Energy Calculations of Large Buildings

ME 416/516

THE UNIVERSITY OF ALABAMA ENGINEERING

Recall how we calculated **residential** loads...

- For residential heat loss through envelope, used:

  $$q = A \cdot \Delta T / R$$

  where R is the effective, overall R-value for the layers through which heat is transferred.
- For summer heat gain through envelope, used:

  $$q = A \cdot CLTD / R$$

  where CLTD is the effective "cooling load temperature difference" that accounts for outside surface heating by the sun.

Large Building Load Calcs...

- For large buildings, conventional to use:

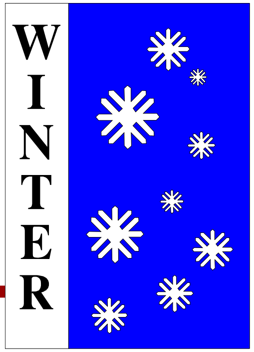
$$q = U \cdot A \cdot \Delta T \text{ or } q = U \cdot A \cdot CLTD$$

- U is the effective **overall heat transfer coefficient**.
- Comparing relations that use R to those that use U,

$$U = 1/R$$

i.e., overall heat transfer coefficient is simply the reciprocal of effective R-value.

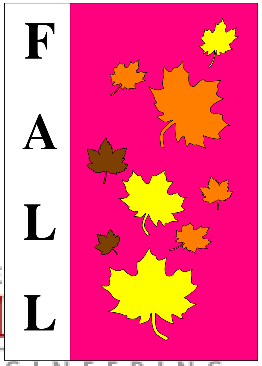
Seasonal Performance Measures



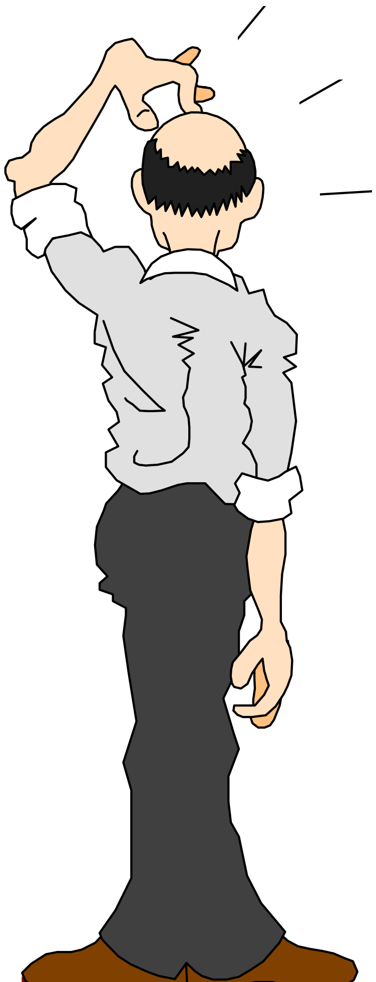
- To simplify energy calculations, we use ratings that give an average efficiency over an entire heating or cooling season. We've seen:

- AFUE- Annual Fuel Utilization Efficiency for a fossil fuel fired furnace or water heater.

- HSPF- Heating Seasonal Performance Factor for an electric heat pump.
- SEER- Seasonal Energy Efficiency Ratio for electric cooling equipment.



What's Wrong with Seasonal Measures?



- The main problem with these ratings is that they do not account for equipment performance variations that occur hourly in response to changes in the weather.
- The design of HVAC systems for larger buildings requires a more sophisticated energy calculation procedure to account for variations in performance.

The Bin Method

- The "bin method" refers to a procedure where monthly weather data is sorted into discrete groups (bins) of weather conditions.
- Each bin contains the number of average hours of occurrence during a month or year of a particular range of weather condition.
- **Example**: The city of Tideville has the following dry bulb temperature bin data for the month of April:

T_{db}	Hours	Range
82	2	80-84
77	14	75-79
72	38	70-74
67	89	65-69
62	115	60-64
57	128	55-59
52	106	50-54
47	88	45-49
42	75	40-44
37	43	35-39
32	18	30-34
27	4	25-29

Bin Data

- The top row of the table indicates that April *averages* 2 hours when T_{db} is 80, 81, 82, 83 or 84°F, etc.
- The bin data are based on long-term weather measurements from National Weather Service.
- Similar bin tables are available for many weather stations for parameters including T_{wb}, mean coincident T_{wb} with T_{db}, wind speed, solar insolation, rainfall, etc., both monthly and annually.
- ASHRAE sells a CD-rom with much of the U.S. data, and NWS has a lot of data also (Web availability?)

Use of Bin Da

- Instead of using a single design condition for an entire year, an engineer can calculate loads for each bin condition, multiply the bin load by the hours of occurrence for that bin, then sum the load for each bin to get the total load.

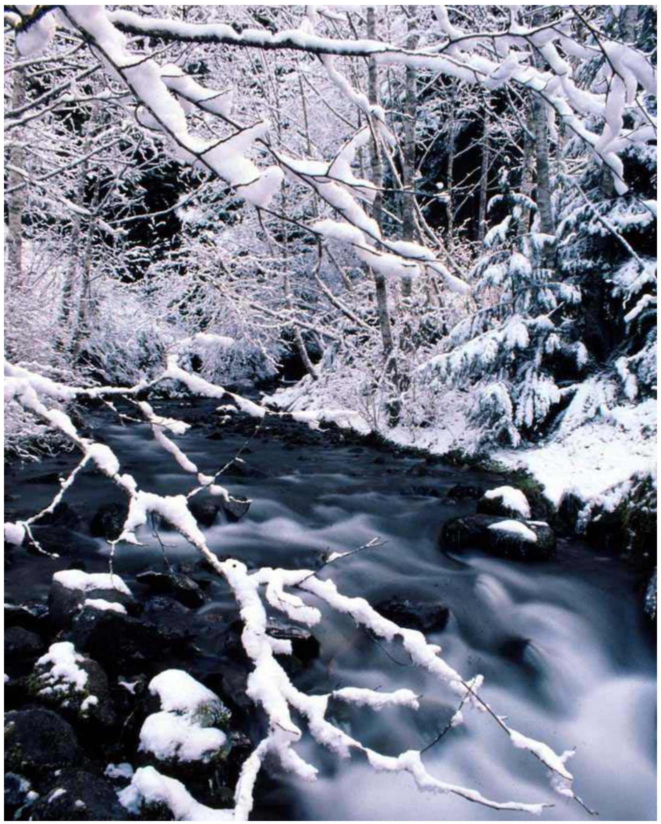
Example: Find the April heating load for a building in Tideville that is kept at T_i = 68°F and has an overall value of UA = 112,000 Btu/hr-°F, where $q = U \cdot A \cdot \Delta T$.

T_{db}	Hours	ΔT (°F)	q MBtuh	Q MMBtu
82	2	-----	-----	-----
77	14	-----	-----	-----
72	38	-----	-----	-----
67	89	-----	-----	-----
62	115	6	672	77.3
57	128	11	1232	157.7
52	106	16	1792	190.0
47	88	21	2352	207.0
42	75	26	2912	218.4
37	43	31	3472	149.3
32	18	36	4032	72.6
27	4	41	4592	18.4
			Q_{total} =	**1091**

Bin Method Energy Calculations

- The previous example illustrates advantages of load calculation by the bin method.
- Although the example given showed a directly linear relationship between ΔT and q, there are cooling or heating loads that vary *nonlinearly*.
- Using the bin method results in a more accurate calculation of the total load, Q.
- When the weather varies hour-by-hour, the demand put on the heating and cooling equipment varies, plus equipment performance varies at different weather conditions.

Bin Method Accounts for Weather Effects Better



- The accuracy of calculating the equipment energy use is improved by using the bin method even more than was the load calculation.
- For equipment that operates on the refrigeration cycle, such as air conditioners and heat pumps, performance and capacity depend strongly on the weather, for several reasons.

1^{st} Weather Effect on Equipment Performance

The maximum possible efficiency of refrigeration cycle drops as ΔT increases. For example, the theoretical COP of a heat pump (heating) is:

$$COP_{Carnot} = T_H/(T_H - T_C)$$

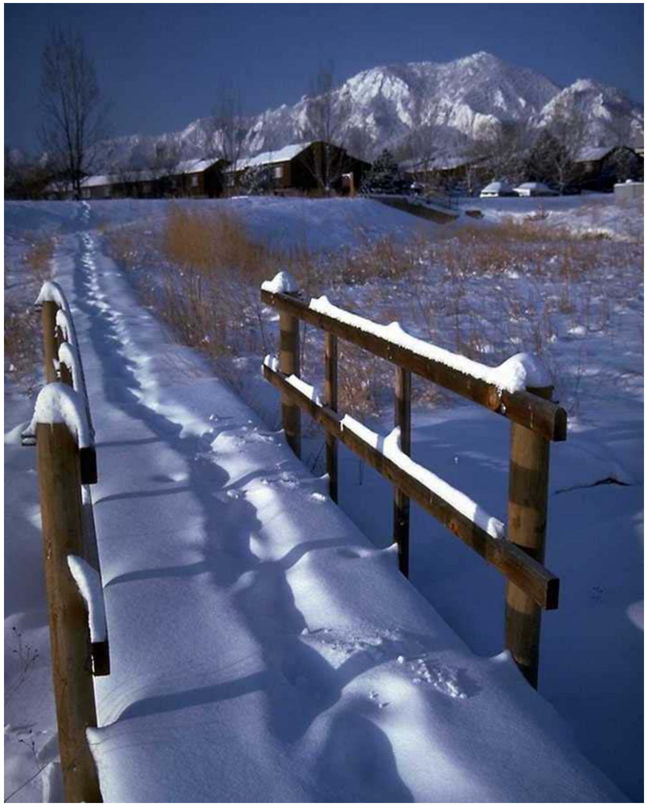
- Here $T_H = T_i$ and $T_C = T_{od}$. For T_i = 67°F, the max. theoretical COP is about 26 for T_{od} = 47°F but only about 6.5 for T_{od} = 17°F, a drop of 75%.
- Actual COP's are much lower COP_{Carnot}. Standard 90.1, for example, requires small heat pumps to have COP > 3 at 47°F and COP > 2 at 17°F.

2nd Weather Effect: A/C Capacity Drops at *High* T_{od}

- A/C and heat pump capacity drops as ΔT rises.
- In order to reject heat to hot outside air, an A/C, e.g., must have a condenser refrigerant temperature significantly higher than T_{od}.
- As T_{od} rises, the compressor outlet pressure rises to reject heat. There is a limit to how much pressure increase can be achieved by motor, so as outdoor temperature gets higher, the ΔT between refrigerant and air gets smaller.
- Heat rejection, which is proportional to this ΔT, drops, thereby reducing A/C capacity.

3rd Weather Effect: HP Capacity Drops at *Low* T_{od}

- Same capacity loss occurs for a heat pump (heating) as T_{od} drops, but the situation is worse.
- A heat pump also loses capacity in cold weather because it has to go into ***defrost mode***, where it actually runs in reverse, blowing warm air out through the outdoor unit to melt ice that has frozen on the coils during the normal mode of operation.



4th Weather Effect: Capacity is Exceeded in Extreme Weather

- A final effect of weather conditions is that as ΔT increases, the heating or cooling load rises proportionally, and at some point the machine capacity is exceeded.
- For A/C, the building gets warmer.
- For heat pump, auxiliary "strip" resistance heat is activated, working at COP = 1.
- If the system is sized adequately, the thermal capacity of the system will allow the building to flywheel through “normal” extreme weather without getting excessively hot or cold.

Part-Load Performance

- A heating or cooling system (large or small) operates at only a fraction of its capacity most of the time, at the ***part-load condition***.
- The part-load efficiency is less than full-load because of transient losses, the need to reheat or recool ductwork when the system comes back on, operation of pumps and fans at full speed when not needed, throttling losses, etc.
- The system efficiency is ***derated*** to account for reduced part-load performance.

Part-Load Derating

- Efficiency, e.g., COP, is derated at part load as:

  $$COP_{part} = COP_{full} * CCAF$$

  where

  $$CCAF = [1 - 0.25*(1 - PLF)]$$

  and the part-load factor PLF is the fraction of full load at which the system is operating:

  $$PLF = Load/Capacity$$

- For periods where load exceeds capacity, the system operates at full capacity, PLF = 1, and CCAF = 1.

Bin Method Example

- A building in Tideville has a heat pump that operates with the temperature dependent capacity and COP shown in the following table.
- The COP at part load operation is calculated as
- When the cooling load exceeds the heat pump capacity, auxiliary strip heat kicks in to make up the difference. The strip heat has COP =1.
- Find the demand in kW for the system and the monthly energy use in kWh.

T_{db}	Hours	q MBtuh	Cap	PLF	COP rated	COP part
82	2	-----				
77	14	-----				
72	38	-----				
67	89	-----				
62	115	672	3506	0.192	2.92	2.33
57	128	1232	3300	0.373	2.91	2.45
52	106	1792	3094	0.579	2.89	2.59
47	88	2352	2901	0.811	2.86	2.72
42	75	2912	2695	1.081	2.81	2.81
37	43	3472	2500	1.389	2.67	2.67
32	18	4032	2294	1.758	2.5	2.50
27	4	4592	2098	2.189	2.33	2.33

T_{db} °F	Hours	q MBtuh	Cap MBtuh	COP part	kW	kWh
82	2	-----				
77	14	-----				
72	38	-----				
67	89	-----				
62	115	672	3506	2.33	84.5	9721
57	128	1232	3300	2.45	147.1	18833
52	106	1792	3094	2.59	203.1	21528
47	88	2352	2901	2.72	253.0	22264
42	75	2912	2695	2.81	281.1	21082
37	43	3472	2500	2.67	274.4	11800
32	18	4032	2294	2.50	268.9	4841
27	4	4592	2098	2.33	263.9	1056
					Total	111124

Notes on Bin Method Example

- No heating is done when temperature is above 65°F (depending on internal heat sources, etc., no heating may be necessary until T_{od} is considerably lower).
- "Cap." is the capacity (total heat input rate that can be provided) of the heat pump that is heating the building. Note that capacity drops as T_{od} gets lower.

More Notes on Bin Method Example

- The "kW" column is the electric power demand of the heat pump at a given condition, obtained from:

  kW = q (Btu/hr)/(COP * 3412 Btu/kWh)

  where q is the building load for conditions where PLF < 1 and q is the heat pump capacity for conditions where the heat pump is operating continuously.

- The “kWh” column is the product of kW and the number of hours in a particular bin.

T_{db} °F	Hours	q MBtuh	Cap. MBtuh	COP part	Aux kW	Aux KWh
82	2	-----				
77	14	-----				
72	38	-----				
67	89	-----				
62	115	672	3506	2.33	0.0	0
57	128	1232	3300	2.45	0.0	0
52	106	1792	3094	2.59	0.0	0
47	88	2352	2901	2.72	0.0	0
42	75	2912	2695	2.81	63.6	4770
37	43	3472	2500	2.67	284.9	12250
32	18	4032	2294	2.50	509.4	9169
27	4	4592	2098	2.33	730.9	2924
					Total	29112

More Notes on Bin Method Example

- The "Aux. kW" column is the demand of the auxiliary electrical resistance heater:

  Aux. kW = (q - Cap.)/3412 Btu/kWh

- The “Aux. kWh” column is the product of the Aux. kW column and the hours in a bin.
- The sum of the heat pump kWh and the auxiliary kWh gives the total heating energy use for the month of April, which is 140,236 kWh.