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Thermal effectiveness of a vapor compression cycle

The second law of thermodynamics states essentially that heat cannot be made to flow from a region of low temperature to one of higher temperature without the input of energy from an external source. This sets the ground rules: A building enclosed in higher temperature surroundings cannot be cooled without consuming energy. The corollary to the Carnot principle takes us a step closer to quantifying the dictates of the second law by stating that no refrigeration machine operating between a constant temperature source (T_0) and a constant temperature rejection sink (T) can have a coefficient of performance (CP) high than a reversible cycle. A simple thermal analysis of the Carnot cycle (a reversible cycle) further reveals that the CP of the Carnot cycle is:

$$\mathrm{CP} = \frac{T_0}{T - T_0}.$$

This is the Carnot or ideal CP. All too often, the tendency is to blame Carnot for our second law energy conversion losses or nonproductive burdens. Consider a simple analysis of how well we are doing compared to the ideal energy requirement. An example will start with 1 ton (12,000 Btuh) of cooling and proceed through an analysis of the useful (product) and nonuseful (process) energy flows through a simple refrigeration system from the cooling coil (input) to the ambient surroundings. For the analysis, conditions are set at 75 F DB and 50 percent RH indoors and a 95 F ambient sink. The Carnot energy required to accomplish heat pumping from 75 to 90 F is 449 Btu; the Carnot energy required to dehumidify, reducing the low-temperature sink to 55 F dew point, is 483 Btu.

The sum of these two ideal energy inputs is the theoretical or Carnot energy required to produce 1 ton of cooling; i.e., 0.273 kW. Another interesting observation is that theoretically, dehumidification alone requires 7.5 percent more energy than the sensible cooling.

Continuing through the analysis, the energy losses or burdens are:

- *Cooling coil heat transfer burden*—The increase in Carnot energy required to provide for a 10 F temperature differential between conditioned air dew point and 45 F entering water temperature is 256 Btu.
- *Chiller heat transfer burden*—The increase in Carnot energy required to provide for a 5 F temperature differential between the leaving (45 F) chilled water and the evaporating refrigerant at 40 F is 132 Btu.
- *Condenser heat transfer burden*—Current product catalog literature was scanned to find a "typical" condensing temperature for a 95 F ambient, air-cooled chiller-condenser combination. This was found to be 121 F condensing temperature. Thus, the heat transfer burden, imposed is represented by the temperature differential 26 F (121–95 F). Incorporating this in the Carnot CP produces a condenser heat transfer burden of 624 Btu.
- *Fluid and thermodynamic cycle burden*—The ideal vapor compression cycle closely approximates the Carnot cycle; the deviations being the superheat resulting from isentropic compression diverging from the vapor dome and the constant enthalpy expansion in lieu of an isentropic expansion. When these deviations are considered with a given refrigerant, the burden of that particular fluid can be determined. For this analysis, the

most common air conditioning fluids, R12 and R22, were considered. The R12 burden was found to be 596 Btu and R22 was 637 Btu.

- *Mechanical and electrical burdens*—At this point in the analysis, Carnot necessarily yielded to available hardware. Again, a product catalog scan and selection of one of the lower kW per ton chiller-condenser combinations revealed that the burden imposed by mechanical and electrical cycle motivation was 1486 Btu.
- *Condenser motivation energy*—In addition to the Carnot heat transfer burden, energy is required to move the cooling fluid through the condenser heat exchanger. Product catalogs were again consulted for a "typical" but conservative value, and the condenser fan resulted in a burden of 471 Btu.
- *Fluid distribution burden*—Since a water chiller was selected for the analysis, the fluid-motivation energy should be considered. Based on a 50-ft pumping head, it is calculated to be 122 Btu.

Table 60-1 shows Btu per ton-hr values for each energy use and burden, and the percentage of input represented by each. Summing all the energy components reveals an input of 4660 Btu per ton-hr or 1.36 kW per ton. If the Carnot CP energy requirement is considered as the ideal, and the thermal effectiveness is defined as the ideal energy requirement divided by the actual, the system is found to be 20 percent effective. Figure 60-1 illustrates the same data in a classical first law thermal flow diagram.

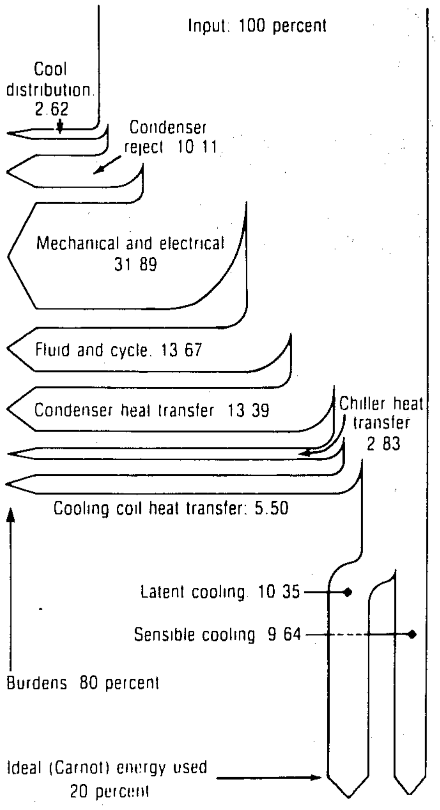

Fig. 60-1. Thermal balance flow diagram.

The purpose of this brief excursion into the thermal effectiveness of a refrigeration cycle is to illustrate the theoretical potential for energy consumption reduction in a major subsystem of the building environmental system. If, for instance, the energy effectiveness in heat transfer technology and application could be doubled, this would decrease the consumed energy in refrigeration systems well in excess of 10 percent. Other areas of concentration indicated are in mechanical and electrical technology and thermal fluids.

Table 60-1. Thermal requirements per ton-hour.

	Btu	%
Carnot sensible cooling	449	9.64
Carnot latent cooling	483	10.34
Cooling coil heat transfer	256	5.50
Chiller heat transfer	132	2.83
Condenser heat transfer	624	13.38
Fluid and thermodynamics	637	13.67
Mechanical and electrical	1486	31.88
Condenser heat rejection	471	10.11
Cooling fluid distribution	122	2.65
Total energy input	4660	100.00

This analysis has considered only the design capacity energy use and burdens. As the building system operates at reduced loads, the seasonal energy effectiveness is seen to generally reduce radically.

Thus, the question might be asked, would it be more cost and energy effective if we devoted some of the vast sums of money now being spent on such projects as solar energy conversion to more mundane efforts, such as heat transfer, fluids, mechanical concepts, and electrical convertors?