Building Science

Heat Flow & Insulation

To Date

- Previously,
  - Why Building Science
  - What do Buildings do?
- Last week
  - Site, shape, size, orientation

The Building Enclosure

- The part of the building that physically *separates* the *interior* and *exterior* environments.
- Includes all of the parts that make up the wall, window, roof, floor, etc… from the innermost to the outermost layer.
- Functions – Control, Support, Finish (sometimes distribute)

Building Enclosure Components
Building Enclosure Functions

- Basic Functions
  - Support
  - Control
  - Finish
  - Distribute (sometimes)

Control - Mass and Energy Flows

Overview

- Heat
  - modes of heat transport
- Insulation
  - how insulation works
  - impact of deficiencies esp. air flow

Why Insulate?

- Occupant Comfort
- Energy Savings
- Control surface and interstitial condensation
- Save duct and heating plant costs (Capital)
- Meet Codes and specs

Heat & Temperature

- Heat
  - A form of energy (like Light & Sound)
- Temperature
  - A measure of the amount of thermal energy
- Heat Flow
Heat Flow

- Always moves from more to less
- Rate of flow depends on:
  - Temperature Difference
  - Material Properties
  - Type & Mode

Type of Heat flow
- steady-state or dynamic
- one-, two- or three-dimensional

Mode of Heat Flow
- Conduction
- Convection
- Radiation

Conduction
- Heat Flow by direct contact
- Vibrating molecules
- Most important for solids

Convection
- Heat Flow by bulk movement of molecules
- Most important for liquids and gases
- E.g. air flow (forced air furnace)
Convection
- Also heat flow from solid to liquid or gas
- Critical for surface heat transfer (e.g. radiators)

\[ q_{\text{convection}} = 1.42(\Delta T/L)^0.25A(\Delta T) \]

Radiation
- Heat flow by electromagnetic waves
- Heat radiates from all materials, e.g. campfire
- Passes through gases and vacuum (NOT Solid)

\[ q_{\text{radiation}} = \varepsilon_1\varepsilon_2A(\sigma(T_1^4 - T_2^4)) \]

Radiation
- Important for surfaces, air spaces, voids
- Foil faced insulation, radiant barriers only work when facing an air space
- Radiation within pores important for high void insulation (e.g., glass batt)
- e.g. Thermos bottle

Calculating Heat Flow
- Conduction
  - \[ q = UA(T_1 - T_2) \]
- Convection
  - E.g. \[ q = 1.42(\Delta T/L)^{0.25}A(\Delta T) \]
- Radiation
  - E.g. \[ q = \varepsilon_1\varepsilon_2A(\sigma(T_1^4 - T_2^4)) \]
Calculating Heat Flow

\[ q = UA(T_1 - T_2) = UA(\Delta T) \]

- Where
  - \( q \) = heat flow rate (W = J/s)
  - \( A \) = area that the heat is flowing through (m²)
  - \( \Delta T \) = temperature difference across layer (°C)
  - \( U \) = conductance of the layer (W/m²K)

Conductance?

- Conductance is a layer property
- Expresses how easily heat can flow through a layer of the material
  \[ U = \frac{k}{l} = \frac{1}{R} \]
  Conductance = Conductivity / Thickness = 1 / Resistance

- R-Value is an expression of how well a layer of the material resists heat flow

Materials

- Thermal conductivity (& resistance) varies with
  - material type (conduction, radiation)
  - density and pore structure
  - moisture content
  - temperature difference
- Combination of insulation of air + material
- *Still* air is about R6/inch
- Only gas fills (e.g. HCFC) can improve this
Materials

- High conductivity and high density
  - e.g. wood R1/inch and 45 pcf
  - versus concrete R0.1/inch and 140 pcf
- Low conductivity and low density
  - e.g. glass batt R3.5/inch and 1 pcf
- Compromise
  - cellulose, R3.5/inch and 3 pcf

Fibers

- Mineral Fiber Insulation (vs organic fibers)
  - glass fiber
  - rock fiber
  - slag fiber
  - rockwool
- Glass vs rockwool
  - melts a much lower temperature
  - has thinner fibers so can use lower density
  - Lower density means more air permeance, less strength, and low volume shipping

Foams

- Expanded Polystyrene (EPS)
  - R-value of 3.6 to 4.2
- Extruded Polystyrene (XPS)
  - higher R-value, usually 5/inch or higher
  - usually more strength
- Polyisocyanurate (PIC)
  - starts high R-value, then ...
- Polyurethane (PUR)
- Phenolic
- all have fire “issues”
Assemblies

- Building enclosures are typically assemblies of several layers of different materials
- The overall resistance must be calculated
  \[ R_{\text{tot}} = R_1 + R_2 + R_3 \ldots \]
- The conductance of the assembly is then
  \[ U = \frac{1}{R_{\text{tot}}} \]

Air Spaces & Surface Films

- All 3 modes of heat transfer play a role
- The effects are lumped into a coefficient, \( h_a \), which can be used in the conduction equation as an effective conductance

### Air Spaces

<table>
<thead>
<tr>
<th>Situation (non reflective surfaces)</th>
<th>RSI Value</th>
<th>Conductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flow Down (20-100 mm)</td>
<td>0.18</td>
<td>5.5</td>
</tr>
<tr>
<td>Heat Flow Across (20-100 mm)</td>
<td>0.17</td>
<td>5.9</td>
</tr>
<tr>
<td>Heat Flow Up (20-100 mm)</td>
<td>0.15</td>
<td>6.5</td>
</tr>
</tbody>
</table>
Surface Films

<table>
<thead>
<tr>
<th>Surface Position</th>
<th>Flow Direction</th>
<th>Resistance (m²K/W)</th>
<th>Conductance (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still Air (e.g. indoors)</td>
<td>RSI [m²K/W]</td>
<td>[W/m²K]</td>
<td></td>
</tr>
<tr>
<td>Horizontal (i.e. ceilings &amp; floors)</td>
<td>Upward</td>
<td>0.11</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>Downward</td>
<td>0.16</td>
<td>6.1</td>
</tr>
<tr>
<td>Vertical (i.e. walls)</td>
<td>Horizontal</td>
<td>0.12</td>
<td>8.3</td>
</tr>
<tr>
<td>Moving Air (e.g. outdoors)</td>
<td>Stormy 6.7m/s (winter)</td>
<td>Any</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Breeze 3.4m/s (summer)</td>
<td>Any</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Average Conditions</td>
<td>Any</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Example: Calculating the Conductance of an Assembly

<table>
<thead>
<tr>
<th>Layer Material</th>
<th>Conductivity</th>
<th>Thickness</th>
<th>Conductance</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior film</td>
<td>N.A.</td>
<td>N.A.</td>
<td>8.3</td>
<td>0.120</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.8</td>
<td>0.150</td>
<td>12</td>
<td>0.083</td>
</tr>
<tr>
<td>Type 4 XPS</td>
<td>0.029</td>
<td>0.075</td>
<td>0.39</td>
<td>2.56</td>
</tr>
<tr>
<td>Air space</td>
<td>N.A.</td>
<td>25</td>
<td>N.A.</td>
<td>0.17</td>
</tr>
<tr>
<td>Brick</td>
<td>1.3</td>
<td>0.090</td>
<td>14.4</td>
<td>0.069</td>
</tr>
<tr>
<td>Exterior film</td>
<td>N.A.</td>
<td>N.A.</td>
<td>34</td>
<td>0.029</td>
</tr>
<tr>
<td>RSI total</td>
<td></td>
<td></td>
<td>3.04</td>
<td></td>
</tr>
<tr>
<td>Overall Heat Transfer, U</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

But there are Complications

- The actual thermal resistance of an assembly is affected by
  1. **Thermal Bridges**
  2. **Thermal Mass**
  3. **Air Leakage**
Thermal Bridging

- Warm Interior
- Cold Exterior
- Siding
- Sheathing
- Batt + Framing
- Drywall

Thermal bridging:
- Heat flow

Clear Wall
- R-value

Corner
- Window Opening

Simple
- R-value
- Through Studspace

With exterior insulation
- 2x4 wood stud w/R12 batt
- 2x4 steel stud w/R12 batt

IR - I0000100.004
5/1/93 12:19:36 AM
14.0
22.0 °C
14
16
18
20
22
14
15
16
17
18
19
20
21
22
IR - I0000100.014
5/1/93 1:20:44 AM
14.0
22.0 °C
14
16
18
20
22
14
15
16
17
18
19
20
21
22
IR - I0000100.004
5/1/89 12:05:03 AM
14.0
22.0 °C
14
16
18
20
22
14
15
16
17
18
19
20
21
22
IR - I0000100.013
5/1/89 12:54:19 AM
14.0
22.0 °C
14
16
18
20
22
**Thermal Mass**
- Only comes into play when the heat transfer is not steady state
- Dampens the temperature changes experienced on the other side of the assembly

**Air Leakage**
- Air moving through the assembly allows heat to bypass the insulation
- Three types of air leakage to be concerned about:
  1. Through Wall
  2. Convective Loops in Wall
  3. Wind Washing

**Thru Wall Airflow**
- Air leakage accounts for 30 to 50% of a well-insulated house space conditioning
- Air leakage is a major moisture source
- Control, minimize leaks
- Air barrier system can be anywhere in wall
- Many materials stop airflow, most systems don’t
- Build tight, ventilate right
**Typical Air Leakage Points**

Convection Loops

**Cold Climate**

Robs insulation capacity

- Hot air = light
- Cold air = heavy

Result: Air Flow

- Energy cost
- Cold surfaces

**Convective Loop in Wall (Internal Stack Effect)**

- Gaps in batt insulation on both sides
- Stapled paper!

Inside

- Hot air = light

Outside

- Cold air = heavy

Common batt performance problem

**Convective Loop in Wall (Internal Stack Effect)**

- Gaps in batt insulation on both sides
- Closed circuit

Cold Climate

- Hot air = light
- Cold air = heavy

Result: Air Flow

- Air permeable insulation
**Convective Loops**

- Convection varies directly with temperature difference
- Requires flow path through cracks/insulation

**Solutions**
- Minimize temperature difference by using layers of insulation
- Fill space completely
- Use low air permeance insulations

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**Wind Pressure Distribution**

**Plan View**

- Windwashing
  - Need some airtightness outside studspace
  - Sealed housewrap, attached building paper
    - prevent flapping and thus pumping
  - Sheathing sealed with tape
    - both OSB and insulated sheathing
    - high density MI
  - High density cavity insulation
    - some foams, maybe dense cellulose
So what is the real R-value?

- Thermal Resistance (i.e. 1/conductance)
  - R-value
  - Thermal Bridging
- Airtightness
  - about 30 - 50% of energy loss
- Mass
  - smooths peaks and valleys
  - takes advantage of heat within (sun, equipment)
- Buildability / Inspectability
  - do you get what you spec/design?

Typically quoted R-values

- Give heat flow as equivalent conductance
  - Rarely includes thermal bridging
  - or three dimensions
- Never intended to include
  - airtightness
  - mass

Thermal Performance

**R-values and Real R-values**

- Walls are three-dimensional and must be considered as such.
- Simple R-values are inadequate to describe thermal performance of some walls
- Dynamic behaviour and/or three-dimensional details greatly affect energy consumption.

Different Types of R-values

- Center-of studspace ($R_{cs}$)
  - Typical value given. Calculated between framing members
- Clear-wall ($R_{cw}$)
  - More realistic 2-D. Calculations/tests of a section of wall.
- Whole-wall ($R_{ww}$)
  - Most realistic 3-D steady state. Calculations/tests
  - walls with interfaces, corners and openings, doors windows
- True Energy ($R_{te}$)
  - Includes time effects, e.g., 4-D = “mass effect”.
  - Dynamic Whole wall
  - Highly climate and building dependent.

Codes and R-values

- Implications: traditional framed walls have usually over-reported R-values
- New ASHRAE 90.1 uses clear-wall plus mass effect
  - Most local codes do not consider

**True energy equivalent R-values will vary with climate and building type, but consumption will always be lower for walls with thermal mass, and lowest for walls with thermal mass on the inside.**

### Typical R-values

<table>
<thead>
<tr>
<th>Wall Description</th>
<th>Wall Description</th>
<th>Center of cavity</th>
<th>Clear wall</th>
<th>Whole wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5&quot; SS@16 o.c. R12</td>
<td>3.5&quot; SS@16 o.c. R12 + 1&quot; EPS</td>
<td>12-13</td>
<td>12</td>
<td>7.4</td>
</tr>
<tr>
<td>3.5&quot; SS@16 o.c. R12</td>
<td>3.5&quot; SS@16 o.c. R12 + 1&quot; EPS</td>
<td>16-18</td>
<td>16</td>
<td>11.8</td>
</tr>
<tr>
<td>2x6 WS@24 in. o.c., R19 batt</td>
<td>2x6 WS@24 in. o.c., R19 batt</td>
<td>20</td>
<td>19</td>
<td>16.4</td>
</tr>
<tr>
<td>2x4 WS@16 in. o.c., R12 batt</td>
<td>2x4 WS@16 in. o.c., R12 batt</td>
<td>12-13</td>
<td>12</td>
<td>10.6</td>
</tr>
<tr>
<td>EPS block forms</td>
<td>EPS block forms</td>
<td>15.2</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Stressed Skin 6&quot; core</td>
<td>Stressed Skin 6&quot; core</td>
<td>25</td>
<td>25</td>
<td>24.7</td>
</tr>
</tbody>
</table>

*With information from Oak Ridge National Labs*

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Example House

- Excel

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Insulation Systems

- Fiberglass or rockwool batt
  - Blow in batt
- Cellulose
- foam in place
- insulated sheathings
- radiant barriers
- SIPS
### Batt Insulation
- Low-density rockwool and glass fibre
- R3.2 to 3.8 per inch
- Very low vapour resistance
- Very high air permeability
- Non-combustible
- Inexpensive
- Beware convective loops and wind washing

### Cellulose
- R value of 3.2 to 3.7 depending on density
- Controls convection at over 3, maybe 4 pcf
- Can fill irregular cavity spaces
- Variations with installation method
- Settling can be a problem with low density
- Don’t blow too wet
- Provides moisture storage
- Controls rot/mold by leaching borate
- Is not part of an air barrier system!
**Cellulose Install**

- Net or adhesive holds sprayed fiber in cavity
- Can use glass, rockwool, cellulose
- Fills space and around obstructions
- Avoids settling problems?
- Control convection

**Blow-in-batts**

**Spray Foam**

- Primarily polyurethane foam
- Open cell (CO₂ blown) Icynene
  - R4/inch
  - 16 perms for 3 inch
  - 1.6 lps/m² @ 75 Pa
- Closed cell (HCFC/pentane blown)
  - R6-7/inch
  - 1 or 2 perms
  - <0.01 lps/m² @ 75 Pa

**Spray Foam**

- Open cell
  - Neither air or vapour barrier
  - Stops convection / wind washing
- Closed cell
  - Air barrier and part vapour barrier
  - Excellent air seal in difficult areas!
  - Beware: adhesion and movement/shrinkage cracks
- Both Expensive
Radiant barriers

- Often misunderstood
- Performance depends on temperature difference
- How reflective is the material? Is all dust and corrosion avoided?
- Must have an air space!!

Website

- University of Waterloo
  - Building
  - Engineering
  - Group

www.civil.uwaterloo.ca/beg