>MCWS</td>
</tr>
<tr>
<td>9%</td>
<td>MCDB</td>
<td></td>
<td>MCDB</td>
<td>PCWD</td>
</tr>
</tbody>
</table>

- **DB:** 74.6  **MCWB:** 89.0  **DB:** 73.4  **MCWB:** 86.1  **DB:** 71.9  **MCWB:** 77.9
- **DB:** 77.9  **MCWB:** 88.2  **DB:** 85.2  **MCWB:** 74.3  **DB:** 82.6  **MCWB:** 11.6  **MCWB:** 230

#### Extreme Annual Design Conditions

<table>
<thead>
<tr>
<th>Extreme Annual WS</th>
<th>Extreme Max WB</th>
<th>Extreme Annual Mean DB</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
<td>Min</td>
</tr>
<tr>
<td>24.8</td>
<td>21.1</td>
<td>19.2</td>
<td>-10.7</td>
</tr>
<tr>
<td>99.2</td>
<td>-16.6</td>
<td>101.2</td>
<td>99.2</td>
</tr>
</tbody>
</table>
City of Chicago requirements for design conditions

- The City of Chicago Building code has required design conditions that differ slightly from ASHRAE

- Winter Design Condition: \( T_{db} = -10°F \)

- Summer Design: \( T_{db} = 92°F, T_{wb} = 74°F \)

- The maximum allowable interior design temperature is 72°F for heating and 75°F for cooling
The peak heating load is simple and relies on two modes: 

**Overall envelope transmission** and **infiltration**

- **Transmission load** (enclosure losses) is the heat lost to the outside through the building enclosure.

- **Infiltration load** (ventilation losses) is the heat required to warm up the cold outside air that leaks into the building through cracks or is brought in via ventilation.
Heating load calculations

\[
Q_{h,\text{max}} = (UA)_{\text{total}} (T_{\text{in}} - T_{\text{out}}) - Q_{\text{gain}}
\]

Example:
- Find the design heat load for a 12 m x 12 m x 2.5 m (39.4 ft x 39.4 ft x 8.2 ft) building with 0.25 m (10 in) of fiberglass insulation (\(k = 0.06\) W/mK) in a flat roof and 0.15 m (6 in) of fiberglass insulation in the walls
  - Double glazed windows (\(U = 3\) W/m²K) cover 20% of the sides
  - The air exchange rate is 0.5 per hour
  - Ignore floor heat transfer
  - Design conditions of -10°C (14°F) out and 22°C (71.6°F) in
  - Internal gains = 1 kW (3.4 kBTU/hr)
A note on thermal zones

• We’ve relied on single zone assumptions so far

• Larger buildings will be divided into multiple zones
  – Need to calculate loads separately

• Need to consider the number of zones to control in selection HVAC equipment

• Perimeter versus core
Heating equipment selection

Questions to ask in choosing a heating system:

- What fuel is it going to burn?
- What medium is it going to heat?
- How much is it going to heat it?
- Where are you going to put it?
- What else do you need to make it work?
Heating: Choosing a fuel type

• How to choose between gas furnaces, water boilers, or electric heaters?

• Availability
  – Emergencies, back-up power, peak demand

• Storage
  – Space requirements, aesthetic impacts, safety

• Cost
  – Capital, operating, maintenance

• Code restrictions
  – Safety, emissions
Heating: Selecting a heat transfer medium

- **Air**
  - Inefficient heat transfer medium (low density and low $C_p$)
    - Needs electricity to move air with fans
  - But can be combined with cooling, has low maintenance, and equipment is simple

- **Steam**
  - Necessary for steam loads, little/no pumping
  - But: lower heat transfer, condensate return, bigger pipes

- **Water**
  - Better heat transfer, smaller pipes, simpler
  - But: requires pumps, lower velocities, can require complex systems
Typical gas furnace

Gas furnace efficiency is typically 80-90%

Electric furnace is ~100%

FIGURE 5-2
(a) Cutaway view of a typical open-chamber type gas-fired furnace; (b) typical closet installation; and (c) typical utility room installation. (Courtesy: Lennox Industries, Inc., Richardson, TX.)
Moving conditioned air around: Air Handling Units (AHU)

AHU schematic

- Exhaust
- Flow control dampers
- Outdoor air
- From room
- Return fan
- Supply fan
- To room
- Fresh air
- Mixing
- Filter
- Evaporator
- Fan
- Air from building
- To building
- Gas/Electric Heater
- Compressor and Condenser
Control of air systems

• Vary temperature, constant flow

• Constant temperature, vary flow

• Vary temperature, vary flow
How does a residential thermostat work?

- **On-off systems**
  - Residential and small commercial
- **Vary volume by turning system on and off**
- **Thermostat operates within a certain range**

![Graph showing temperature variations over time with on and off points for a thermostat.]
Constant volume: Temperature control

- Proportional control or Proportional Integral control
  - Thermostat measures: $\Delta T = T_{\text{set point}} - T_{\text{zone air}}$
  - Sends signal to the valve of cooling/heating coil
Multizone constant air volume with reheat

Require less cooling
Variable air volume

Vary the flow
Water systems

Fan coil units

Baseboard heaters

Radiant panels
FLUID FLOWS

In buildings
Fluid flows in buildings

• We use liquids and gases to deliver heating or cooling energy in building mechanical systems
  – Water, refrigerants, and air

• We often need to understand fluid motion, pressure loses, and pressure rises by pumps and fans in order to size systems

• We can use the Bernoulli equation to describe fluid flows in HVAC systems

\[ p_1 + \frac{1}{2} \rho_1 v_1^2 + \rho_1 gh_1 = p_2 + \frac{1}{2} \rho_2 v_2^2 + \rho_2 gh_2 + K \frac{v^2}{2} \]

- Static pressure
- Velocity pressure
- Pressure head
- Friction
Pressure losses

- We often need to find the pressure drop in pipes and ducts
- Most flows in HVAC systems are turbulent

\[ \Delta p_{\text{friction}} = f \left( \frac{L}{D_h} \right) \left( \frac{1}{2} \rho v^2 \right) \]

\[ D_h = \frac{4A}{P} = \text{hydraulic diameter} \]

\[ K = f \left( \frac{L}{D_h} \right) \quad \text{In a straight pipe} \]

\[ K = f \left( \frac{L}{D_h} + \sum_{\text{fittings}} K_f \right) \quad \text{In a straight pipe with fittings} \]
Reynolds number

- Reynolds number relates inertial forces to viscous forces:

\[ \text{Re} = \frac{VL}{\nu} \]

- Kinematic viscosity

\[ \nu = \frac{\mu}{\rho} = 1.5 \times 10^{-5} \text{ m}^2/\text{s} \] (for air at T=25°C)

L = D_n in a pipe or duct

![Fig. 4  Velocity Profiles of Flow in Pipes](image)
Pressure losses and rises

Return side: Negative pressure

Supply side: Positive pressure

Energy input into system by fan
Duct friction charts
Fan and system pressures

- Fan curves
- System curves
Fan and system curves: Ideal

\[ W_{\text{fan}} = \frac{\Delta P \cdot \dot{V}}{\eta_{\text{fan}}} \]
Fan and system curves: Real

\[ W_{\text{fan}} = \frac{\Delta P \cdot \dot{V}}{\eta_{\text{fan}}} \]
Next time

- Cooling load methods (various)
- Energy estimation methods
- HW #5 due