Insulation
Motivation

- Insulation is a vital component in reducing energy losses in building envelopes, pipes, ducts, boilers and process heating applications.
- Many older buildings and equipment installations have inadequate or deteriorated insulation.
- Given the potential energy savings additional insulation is often economically justifiable.
Insulation is not a new idea…

I had a professor at UK who had an NSF grant to study fibrous insulation- of gooney birds in the south Pacific… but that’s another story. The same guy built a solar collector with a “sun-absorber” consisting of artificial fur.
Insulation Properties

- Thermal conductivity is obviously the defining property of an insulator- should have low $k$ so that it poses a high resistance to heat transfer.
- $k$ varies with temperature, often significantly. A good rule of thumb when designing insulation systems is to use $k$ at the average temperature experienced by the insulation.
- $k$ can be an intrinsic property of the material of which the insulator is made or it can depend on the construction and use of the insulator.
Thermal Conductivity Can Depend on Composition

- Solid insulators, e.g., firebrick, have an intrinsic value of $k$ that does not depend on whether or not you apply a load, for example.
- Many insulators are made of fibers or foams that have tiny gas voids (or evacuated voids).
- Gases are much better insulators than solids, so the greater the void fraction, the higher $k$.
- However, when these insulators are compressed, by a load, they lose some of their insulating value.
k depends on degree of compression and density of fill...
“Effective” Thermal Conductivity

- Gas/solid combined insulators are characterized by an effective thermal conductivity.
- Fourier’s Law says \( q_{\text{cond}} = k \cdot A \cdot \Delta T/\Delta x \), so effective \( k \) is measured as \( k = q \cdot \Delta x / A \cdot \Delta T \).
- Radiation as well as conduction can influence the value of a complex insulator's effective \( k \).
- "Superinsulators" combining evacuated layers with silvered, low emissivity fabrics have been developed with \( k \)'s one-hundredth that of ordinary fiberglass insulation.
Temperature Rating

- Insulation has limits posed by temperatures at which melting, deformation, embrittlement, burning or other decline in performance occurs.
- High temperature more a problem than low.
- Insulation that can take high T (often ceramics or ceramic fibers) are called **refractories**.
- Common refractories include calcium silicate and alumina (Al₂O₃).
- Usually, the higher the T rating of insulation, the higher its k or lower its R-value.
Cell Structure

- This applies primarily to foamed insulators, which have either open or closed cell structures.
- Closed cell insulation is composed of small cells (~bubbles) having a wall that is relatively impervious to moisture (e.g., Styrofoam).
- Closed cell insulators will not soak up water and thereby lose their insulating value because the air voids have been replaced by water.
- Open cell insulators behave more like sponges and require some sort of vapor barrier to prevent them from becoming waterlogged.
**Fire Hazard**

- Fire hazard ratings measure insulator's contribution to fire through flame spread and smoke.
- Flame spread and smoke hazards are measured on a scale where 100/100 applies to red oak. A measure of 25/150, e.g., means that the flame spread rate is 25% of that over red oak and the smoke produced is 50% greater than produced by red oak under the same test conditions.
- Another important consideration that has gained importance lately is the smoke toxicity.
Insulation Form

- Insulators are commercially available in a variety of forms, including: blankets, batts, rigid boards, blocks, cylindrical shells, loose/bulk, etc.
- Standard sizes are available for a variety of applications.
- Special shape needs at high T can be met by “castable” refractories that are mixed up like mortar then are cured to a solid, permanent form, often by intense heating.
Shapes available for many applications
Many insulations are made with organic binders, solvents that slowly "outgas" as insulation ages.

Some of these emissions are carcinogenic, e.g., formaldehyde released by polyurethane that was once commonly used for mobile homes.

Other "emissions" result from growth of microorganisms in the cells of insulation. Some cases of "sick building syndrome" have been linked to emissions from growths in building insulation.
Insulation Types

- Mineral fiber/rock wool - consists of fibers spun from molten rock - a good refractory.
- Cellulose - often made from recycled paper - good cheap insulation as long as it’s kept dry.
- Fiberglass - Probably the most popular insulation and obtainable in a variety of forms and sizes. Although the glass fibers themselves are fairly refractory, organic binders used break down at high temperatures, thus limiting the high temperature applicability of fiberglass.
“Blown” cellulose insulation
Fiberglass batts with many R-values for buildings
More fiberglass insulation...
Foams

- Available in many open and closed cell types.
- Foams are generally made of combustible organic compounds.
- Those that have the best fire ratings tend to have the poorest insulating value.
- Temperature ratings are generally low.
- These are often good to very low (cryogenic) temperatures.
- Common uses: Near ambient temperatures, construction, insulation of cold piping, applications that require water-soak resistance.
Foam insulation applications
Refractories

- Typically hard, relatively dense material used in high temperature applications such as insulating the hottest parts of a boiler, combustor flues, industrial ovens, etc.

- Refractories are available in several forms, including special precast shapes of alumina or silica, spun ceramic fibers, "castable" refractory that is plastered onto a desired location and cured in place, and fire bricks.
Refractory insulation

Firebricks

Ceramic refractory shapes
Brief Heat Transfer Review

Conduction Through Plane Walls

- Governed by: \( q = kA\Delta T/\Delta x \), where \( q \) is heat transfer rate, \( k \) is thermal conductivity, \( A \) is area perpendicular to heat flow, and \( \Delta T \) is the temperature difference through the wall of thickness \( \Delta x \).
- \( \Delta x/k \) is the R-value which we simply call \( R \).
- Using \( R \), \( q = A\Delta T/R \).
- For heat transfer through several layers of differing R-values, use circuit analogy: \( q = A\Delta T/\Sigma R \).
Conduction through Cylindrical Layers

- For a single, cylindrical shell of material having thermal conductivity $k$, inner radius $r_i$, outer radius $r_o$, and length $L$:

  $$q_{\text{cond}} = \frac{\Delta T}{R_{\text{th}}} \quad \text{and} \quad R_{\text{th}} = \frac{\ln(r_o/r_i)}{2\pi k L}$$

- For a cylindrical system of several layers, we can also use the circuit analogy:

  $$q_{\text{cond}} = A \frac{\Delta T}{\sum R_{\text{th}}}$$

- In both of these cases, we are using thermal resistance, which depends on area, rather than the R-value.
Convection

- Governed by Newton's Law of Cooling: \( q = hA\Delta T \).
- Using the circuit analogy, the thermal resistance imposed by convection is: \( R_{th} = 1/hA \).
- In terms of R-value: \( R = 1/h \).
- These relationships apply to both plane wall and cylindrical systems.
Method for Pipe Insulation

- Pipe insulation heat transfer calculations can be approached as heat exchanger problems.
- An overall heat transfer coefficient, $U$, can be calculated. We choose to base $A$ on pipe outside area, $A_p = 2\pi r_p L$, for which $U_p$ is:

$$U_p = \frac{1}{r_p \left( \frac{1}{r_i h_i} + \frac{\ln \frac{r_p}{r_i}}{k_p} + \frac{\ln \frac{r_o}{r_p}}{k_{ins}} + \frac{1}{r_o h_o} \right)}$$
U for Pipe Problem (Cont’d)

- In the equation for $U_p$, $r_p$ is pipe/tube outside radius, $r_i$ is pipe inside radius, $r_o$ is insulation outer radius, and $k_p$ and $k_{ins}$ are pipe and insulation thermal conductivities, respectively.
- $U_p$ can be computed once the dimensions are specified and $h_i$ and $h_o$ are calculated.
- One complication, which we’ll come back to, is that radiation heat transfer is important if $\Delta T$ between outer surface and ambient is large.
Convection Coefficients

- There are many convective h.t. correlations for various situations that we studied in ME 309. Here we’ll look only at a few, most common.
- Turbulent pipe flow (Reynolds-Colburn analogy):

  \[ h = \frac{\rho V c_p f}{8 \Pr^{2/3}} \]

  In this equation, \( \rho \) is the fluid density, \( V \) is mean velocity, \( f \) is the Darcy-Weisbach friction factor, and \( \Pr \) is the Prandtl number, \( \Pr = \nu/\alpha \).
Forced Convection Outside Cylinder

- Use $\text{Nu}_D = 0.3 + A \cdot B$, where $\text{Nu}_D = \frac{h_o D_o}{k_f}$, and

$$A = \frac{0.62 \text{Re}_D^{1/2} \text{Pr}^{1/3}}{\left[1 + (0.4/\text{Pr})^{2/3}\right]^{1/4}}$$

$$B = \left[1 + \left(\frac{\text{Re}_D}{282,000}\right)^{5/8}\right]^{4/5}$$

- $\text{Re}_D$ is Reynolds number for outside fluid velocity $V$ based on insulation OD, and $\text{Pr}$ and $k_f$ are outside fluid Prandtl number and thermal conductivity.

- Fluid properties are evaluated at film temperature $T_f = \frac{1}{2}(T_s + T_f)$
Natural Convection in *Air* Outside Cylinder

- Find Rayleigh number for outside fluid properties, with surface temperature $T_s$ and $\Delta T = (T_s - T_{air})$:

$$Ra_D = \frac{g \beta \cdot \Delta T \cdot D^3}{\nu \alpha}$$

- For atmospheric *air*, $Ra_D < 10^9$:

$$h_o = 0.27 \left( \frac{\Delta T}{D} \right)^{1/4}$$

- For atmospheric *air*, $Ra_D > 10^9$:

$$h_o = 0.22 \left( \Delta T \right)^{1/3}$$
In equations for $Ra_D$:

- $g$ is the acceleration of gravity
- $\beta = \text{volumetric coefficient of thermal expansion}$. For ideal gas (air), $\beta = 1/T_f$, for $T$ in absolute degrees, and where $T_f = (T_s + T_{air})/2$.
- $\nu$ and $\alpha$ are kinematic viscosity and thermal diffusivity, evaluated at $T_f$.

In equations for $h_o$:

- $h_o$ is in units of Btu/hr-ft²-°F
- $D$ is in units of ft and $\Delta T$ is in units of °F
 Radiation Heat Transfer

- If pipe surface temperature $T_s$ is significantly different from $T_{air}$, pipe loses (or gains) heat by radiation as well as convection, so:

$$q_{rad} = \sigma \varepsilon A (T_s^4 - T_{air}^4)$$

where $\sigma = 0.1714 \times 10^{-8}$ Btu/hr-ft$^2$-R$^4$, $\varepsilon$ is the surface emissivity, and $A$ is the surface area.

- $\varepsilon \approx 0.95$ for most non-metallic materials, $\varepsilon \approx 0.2$ for aluminum and $\varepsilon \approx 0.4$ for steel.
“h” for Radiation

- It is useful to be able to calculate $q_{rad}$ as $q_{rad} = h_{rad}A\Delta T$.
- Noting that:

$$T_s^4 - T_{air}^4 = (T_s^2 + T_{air}^2) \cdot (T_s + T_{air}) \cdot (T_s - T_{air})$$

- Equate the two expressions for $q_{rad}$ to show:

$$h_{rad} = \sigma\varepsilon \cdot (T_s^2 + T_{air}^2) \cdot (T_s + T_{air})$$
Combined $h_o$

- The total effective outside heat transfer rate for $\Delta T = T_s - T_{air}$ is:

$$q = (h_{conv} + h_{rad}) \cdot A \cdot \Delta T$$

- We define a combined outside heat transfer coefficient, $h_{comb} = h_{conv} + h_{rad}$.

- We are now able to calculate $U$ if the outside surface temperature is known.

- Often, $T_s$ is not known and we need to use a trial-and-error type solution.
Pipe Heat Loss Calculation

- Typically, $T_{f,\text{in}}, T_{\text{air}}, L, D_p$, pipe fluid mass flow rate, and pipe fluid, pipe and insulation properties are known.
- Can find $q$ if insulation thickness is known.
- Can find insulation thickness if $q$ is specified.
- For metal pipes, often the conduction resistance of the pipe is negligibly small.
- If the value of $h_i > h_o$ then $h_i$ can be ignored.
- If both of previous are true, can assume pipe wall outer temperature $\approx T_f$ of inside fluid.
Key to Iterative Solution of Insulation Problems

- Methods have been presented for calculating \( U \), based on \( \Delta T = |T_i - T_{surr}| \), and for calculating \( h_o \) based on \( \Delta T = |T_s - T_{surr}| \).

- Usually the insulation or bare pipe outer surface temperature, \( T_s \), is unknown.

- \( T_s \) is determined by setting \( q = U_p \cdot A_p \cdot \Delta T \) equal to \( q = h_o \cdot A_s \cdot \Delta T \), where \( A_s \) is the outer surface area and the two \( \Delta T \)s are as defined above.

- \( T_s \) is varied until the two \( q \) expressions are equal. Goal Seek in Excel is often useful.
Heat Exchanger Method

- Considering the NTU method, a pipe running through the air or ground is the special case of $C_{\min}/C_{\max} = 0$.
- Use NTU as a check - not absolutely necessary...
- Define: $C_{\min} = \dot{m}_f c_{p,f}$

$$NTU = \frac{U_p \cdot A_p}{C_{\min}}$$

and

$$\varepsilon_{hx} = 1 - \exp\left(-NTU\right)$$

- Finally:

$$q = \varepsilon_{hx} \cdot C_{\min} \cdot \left(T_{f,\text{in}} - T_{\text{air}}\right)$$
Pipe Heat Loss Calculation

Example 1

**Given:** A 1000-ft long, Schedule 40, 4-inch commercial steel pipe carries 250 gpm of chilled water entering at $T_{f,in} = 45^\circ F$ in still air at 100°F. Pipe thermal conductivity is $k_p = 21$ Btu/hr-ft-°F.

**Find:** The rate of heat transfer and the chilled water exit temperature for two cases- (1) pipe has no insulation, and (2) the pipe has 1/2 inch of $k_{ins} = 0.022$ Btu/hr-ft-°F.

**Sol’n:** See Excel file Insulat1.xls...
If a pipe carries a fluid undergoing phase transition (typically condensing steam), the overall thermal capacity of the steam flow is also very large and $C_{\text{min}}$ is undefined.

In this case simply calculate $U$ and calculate the heat loss rate as $q = UA\Delta T$, where $\Delta T$ is the difference between $T_{\text{sat}}$ of fluid in pipe and the ambient/surroundings temperature.

The $h_i$ for phase-changing fluid is very high, so the inside convection resistance is negligible.
Pipe Heat Loss Calculation

**Example 2**

**Given:** A 1000-ft long, 4-in ID, 5-in OD pipe with \( k_p = 10 \text{ Btu/hr-ft-}^\circ\text{F} \) carries a constant flow of saturated steam at 350\(^\circ\text{F} \) with a mass flow rate of 2400 lbm/hr. The pipe runs through 80\(^\circ\text{F} \) air with average velocity \( V = 10 \text{ mph (14.7 ft/s)} \).

**Find:** If insulation with \( k_{\text{ins}} = 0.03 \text{ Btu/hr-ft-}^\circ\text{F} \) and \( \varepsilon = 0.45 \) costs \$6/\text{ft}^3 \) and heat energy costs \$5/\text{MMBtu} \), evaluate the payback of going from 1-inch thick insulation to 2-inch thick insulation.

**Sol’n:** See Excel file Insulat2.xls...