Lecture #8

Concentrating Collectors & Solar Thermal Electric

Pages 73 - 79 of the text discuss concentrating collectors.

Concentrating collectors are used to bring the fluid to a temperature sufficiently high to be used for a heat engine. For example, the system illustrated on p. 78 of the text is located at Krammer Junction, California, and is used to generate electricity for the southern California grid. Fluid heated by the line-focused sunlight transfers its heat to water, thereby boiling it to produce steam for a steam-electric power plant. Thus, we have a solar-fired power plant.

There are several designs for concentrating solar radiation, some with mild levels of concentration, and others with large levels of concentration. The greater the concentration, the greater the temperature of the fluid receiving the sunlight.

The two concentrating collectors of main importance for electricity generation are illustrated on Figure 2.43, p.74 of text. These are:

1) Line-focus, or trough collector

2) Point-focus, or dish collector

A variation of the point collector is the "power tower" shown in the figures on p.77 of the text.

Important characteristics of concentrating collectors are as follows:

1) The level of concentration determines the temperature obtained (stated above)

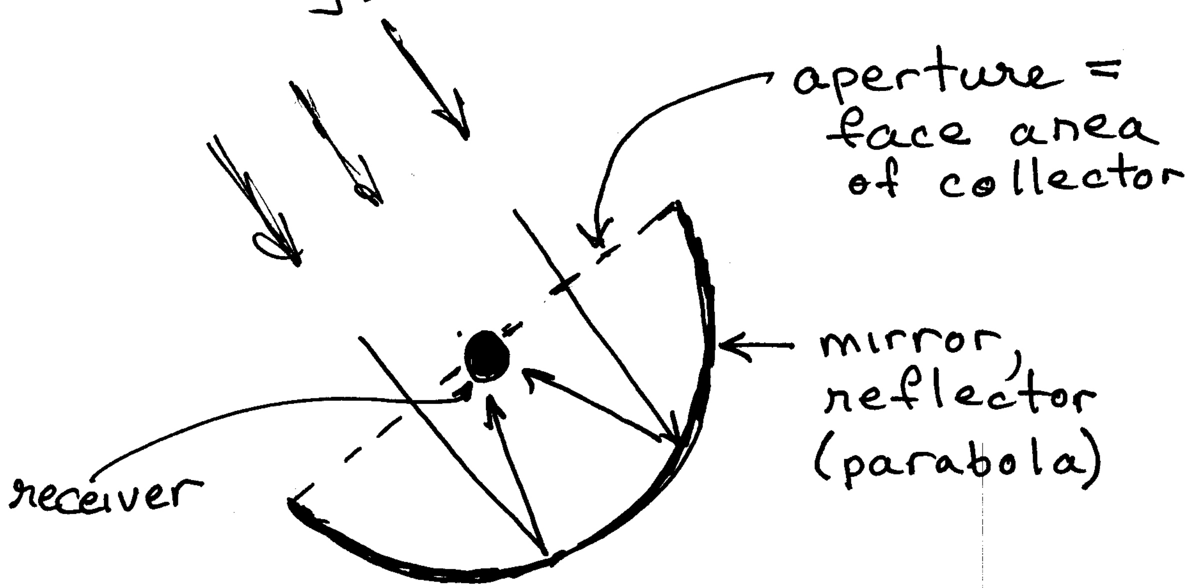
2) With increasing concentration, it becomes increasingly important to track the sun. The trough and dish collectors shown in Figure 2.42 must track the sun.

3) With increasing concentration, the diffuse and reflected solar radiation become more and more useless, since they cannot be focused. The trough and dish collectors shown in Figure 2.42 depend on <u>beam</u> radiation.

4) For the line-focus system, the theoretical maximum amount of concentration is 215. This is set by the diverage angle of the sun's rays (about 1/2 degree). For a point-focus system, the theoretical maximum concentration is $(215)^2$.

5) Because of the high temperature attained by the fluid at the focus line (or point), the predominant heat loss for concentrating collectors is the radiative heat loss. Conductive and convective heat losses are relatively unimportant.

Terminology:



Master equation:

$$Q_{fluid}\,(\text{watts}) = \underbrace{G_{bc} A_a \rho \alpha}_{\text{solar radiation absorbed}} - \underbrace{A_r \epsilon \sigma T_r^4}_{\text{thermal radiation emitted}}$$

where:

G_{bc} = beam solar energy flux normal to collector aperture

A_a = collector aperture area

ρ = reflectivity, or reflectance, of mirror (want this to be as close to 1 as possible)

α = absorptivity, or absorptance of receiver (want this to be as close to 1 as possible for solar wavelengths).

A_r = area of receiver

ϵ = emissivity of receiver (want this to be as close to 0 as possible for thermal wavelengths)

σ = Stefan-Boltzmann constant

T_r = temperature of receiver

Note: 1) the term at the right should really be written as $A_r \epsilon \sigma (T_r^4 - T_{sky}^4)$ -- but since $T_r^4 >> T_{sky}$, T_{sky}^4 is neglected

2) The temperature of the fluid in the receiver is assumed be the receiver temperature, T_r

3) The concentration, or more precisely, the concentration ratio is:

$$X = A_a / A_r$$

4) The efficiency of the collector is:

$$\eta_c = \frac{Q_{fluid}}{G_{bc} A_a} = \rho\alpha - \frac{\epsilon \sigma T_r^4}{G_{bc} X}$$

5) The maximum temperature of the receiver occurs when no heat is carried away by the fluid, i.e. when $Q_{fluid} = 0$. Then

$$T_{r_{max}} = \left(G_{bc} X \frac{\rho \alpha}{\sigma \epsilon} \right)^{1/4}$$

Note: if the receiver is a "gray" body, i.e., $\alpha = \epsilon$, then $T_{r_{max}} = \left(G_{bc} X \frac{\rho}{\sigma} \right)^{1/4}$

In order to determine the power output of the concentrating collector-heat engine system, we need to multiply Q_{fluid} by the efficiency of the heat engine. This depends on the type of heat engine used. Trough collectors tend to be used with the Rankine cycle steam engine, and dish collectors tend to be used with Stirling cycle piston engines.

The heat engine efficiency is:

$$\eta_e = \frac{\text{Net Power Produced}}{\text{Thermal Power Input}} = \frac{P_{net}}{Q_{fluid}}$$

Note: usually this the electrical power produced by the electrical generator driven by the heat engine

Thus:

$$P_{net} = \eta_e \left[G_{bc} A_a \rho \alpha - A_r \epsilon \sigma T_r^4 \right]$$

The overall efficiency is

$$\eta_o = \eta_e \eta_c = \eta_e \left[\rho \alpha - \frac{\epsilon \sigma T_r^4}{G_{bc} X} \right]$$

A reasonable approximation for the efficiency of the Rankine cycle steam engine is $2/3$ × the Carnot Cycle efficiency, or

$$\eta_e \cong \frac{2}{3} \left(1 - \frac{T_L}{T_H} \right)$$

where T_L = temperature of heat rejected from engine

and T_H = temperature of heat added to engine

The values of T_L and T_H are:

$$T_L \cong T_a = \text{ambient temperature}$$

$$T_H \cong T_r = \text{receiver temperature}$$

Thus:

$$\boxed{\eta_0 \cong \frac{2}{3}\left(1 - \frac{T_a}{T_r}\right)\left(\rho\alpha - \frac{\epsilon\sigma T_r^4}{G_{bc} X}\right)}$$

One can read about US solar thermal electric R&D and technology at

www.eren.doe.gov/sunlab

Especially, see:

$\underbrace{\text{www.eren.doe.gov/sunlab/PDFs/solar\_overview.pdf}}$

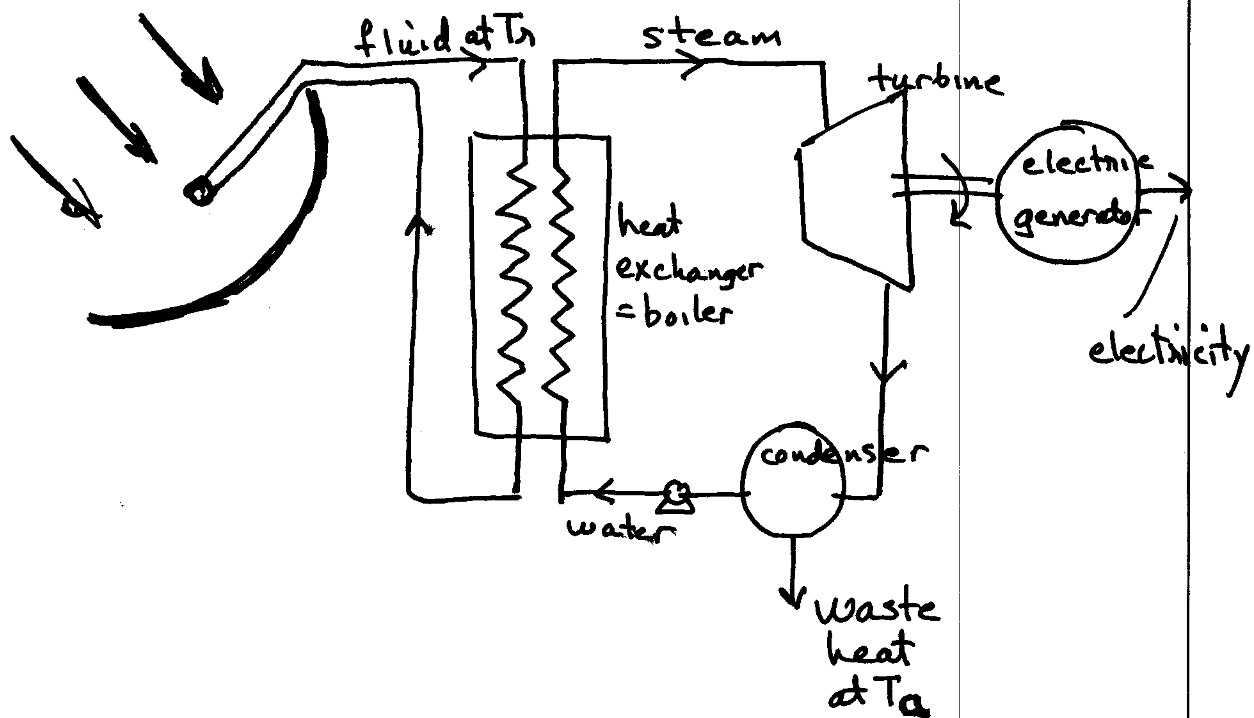
or

solar_trough.pdf

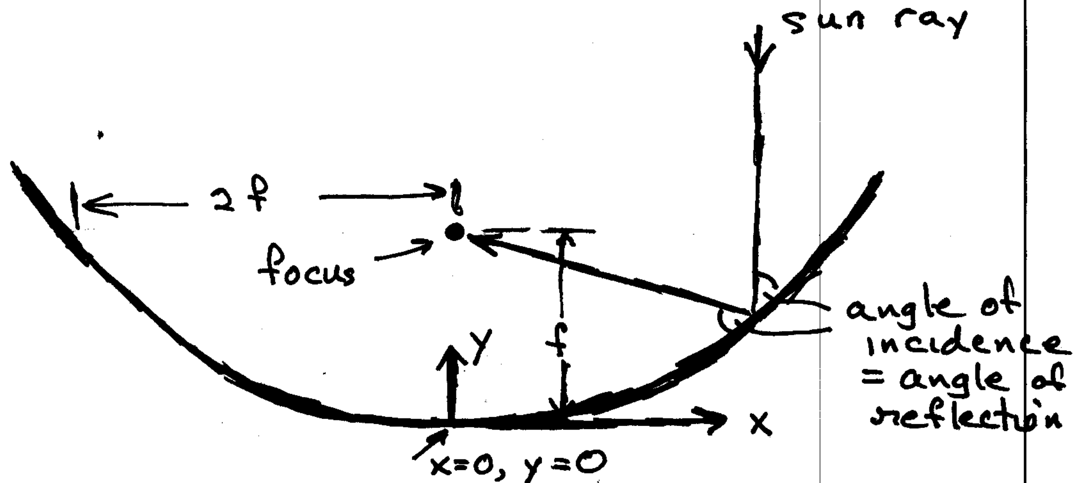
or

solar_dish.pdf

System for trough collector:



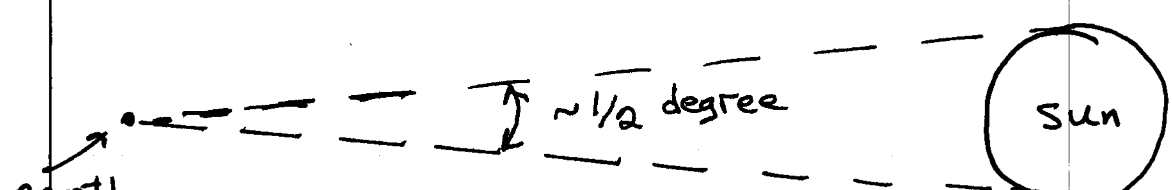
Finally, let's examine the concentration ratio. We assume a parabolic, line-focus collector.



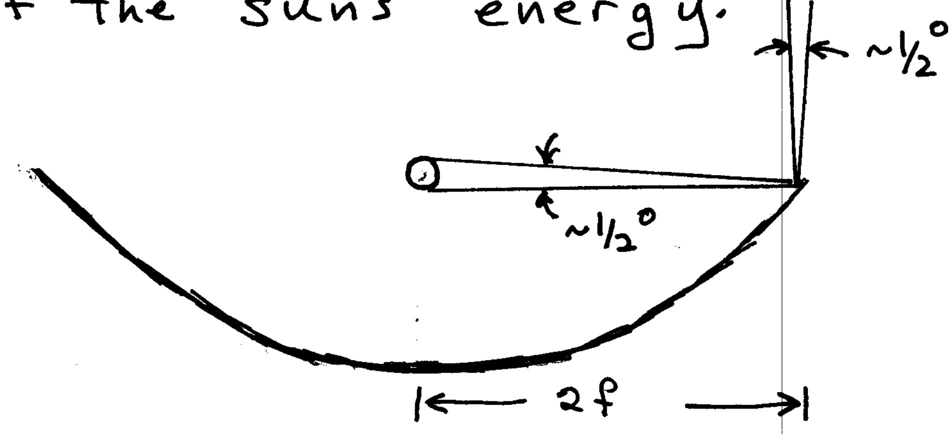
Our coordinate system is attached to the bottom of the collector.
The equation for the parabola is $y = x^2/2f$, where f = distance from $x=0, y=0$ to the focus point.

This parabola has the condition of focusing all vertical incoming rays onto the focus point at $x=0$, $y=f$.

The sun's rays are not exactly parallel. They have a divergence angle of about 1/2 degree.



Consequently, the receiver must have a certain minimum diameter -- otherwise, it will not capture all of the sun's energy.



For the collector illustrated, with receiver in the center of the aperture plane, the diameter of the receiver must be at least

$$d = 2f\theta$$

where θ = sun's rays divergence angle
$\cong$ 1/2 degree (expressed as radians)

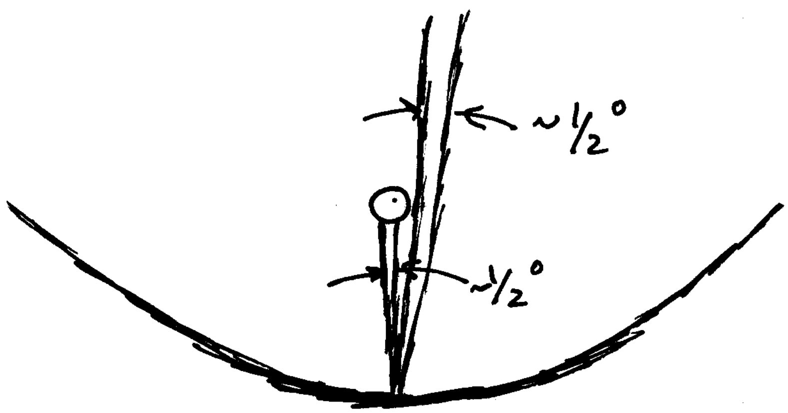
That is:

exact value

$$d = 2f \frac{0.53 \text{ degree}}{57.2958 \text{ degrees/radian}}$$

$$d = 0.0185\, f$$

Note: the rays striking near the bottom of the collector's parabola have "extra" receiver area -- they do not fully fill the receiver area



Thus, the system does not have the maximum possible concentration ratio of 215.

The concentration ratio in this case is:

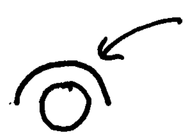
$$X = \frac{A_a}{A_r} = \frac{4fL}{\pi d L}$$ ← length of trough collector

$$= \frac{4f}{\pi d} = \frac{4f}{\pi 2 f \theta} = \frac{2}{\pi \theta}$$

$$= \frac{2}{\pi (0.53/57.2958)}$$

$$= 69$$

What if we shield the top of the receiver, so that it cannot radiate to the sky?



Then

$$X = 2 \times 69 = 138$$

What is the receiver temperature if:

$G_{bc} = 900\ W/m^2$ (very sunny)

$X = 138$

$\rho = 0.95$

$Q_{fluid} = 0$

Gray receiver ($\epsilon = \alpha$)

$$T_r = \left(900 \times 138 \times 0.95 / 5.67 \times 10^{-8}\right)^{1/4}$$

$$= \underline{1201\ K}$$