solar energy generation.

The energy supplied to the grid and the main performance analysis is done by considering the effect of different global irradiation and temperature, i.e. energy output of PV array, energy output of system including inverter.

Load of Solar Thermal Systems

In each solar energy system, there are supply and demand of energy, which, ideally, should be matched.

The supply of solar energy depends on the available solar resource, the technology to convert solar radiation to the usable heat, losses, properties of materials, and system design.

The energy demand depends on applications connected to the collectors - let it be water stoarge tank to be heated for domestic or industrial use, a space, a swimming pool, etc. Both supply and demand are time dependent.

It is understandable that the solar energy varies on the daily basis, usually peaking during the day and diminishing over the night.

The use of available energy also varies over time based on human activities or technical processes involved in the system. Here we use the term "*load*" to define a time-dependent energy need. Load is the amount of energy obtained from the source to do the work.

In a certain system, we can have a solar collector and another system - the *auxiliary* - to meet energy demand requirements.

The solar system alone is not sometimes sufficient and requires such a backup to make sure the application in use does not run out of energy.

The auxiliary can be represented by an on-site natural gas combustion system or grid, for example. Then the system load can be represented as:

$$L = L_s + L_a$$

with subscripts s and a standing for solar and auxiliary, respectively.

It is also useful to define the load rates (e.i. demanded power). The load rate is

$$L' = dL/dt$$

Note L' (rate) is denoted in the D&B book as L with a dot. Load rates are useful because the load are highly variable, and we may see times when the demands are met by solar energy and times when theya are met by auxiliar energy. The one important purpose of system modeling is to determine the hour-by-hour energy performance of the system, match it with loads, and decide how much auxiliary energy must be secured or purchased.

Here we can also define heating and cooling loads. Those depend on system thermal requirements.

For example, if a building is too cold and requires some heating to meet a certain standard, then we deal with a *heating load*. On the contrary, if the building is too warm, due to internal gains and losses, then we deal with a *cooling load,* in other words we need to remove energy from the space.

How can loads be estimated?

Please refer to the following reading to understand what heat gains and losses should be taken into account and what equations can be used.

Component and System Models

The real-life solar energy systems are composed of a number of different components and units. Each of those components has specifics that require certain theoretical background and consideration. Several previous lessons introduced some theory behind those component models - heat transfer from the Sun to the collector; heat transfer from the collector to thermal fluid; concentration of solar radiation on optical devices, etc.

While the basic calculations performed for those components can answer questions about what energy parameters can be output and what efficiency can be expected from each part of the system, the question still remains how those component models can be combined into a system model, that would allow optimization of the performance for a target application.

Overview of those component models is given in the first part of Chapter 10 if the D&B book. In these sections we can also read about the role of the **heat exchangers**, which provide interface between different components and allowheat transfer from one part of the system to another. Figure from the D&B textbook shows a typical solar water heating system, containing a collector, heat exchanger, storage tank, pipes, and pumps.

Throughout the system diagram, temperatures are noted. It is by these temperatures that the system component efficiencies can be calculated and subsequently integrated to find overall efficiency.

"System models are assemblies of appropriate component models." When you put together the equations decribing each of the components into the system model, the simultaneous solving of all those equations may be a serious challenge. Sometimes it is advantageous to treat the systems of equations numerically, especially if some of them are non-linear.

A number of computer simulation software have been developed to help with this task. Commonly, models cover annual cycle of system operation based on available meteorological data.

Thermal analysis performed for the whole system over significant period of time provide valuable information for assessing the economics of the project. There are a couple of useful parameters that we need to introduce here. The first one - **solar fraction (*f*)** is the ratio of the solar energy obtained by the system to the total load:

$$f_i = L_{S,i}/L_i$$

where L_s is the amount of solar energy used in the load, and L_i is the total load per unit of time. Or in integrated form (over a year), the same concept will be expressed as annual solar fraction (F):

$$F = L_S/L$$

The second parameter useful from economical standpoint is **solar savings fraction (F_{sav})**. It accounts for energy expenditures needed to run the solar system equipment (pumps, fans, controllers..) - so call "parasitic energy".

$$F_{sav} = F - (C_{ef}\Delta E)/L$$

where C_{ef} is the ratio of cost of additional electricity for solar system operation to the cost of fuel; ΔE is the amount of required "parasitic" electric energy. Read more about these metrics in the following source:

Equilibrium and steady state are two very different thermal states, but both provide a way to analyze the thermal status of a system.

Recall that an object in outer space absorbing solar radiation could be analyzed at thermal equilibrium to calculate the temperature of the object in light of the radiative heat loss and solar gain.

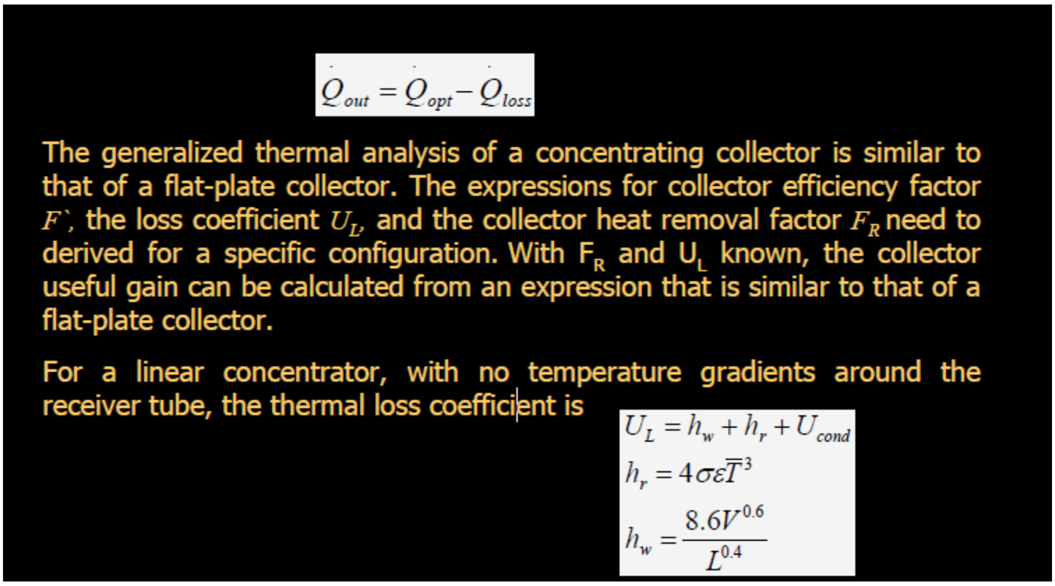
A steady state energy balance is a similar method that is used to analyze heat transfer in light of system dynamics. The Alleyne and Jain article from the *Mechanical Engineering* magazine gives an overview of basic transient system modeling for thermal systems in light of the application of steady state energy balance.

This method is how TRNSYS works, under the hood. Note that to simulate a thermal system, at steady state, the energy balance is calculated iteratively across time, and results in a time dependent solution.

By calculating and tracking the energy through the system at each interface or sub-system, we can obtain the overall energy balance of the whole system. Careful accounting is required to calculate an accurate energy balance.

All energy gain (heat transfer into the system) must equal all energy loss (heat transfer out of the system). When all energy is accounted for, we find a series of energy balance equations and can solve them simultaneously to calculate unknown temperatures, heat flow, and thermal properties.

Topic - Solar performance analysis



$$\dot{Q}_{out} = \dot{Q}_{opt} - \dot{Q}_{loss}$$

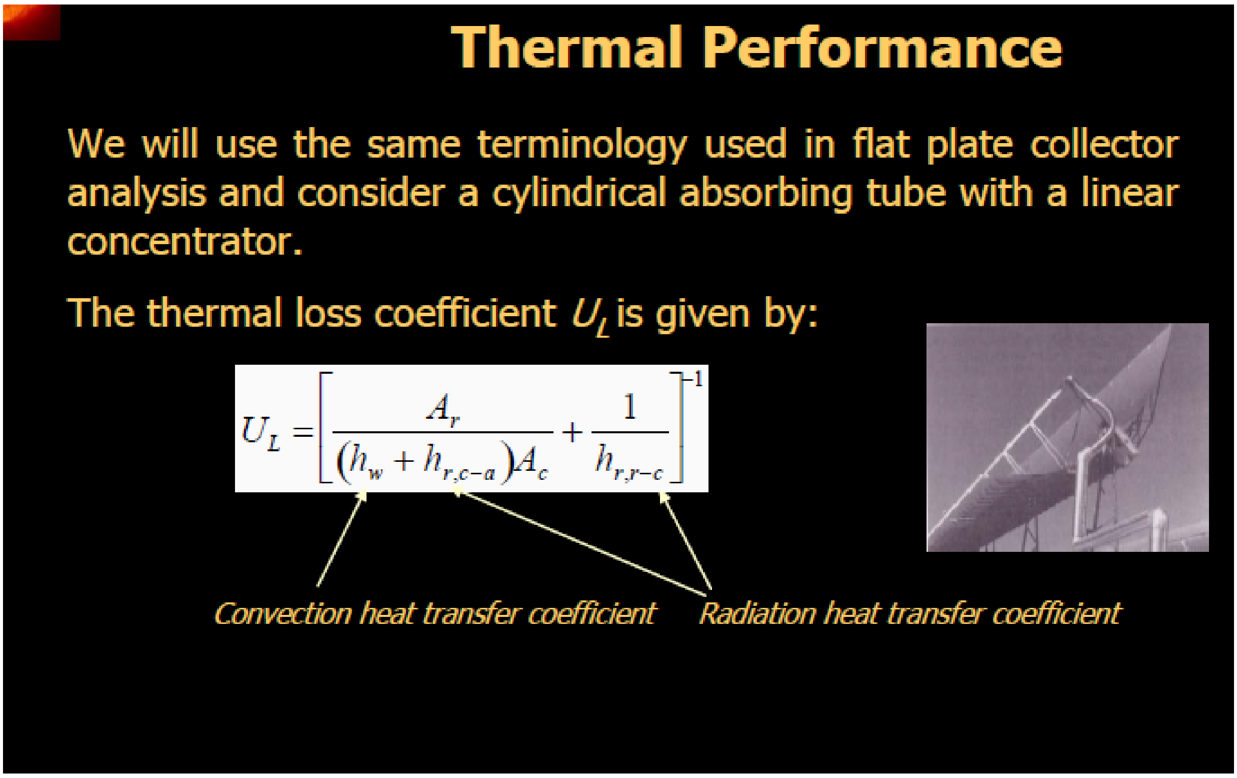
The generalized thermal analysis of a concentrating collector is similar to that of a flat-plate collector. The expressions for collector efficiency factor $F`$, the loss coefficient U_L, and the collector heat removal factor F_R need to derived for a specific configuration. With F_R and U_L known, the collector useful gain can be calculated from an expression that is similar to that of a flat-plate collector.

For a linear concentrator, with no temperature gradients around the receiver tube, the thermal loss coefficient is

$$U_L = h_w + h_r + U_{cond}$$

$$h_r = 4\sigma\varepsilon\bar{T}^3$$

$$h_w = \frac{8.6V^{0.6}}{L^{0.4}}$$



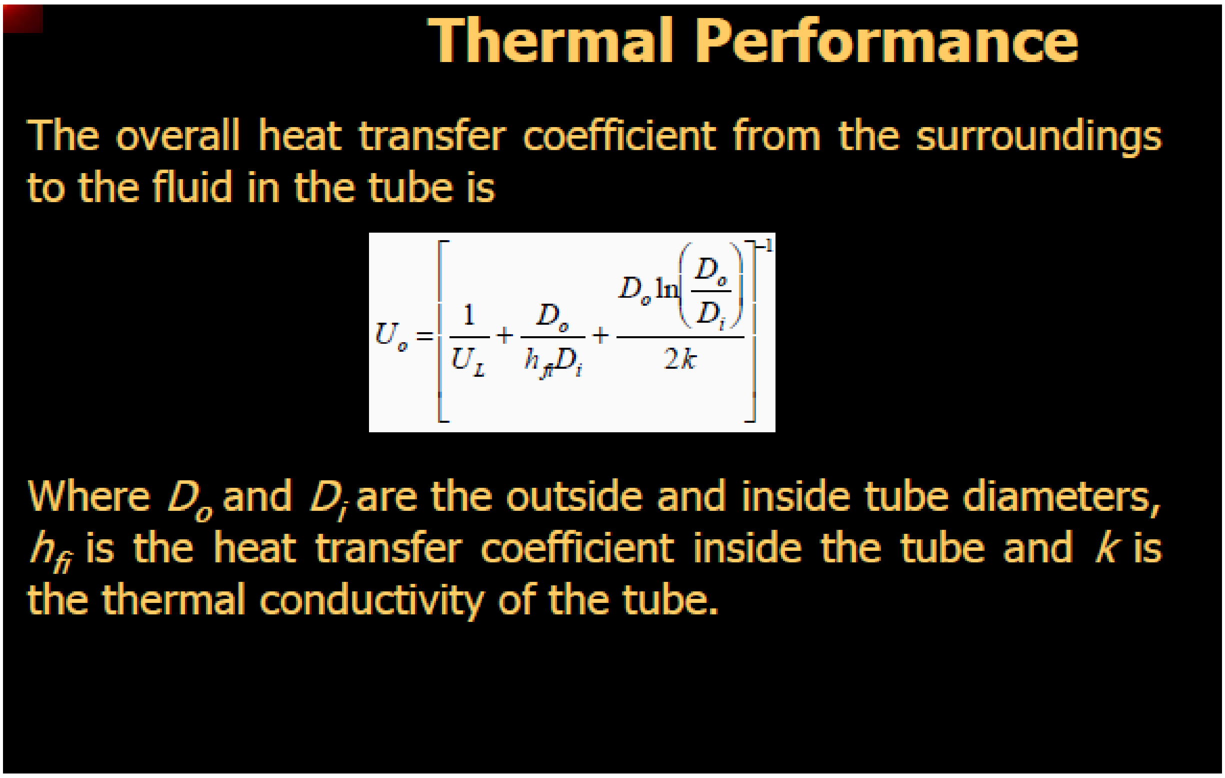
Thermal Performance

We will use the same terminology used in flat plate collector analysis and consider a cylindrical absorbing tube with a linear concentrator.

The thermal loss coefficient U_L is given by:

$$U_L = \left[\frac{A_r}{(h_w + h_{r,c-a})A_c} + \frac{1}{h_{r,r-c}}\right]^{-1}$$

Convection heat transfer coefficient *Radiation heat transfer coefficient*

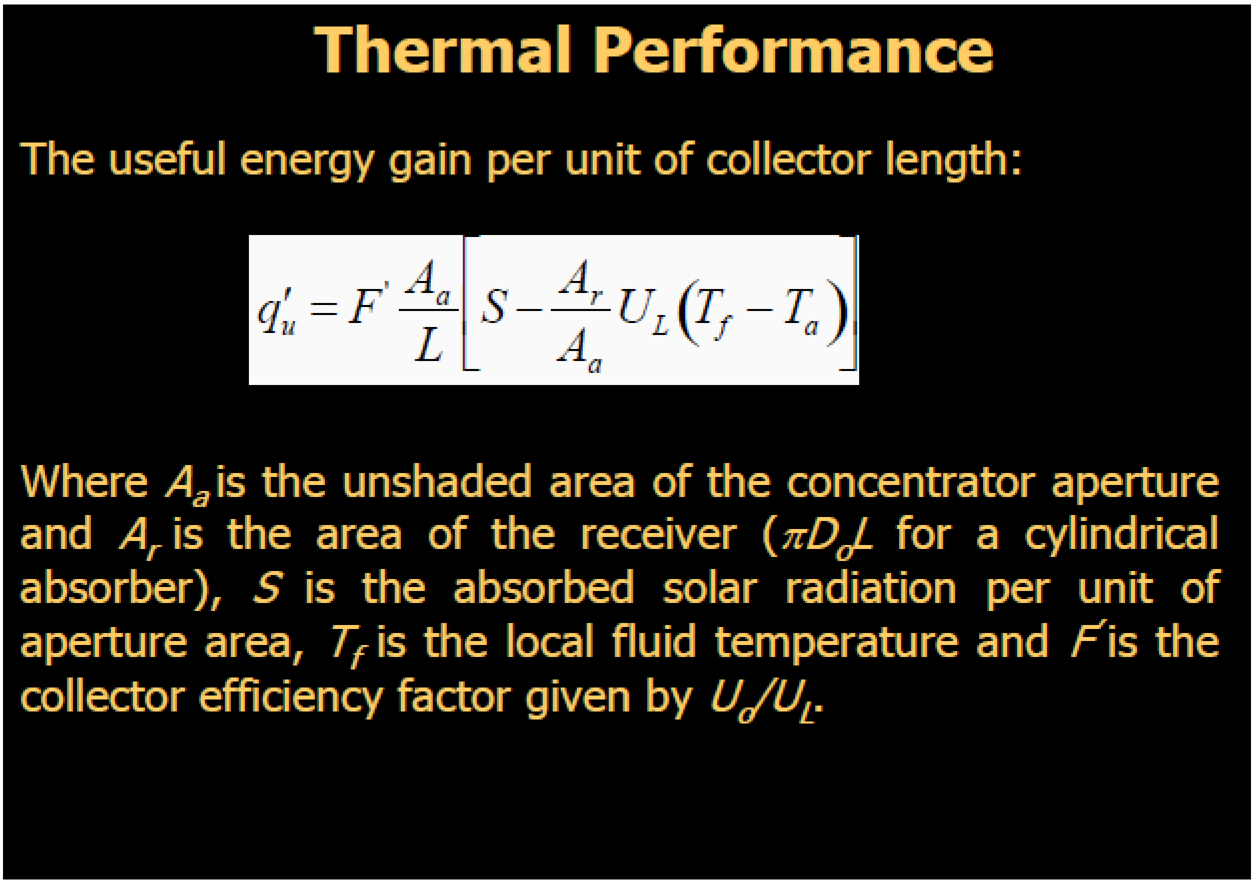


Thermal Performance

The overall heat transfer coefficient from the surroundings to the fluid in the tube is

$$U_o = \left[\frac{1}{U_L} + \frac{D_o}{h_{fi} D_i} + \frac{D_o \ln\left(\frac{D_o}{D_i}\right)}{2k} \right]^{-1}$$

Where D_o and D_i are the outside and inside tube diameters, h_{fi} is the heat transfer coefficient inside the tube and k is the thermal conductivity of the tube.

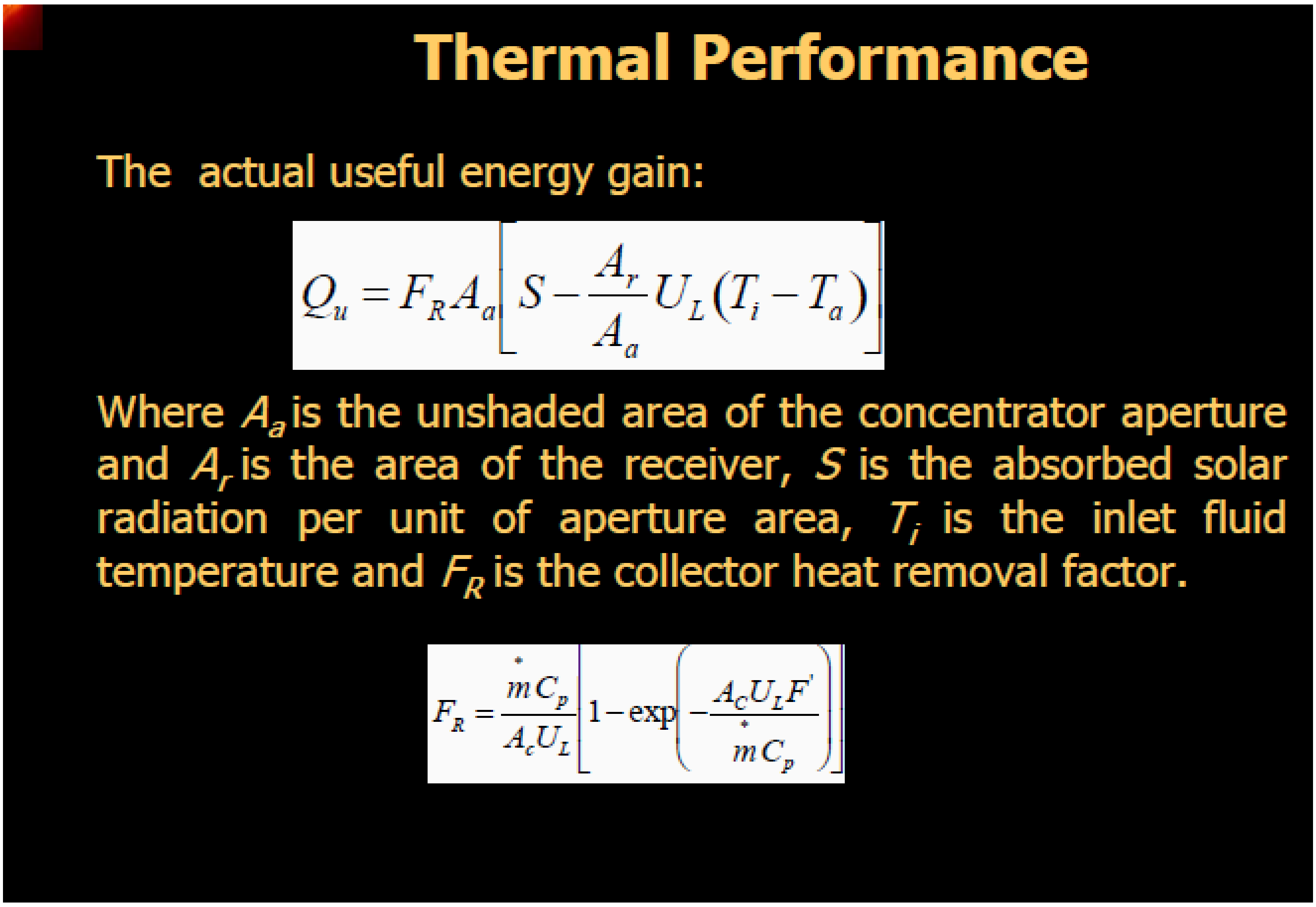


Thermal Performance

The useful energy gain per unit of collector length:

$$q'_u = F' \frac{A_a}{L} \left[S - \frac{A_r}{A_a} U_L \left(T_f - T_a \right) \right]$$

Where A_a is the unshaded area of the concentrator aperture and A_r is the area of the receiver ($\pi D_o L$ for a cylindrical absorber), S is the absorbed solar radiation per unit of aperture area, T_f is the local fluid temperature and F' is the collector efficiency factor given by U_o/U_L.



Thermal Performance

The actual useful energy gain:

$$Q_u = F_R A_a \left[S - \frac{A_r}{A_a} U_L (T_i - T_a) \right]$$

Where A_a is the unshaded area of the concentrator aperture and A_r is the area of the receiver, S is the absorbed solar radiation per unit of aperture area, T_i is the inlet fluid temperature and F_R is the collector heat removal factor.

$$F_R = \frac{\dot{m} C_p}{A_c U_L} \left[1 - \exp\left(-\frac{A_c U_L F'}{\dot{m} C_p} \right) \right]$$