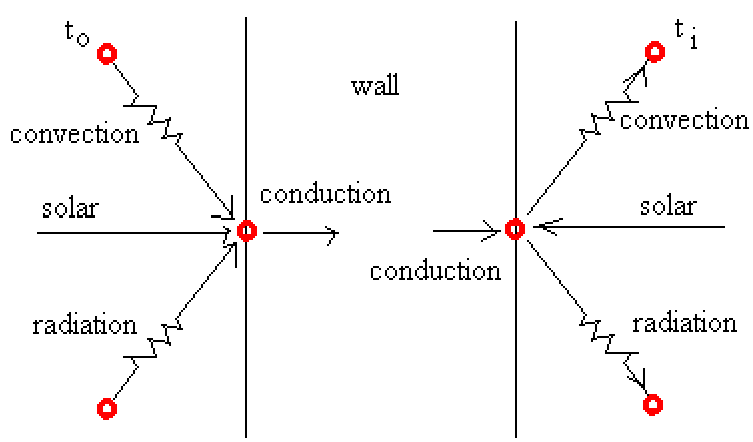
ME 414/514 HVAC Systems

Heat Balance Method

The HBM requires a load calculation program and this method is not discussed in our text. Different pieces of the cooling load problem are looked at in isolation. A program puts all these pieces together for us to perform a complete cooling load analysis for a structure. Hence, engineers working in HVAC are, in practice, forced to rely on commercial software packages for a cooling load analysis.

Basically, the HBM consists of heat balances on the interior and exterior surfaces of a single wall or roof element. Each of the heat fluxes – solar, convection, and radiation - into an exterior surface vary throughout the day as the sun changes position in the sky and as the outdoor ambient and radiation temperature changes. The time-varying nature of the fluxes, coupled with the thermal inertia of the walls and roofs, creates a transient heat conduction problem. Solution methods include:

1. lumped parameter – small pieces with uniform temperature-time
2. frequency response – periodic BCs (Fourier series)
3. numerical integration – finite differences or finite elements
4. Z-transforms – the theory used in the HBM



Z-transforms use either response factors or conduction transfer functions.
Response factors and **Conduction transfer functions (CTF)**: time series coefficients that relate current heat flux to past and present values of interior and exterior temperature (CTFs replace temperature history with heat flux history).

Using CTFs is tedious but not difficult. *Finding* them is difficult, and you have to use a program for that task.

Basically, the heat balances expressed in terms of CTFs must be solved for each hour of the day. The solution procedure may be iterative (initial guess of the surface temperatures and heat fluxes are updated until they converge) or done simultaneously via matrix inversion.

A check on the solution validity is obtained by solving a steady-state problem. The result should agree with the transmission equation from Ch. 5:

$q'' = U(t_i - t_o)$

EXTERIOR SURFACE HEAT FLUX

The three components of the exterior heat flux are solar, convection and radiation.

Solar radiation – high temperature source, UV or short wavelength EMR

$q''_{solar} = \alpha G_t$

Where α = surface absorptivity of short wavelength EMR
G_t = total solar irradiation from Chapter 6 (calculated on the ½ hour)

Exterior convection – Newton's Law of Cooling

$q''_{convection} = hc\,(t_o - t_{os})$

where h_c = exterior convective heat transfer coefficient
t_o = outside air temperature
t_{os} = outside surface temperature

In Topic 5, we used tabulated values for h_c when we were calculating overall U values for walls, roofs, etc. Here, a correlation is given for using a computer:

$$h_c = \sqrt{\left[C_t \Delta t^{1/3}\right]^2 + \left[a V_o^b\right]^2}$$

where C_t = turbulent natural convection constant
Δt = difference between exterior surface temperature and exterior air temperature
a, b
V_o = wind speed in mph or m/s

Exterior radiation –low temperature source, IR or long wavelength EMR

The surface exchanges thermal radiation in the IR spectra with the ground and the sky:

$$q''_{radiation} = \varepsilon\sigma\left[F_{s-g}\left(T_g^4 - T_{os}^4\right) + F_{s-sky}\left(T_{sky}^4 - T_{os}^4\right)\right]$$

The view factors F_{s-g} and F_{s-sky} are from Topic 6 with α, the surface tilt angle.

$$F_{s-g} = \frac{1}{2}\left[1 - \cos(\alpha)\right]$$

$$F_{s-sky} = \frac{1}{2}[1+\cos(\alpha)]$$

The 4th power terms are a nuisance numerically, so the radiation flux is linearized:

$$h_{r,g} = \varepsilon\sigma\left[\frac{F_{s-g}\left(T_g^4 - T_{os}^4\right)}{t_g - t_{os}}\right]$$

$$h_{r,sky} = \varepsilon\sigma\left[\frac{F_{s-sky}\left(T_{sky}^4 - T_{os}^4\right)}{t_{sky} - t_{os}}\right]$$

$$q''_{radiation} = h_{r,g}\left(t_g - t_{os}\right) - h_{r,sky}\left(t_{sky} - t_{os}\right)$$

The sky temperature is approximated as T_o – *10.8 R* (or T_o – *6K*). The correction for a surface tilted at angle α is:

$$t_{sky,\alpha} = \left[\cos\left(\frac{\alpha}{2}\right)\right]t_{sky} + \left[1-\cos\left(\frac{\alpha}{2}\right)\right]t_o$$

All of the **exterior heat fluxes** can be combined to get a simpler-looking relationship.

FENESTRATIONS

Direct, diffuse and reflected solar gain through windows and skylights is calculated using the methods of Topic 6.

INTERIOR HEAT GAINS – People, Lights, Equipment

People

People contribute sensible and latent heat. Tables are available for different occupancies and occupant activities.

$$q_{s\_people} = N\ F_u\ \ q_s$$
$$q_{lat\_people} = N\ F_u\ q_{lat}$$

N = number of people
F_u = use factor (1.0 for fully occupied room)

Sensible heat gain split: 30% convective, 70% radiative
Latent heat gain split: 100% convective, 0% radiative

The split between radiative and convective fractions is needed because convective heat is part of the instantaneous heat load whereas radiative heat contributes to the delayed load.

Lights

$$q_{\_lights} = 3.41\ W\ F_u\ F_s$$

W = total installed wattage
F_u = use factor (1.0 if all installed lights are on)
F_s = fudge factor (to compensate for less heat from fluorescent bulbs)

Heat gain split:
Fluorescent lamps: 41% convective, 59% radiative
Incandescent lamps: 20% convective, 80% radiative

Heat lost to the return air plenum depending on whether or not the fixture is ventilated or unventilated. Not all of the heat from the light enters the conditioned space.

Equipment

$$q_{\_motor} = C\ (P / E_m)\ F_l\ F_u$$

$q_{\_motor}$ = heat equivalent of equipment operation, BTU/hr or W
P = motor shaft power rating, hp or W
E_m = motor efficiency as decimal (not %)
F_l = fraction of rated load delivered
F_u = motor use factor (1.0 when the equipment is running)

C = unit conversion constant, 2545 Btuh/hp or 1 W/W

Motor outside conditioned space, driven equipment inside:

$$q_{\_motor} = C\ (P)\ F_l\ F_u$$

Motor inside conditioned space, driven out:

$$q_{\_motor} = C\ [\ (1 - E_m) / E_m\ ]\ F_l\ F_u$$

Equipment heat gain split: 30% convective, 70% radiative
Electronic equipment heat gain split:
Printer:89% convective, 11% radiative
Copier: 86% convective, 14% radiative
PCs: 74.5% convective, 25.5% radiative (average)

Appliances – hooded steam & electrical

$q_{appliance} = 0.5 \times 0.32\ q_i$

Where

0.32 is the fraction of radiative heat (convective heat is removed from the occupancy by hoods)

q_i is the input rating

Appliances – hooded fuel-fired

$$q_{appliance} = q_i$$

Where q_i is the input rating.

INTERIOR OPAQUE SURFACES

Convection

$q''_{convection} = hc\,(t_{is} - t_i)$

where h_c = exterior convective heat transfer coefficient
t_{is} = inside surface temperature, different for each surface and varies throughout the day
t_i = inside air temperature, design condition

Radiation exchange with objects in the **enclosure**

Modeling the details of all the radiation exchanges between all of the surfaces – walls, ceiling, floor – and objects (furniture) is theoretically possible but impractical because of the detail involved. The text describes the mean radiant temperature /balance method. This model uses a fictitious surface to represent the view that one surface has of all other surfaces. Recall from your undergraduate heat transfer class:

- The sum of the views from one surface to each surface in an enclosure is 1.

$$\sum_{j=1}^{N} F_{1j} = 1$$

- A planar surface cannot see itself.

$$F_{11} = 0$$

- The net radiation exchange in an enclosure is zero.

$$\sum_{j=1}^{N} Q_j = 0$$

Hence, for one surface in an enclosure, the fictitious surface area is the sum of the areas of all the other surfaces; the fictitious surface emissivity is an area-weighted average; the fictitious surface temperature is an area-weighted average; the view factor of the fictitious surface is calculated using the fictitious emissivity and area; a radiation coefficient is calculated using the fictitious view factor and temperatures. The thermal radiation calculated from all this fictitiousness is not correct and needs to be corrected (balanced) so that the net exchange is zero. All of these calculations are amenable to a spreadsheet approach (see Example 8-5).

Radiation gains from **people, lights and equipment**

We saw earlier that people, lights and equipment include a radiative load. These contributions are summed for each hour and treated as uniform fluxes over each interior surface.

All of the **interior heat fluxes** can be combined to get a simpler-looking relationship.

INTERIOR TRANSPARENT SURFACES

Fenestrations

The calculation of transmitted and absorbed irradiation follows the process that we learned in Topic 6. We can refine the calculation by considering absorptance in each pane of a multi-pane window. The calculation procedure is identical that T 6. What is new are the coefficients to separately calculate absorptance in the outer pane and inner pane of a double pane window.

ZONE AIR

Surface convection- sum over all surfaces:

$$Q_{conv} = A\, q''_{convection} = A\, h_c\, (t_{is} - t_i)$$

Internal heat gain convection – add up the contribution from people, equipment and lights

Infiltration

$$\dot{q}_{s,\inf,\theta} = \dot{m}_a C_p (t_o - t_i) = \frac{\dot{V}}{v_o} C_p (t_o - t_i)$$

$$\dot{q}_{s,ilat,\theta} = \dot{m}_a (W_o - W_i) h_{fg} = \frac{\dot{V}}{v_o} (W_o - W_i) h_{fg}$$

System heat transfer

$$q_{system} = a + b\, t_i$$

IMPLEMENTATION

1. determine all zone parameters (surface areas, thermal properties, geometry)
2. find all imposed fluxes (transmitted and incident solar radiation, internal loads, infiltration rates)
3. calculate exterior and interior surface temperatures for each hour of the day
4. calculate the required system heat transfer by using the **zone air heat balance**:

$$\dot{Q}_{system} = -\sum_{j} A_j h_{c,i,j} \left(t_{is,j} - t_i\right) - \dot{m}_{a,\mathrm{inf}} C_p \left(t_o - t_i\right) - \dot{Q}_{\mathrm{int},conv}$$

The difficulty, as we have seen, in this deceptively simple looking equation is finding the interior surface temperature, t_{is}. All of the exterior heat loads (solar, convection, transmission) and interior heat loads (solar through fenestrations, radiation from people, equipment and lights) must be included and modeled.