Solar Energy Conversion Technology

Solar Concentrating Collectors

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- ✓ Fundamentals of concentrating collectors
- ✓ Analysis of parabolic trough collector

Concentrating Solar Power (CSP) Technology

- Concentrating solar power (CSP) technology utilizes **focused sunlight**.
- Concentrators increases the amount of incident energy on the absorber surface as compared to that on the concentrator aperture.
- Utilizes mirrors or lenses to concentrate (focus) sun's energy and convert it into high-temperature heat.

Concentrating Solar Power (CSP) Technology

Concentrating Solar Power (CSP) system follows the sun so that the beam radiation are always focused on to the absorber.

A solar concentrator generally consists of

- A focusing device
- An absorber/receiver provided with or without a transparent cover
- A tracking device for continuously following the sun

Solar Concentrators advantages

- Higher delivery temperatures resulting in better thermodynamic efficiency.
- Reduced heat losses due to less material requirement compared to FPC systems.
- Storing heat at higher temperatures results in reducing the storage cost.

- **Temperature as high as 3500 °C have been achieved.**
- **Solar Collectors are used for thermal as well as PV conversion of solar energy.**

Solar Concentrators Drawback

- No use of diffused radiation.
- Clear sky is preferred in the location.

Functioning of Solar Concentrator

Concentrating solar power systems generate electricity with heat.

- Concentrating solar collectors use mirrors and lenses to concentrate and focus sunlight onto a thermal receiver, similar to a boiler tube.
- The receiver absorbs and converts sunlight into heat.
- The heat is then transported to a steam generator or engine where it is converted into electricity.

CSP technology generate electricity for a variety of applications-

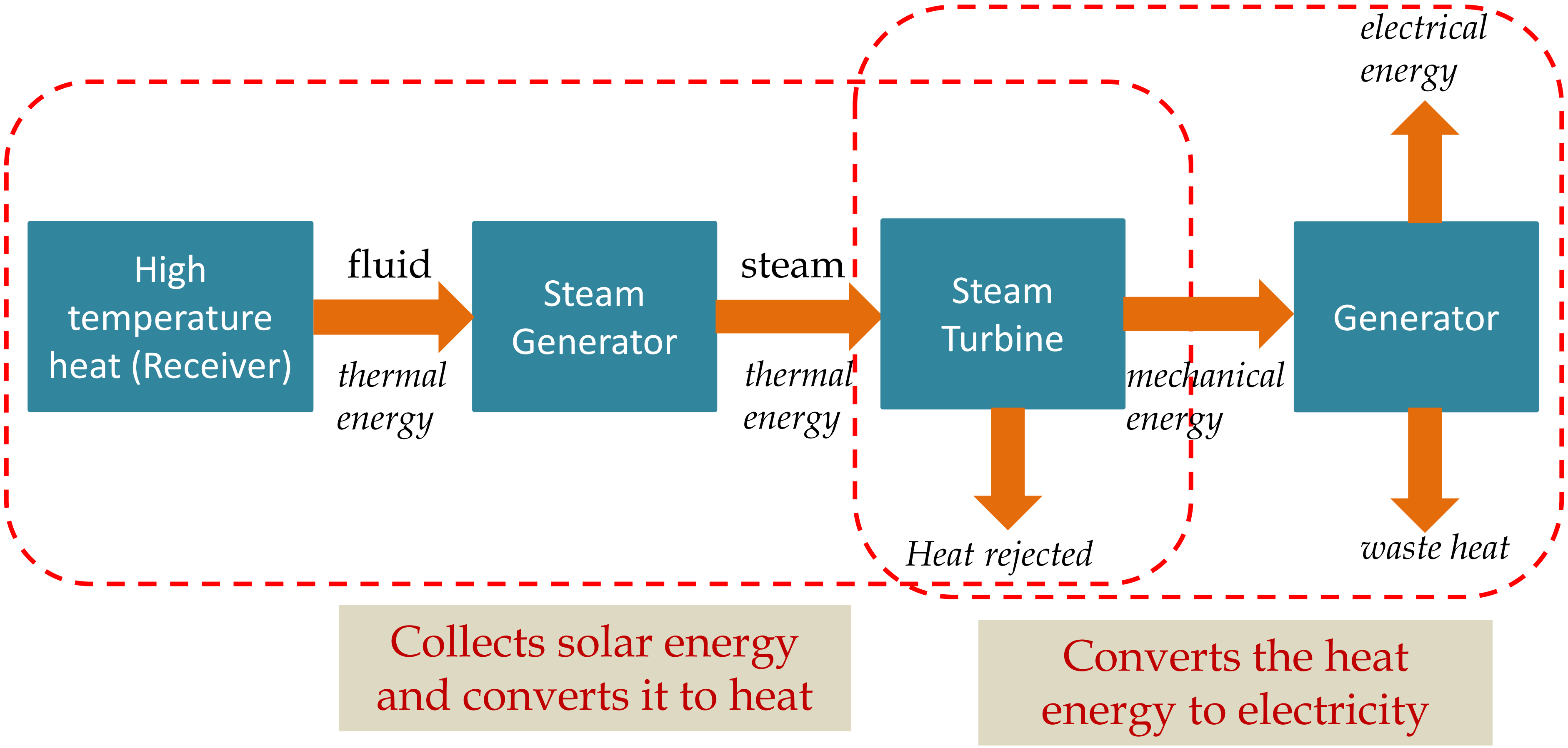
- Ranging from remote power systems as small as a few kilowatts (kW) up to grid connected applications of 200-350 megawatts (MW) or more.
- A concentrating solar power system that produces 350 MW of electricity displaces the energy equivalent of 2.3 million barrels of oil.

Solar Thermo-Mechanical System

- Converts solar thermal energy to mechanical energy through heat engines (using Rankine cycle, Stirling cycle or Brayton cycle).
- Mechanical energy produced may be used as shaft power such as water lifting.
- Mechanical energy produced may also be converted to electricity using generator.

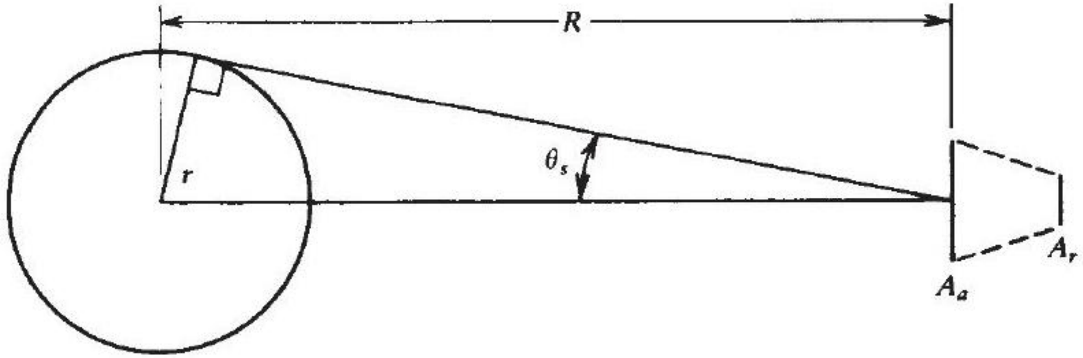
Limitations of conversion of solar thermal energy to mechanical energy:

- Conversion efficiency is low (approx. 9-18 %).
- Efficiency of the collector system decreases as the collection temperature increases while the efficiency of a heat engine increases as the working fluid temperature increases.
- Solar collectors are generally more expensive than engines.
- A part of thermal energy is lost during the transportation of the working fluid from the collector to the heat engine.
- A very large area is required to install the solar collector system.
- Due to the intermittent nature of solar energy, storage of thermal energy is also required.


High temperature heat (Receiver)
fluid
thermal energy
Steam Generator
steam
thermal energy
Steam Turbine
mechanical energy
Heat rejected
Generator
electrical energy
waste heat
Collects solar energy and converts it to heat
Converts the heat energy to electricity

Parameters Characterizing Solar Concentrators

- Aperture Area (A_a): Area through which the solar radiation is incident
- Absorber area (A_{abs}): Total area of the absorber surface that receives the concentrated radiation. It is also the area from where useful energy can be obtained.
- Acceptance Angle ($2\theta_s$): Defines the angular limit to which the incident ray may deviate from the normal to the aperture plane and still reach the absorber /receiver.
- Intercept factor: Fraction of the radiation, which is reflected or refracted from the concentrator anc
- Optical Efficiency: E energy incident on the concentrator's a /lens surface, shape and reflection/trans ding, receiver-cover transmittance, absor incidence effects.

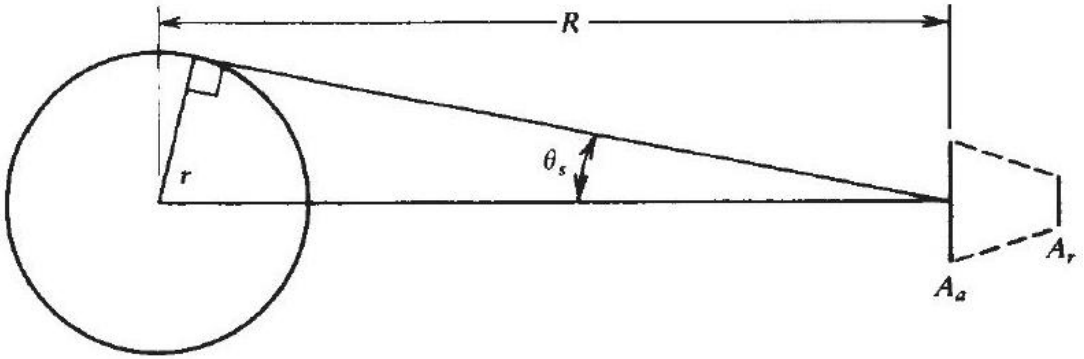


Concentration Ratio

Geometrical Concentration Ratio, C= Ratio of aperture area to the absorber area.

$$C = A_a / A_{abs}$$

Local Concentration Ratio: Ratio of the solar radiation at any point on the absorber surface to the incident radiation at the aperture of the solar concentrator.



Half-angle subtended by the sun at the earth (θ_s) is 0.267 °

A concentrator with large acceptance angle needs only seasonal adjustment while a concentrator with small acceptance angle is required to track the sun continuously.

Radiative Heat Exchange Between the Sun and the Receiver

The sun is assumed to be a blackbody at T_s and the radiation from the sun on the aperture/receiver is the fraction of the radiation emitted by the sun which is intercepted by the aperture.

$$\boxed{Q_{s\to r} = A_a \frac{r^2}{R^2} \sigma T_s^4}$$

Where, $\sigma = 5.6697\text{x}10^{-8}$ W/m^2K^4

A perfect receiver, such as a blackbody, radiates energy equal to $A_r T_r^4$ and a fraction of this reaches the sun.

$$\boxed{Q_{r\to s} = A_r \sigma T_r^4 E_{r\to s}}$$

Maximum Concentration Ratio

When T_r and T_s are the same, the second law of thermodynamics requires that $Q_{s\rightarrow r}$ be equal to $Q_{r\rightarrow s}$.

$$\frac{A_a}{A_r} = \frac{R^2}{r^2} E_{r\rightarrow s}$$

Since the maximum value of $E_{r\rightarrow s}$ is unity, the maximum concentration ratio for circular concentrators is

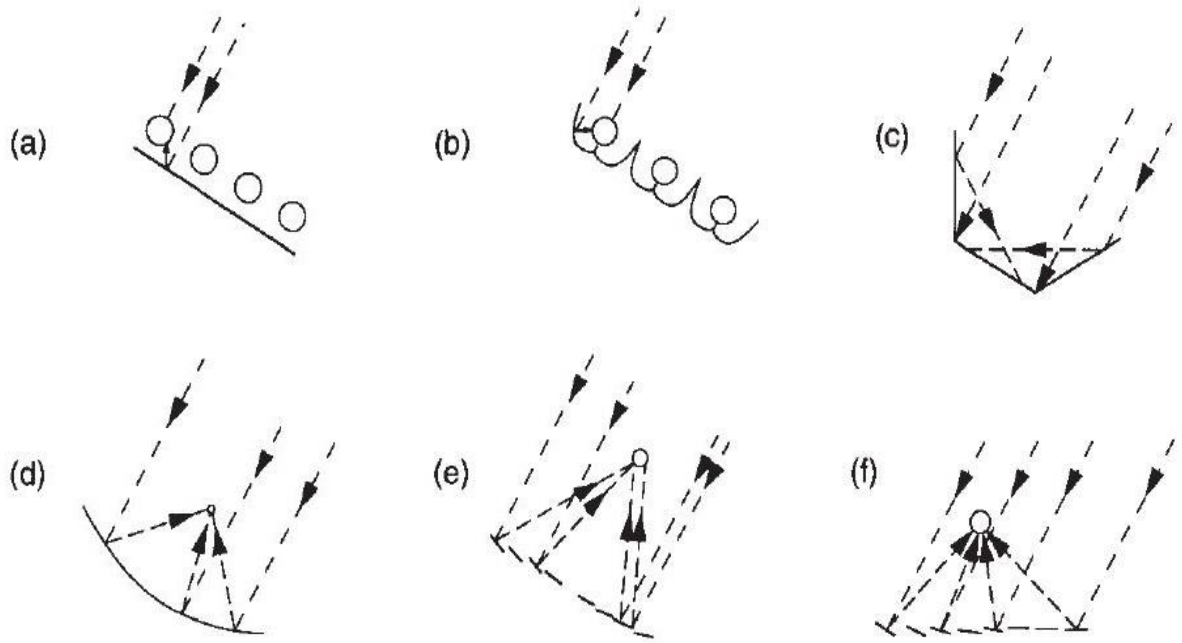
$$\left(\frac{A_a}{A_r}\right)_{circular,\,max} = \frac{R^2}{r^2} = \frac{1}{\sin^2\theta_s}$$

For linear concentrators, maximum concentration ratio is

$$\left(\frac{A_a}{A_r}\right)_{linear,\,max} = \frac{R}{r} = \frac{1}{\sin\theta_s}$$

With $\theta_s = 0.267^{\circ}$, the maximum possible concentration ratio for circular concentrators is 46,000 and for linear concentrators, it is 215.

Concentrating collectors configurations



Concentrating collector configurations: (a) tubular absorbers with diffuse back reflector; (b) tubular absorbers with specular cusp reflectors; (c) plane receiver with plane reflectors; (d) parabolic concentrator; (e) Fresnel reflector; (f) array of heliostats with central receiver.

$$C_{max,3\text{-}D} = \frac{1}{\sin^2\theta}, \; \textit{for a point focusing system}$$

$$C_{max,2\text{-}D} = \frac{1}{\sin\theta}, \; \textit{for a line focusing system}$$

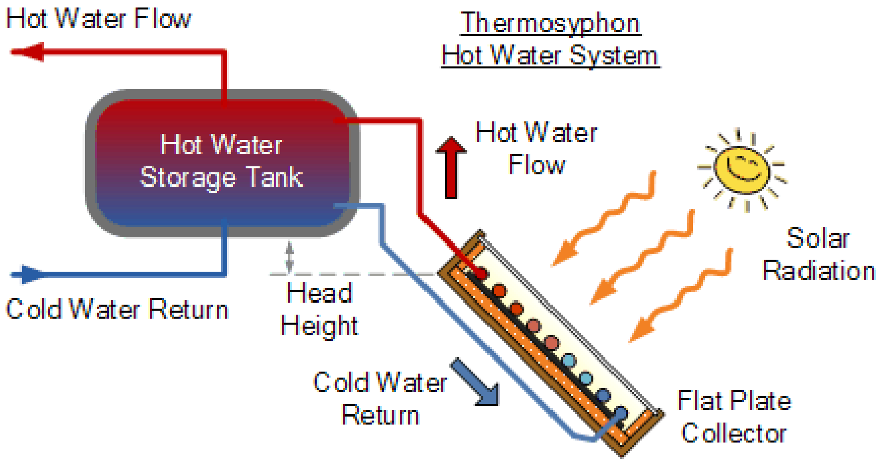
Concentration ratio for a line-focus concentrator is 215 and for a point focus concentrator it is 46000.

In the first three types, the maximum concentration ratio is 4.

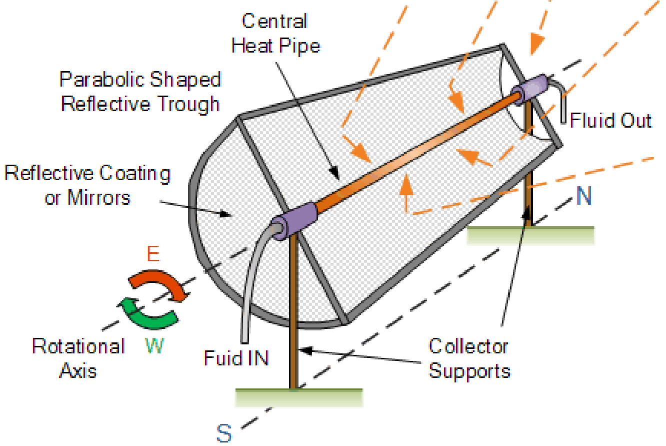
The actual values of C is much lower since acceptance angle is usually greater than 0.267°. These include tracking errors, imperfections in the reflecting or refracting components of the concentrator, mechanical misalignment etc.

Comparison of FPC and Concentrating collector

- Area absorbing solar radiation is the same as the area intercepting solar radiation.
- FPC can be designed to get a temperature around 100-110 ^{o}C to heat liquids/gases.
- Advantage of using both beam and diffuse solar radiation.
- Do not require orientation towards the sun.
- Mechanically simpler in design and require little maintenance.



- Concave reflectors or mirrors are used to concentrate the radiation falling into a smaller receiver to increase the energy flux.
- Temperature ranges from 260 ^{o}C to 3500 ^{o}C depending upon the application and type of concentrator used.
- Utilizes direct beam radiation and reject majority of the diffused radiation.
- Oriented in varying degrees to track the sun so that beam radiation is directed on to the absorbing surface.
- Maintenance is difficult – particularly to retain the quality of optical systems for long periods of time against dirt, weather, oxidation etc.
- All these factors add to the cost.



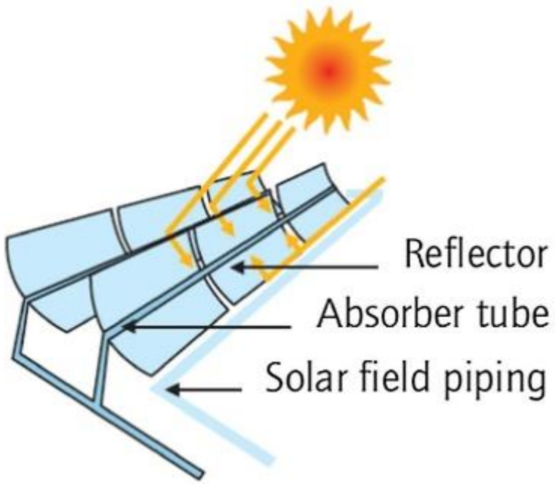
Mode of classification of Concentrating collectors

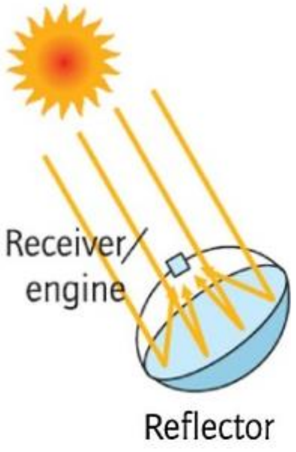
- **Based on aperture type**
  - Refracting type utilizing Fresnel lenses
  - Reflecting type utilizing mirrors
    - Reflecting surface my be parabolic, spherical or flat (continuous or segmented)
- **Based on image formation**
  - Non-imaging type
  - Imaging type
    - Line focusing type
    - Point focusing type
- **Based on operating temperature**
  - Low, medium and high temperature
- **Based on Tracking mechanism**
  - Single axis tracking
  - Two axis tracking

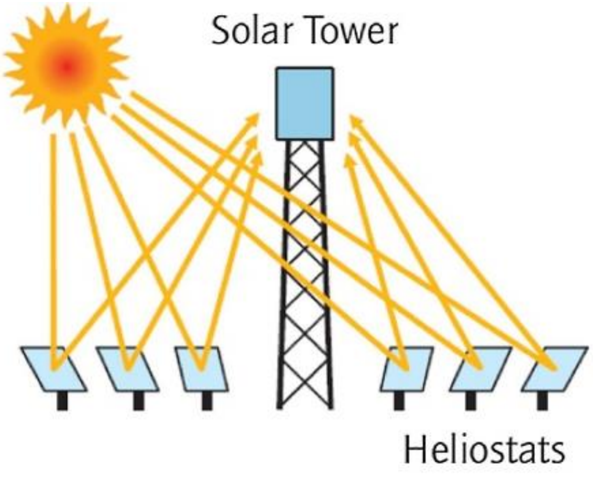
Concentric Solar Technology based on application

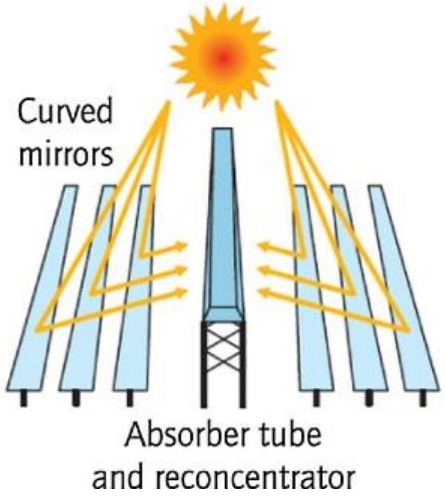
Concentric Solar Technology (CST)

- Parabolic trough
- Dish Stirling
- Central Tower
- Fresnel Collector









Comparison between different Concentrating Solar Power (CSP) technology

CSP Technology	Storage Integration Possibility	Advantages	Disadvantages
Parabolic trough collector (PTC)	Possible	• Relatively low installation cost • Large experimental feedback	• Relatively large area occupied • Low thermodynamic efficiency due to low operating temperature
Linear Fresnel Reflector (LFR)	Possible	• Relatively low installation cost	• Low thermodynamic efficiency due to low operating temperature
Solar Power Tower (SPT)	Highly possible with low storage cost	• High thermodynamic efficiency due to high operating temperature	• Large space area occupied • Relatively high installation cost • High heat losses
Parabolic Dish (PD)	Difficult	• Relatively small area occupied • High thermodynamic efficiency due to high operating temperature	• Relatively high installation cost • Little experimental feedback

Thermal Analysis of Concentrating collectors:

Under steady-state condition, energy balance equation on the absorber yields:

$$\boxed{q_u = A_a S - q_l}$$

(assuming diffuse component of solar radiation is negligible)

Where q_u = rate of useful heat gain

A_a = effective area of the aperture of the concentrator

S = Solar beam radiation per unit effective aperture area absorbed in the absorber

q_l = rate of heat loss from the absorber

The rate of heat loss in terms of overall loss coefficient,

$$\boxed{q_l = U_l A_p \left(T_{pm} - T_a\right)}$$

where

U_l = overall loss coefficient

A_p = area of the absorber surface

T_{pm} = average temperature of the absorber surface

T_a = temperature of the surrounding air

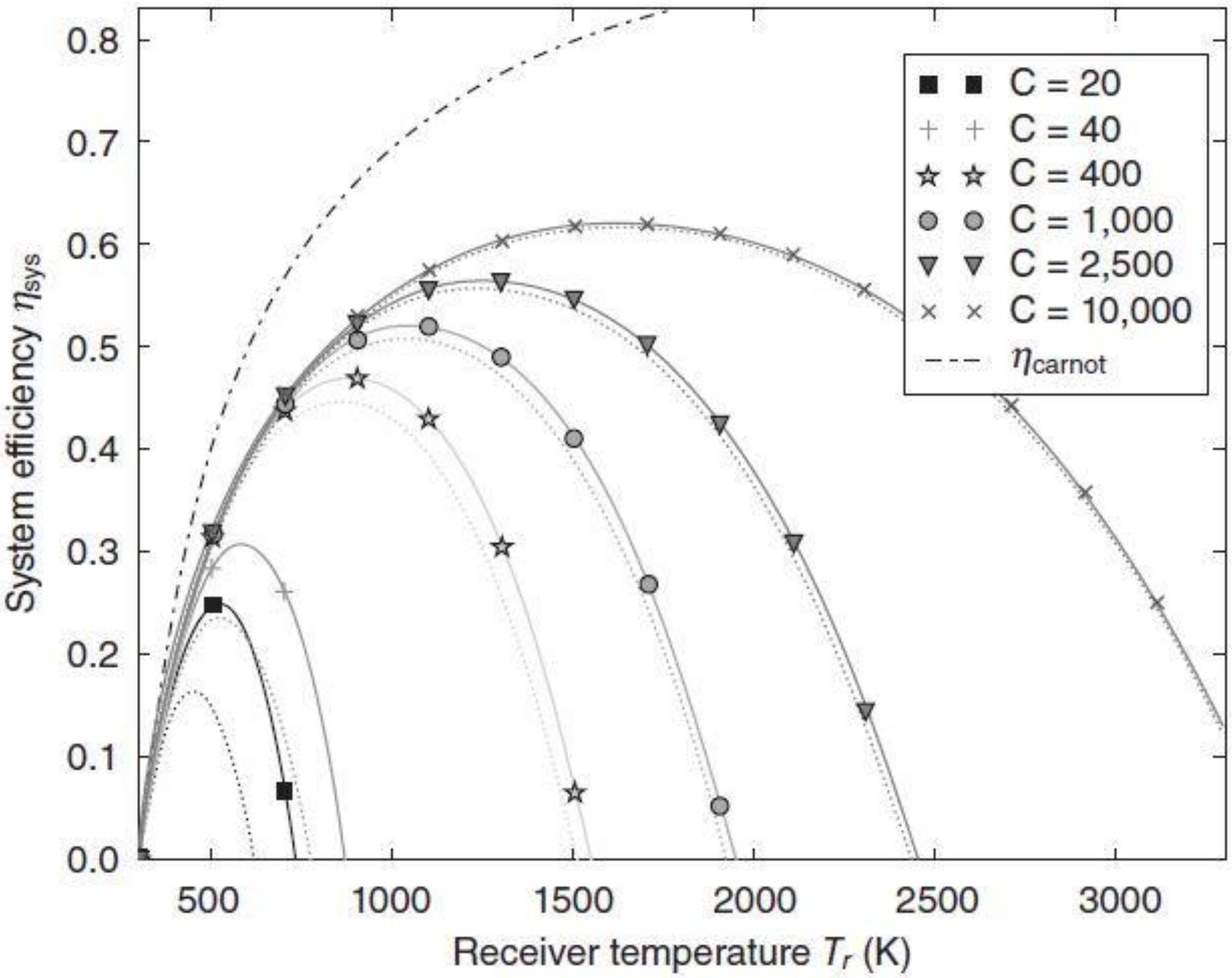
By combining the above two equations:

$$\boxed{q_u = A_a \left[S - \frac{U_l}{C}\left(T_{pm} - T_a\right) \right]}$$

where

$$\boxed{C = \frac{A_a}{A_p} = concentration\ ratio}$$

CSP system efficiency as a function of receiver temperature



[Source: Concentrating solar power technology: Principles, developments and applications, Woodhead Publishing]

Flat Plate collector, C = 1
Parabolic trough, C = 80
Solar Tower, C = 500
Parabolic dish, C = 2000

Overall efficiency of CSP,

$$\eta_{system} = \eta_{collector} \times \eta_{carnot}$$

With increase in temperature,

$$\eta_{collector} \downarrow \ \& \ \eta_{carnot} \uparrow$$

Concentrating Solar Power Applications

Utility/ Commercial Scale

Power Generation:

- ✓Stand alone
- ✓Grid connected systems
- ✓Hybrid systems

Thermal Needs:

- ✓Hot Water and Steam (Industrial & Commercial Uses)
- ✓Air Conditioning – Absorption Chillers
- ✓Desalination of seawater by evaporation

Solar Chemistry:

- ✓Manufacture of metals and semiconductors
- ✓Hydrogen production (e.g. water splitting)

Materials Testing Under Extreme Conditions:

- ✓e.g. Design of materials for shuttle reentry

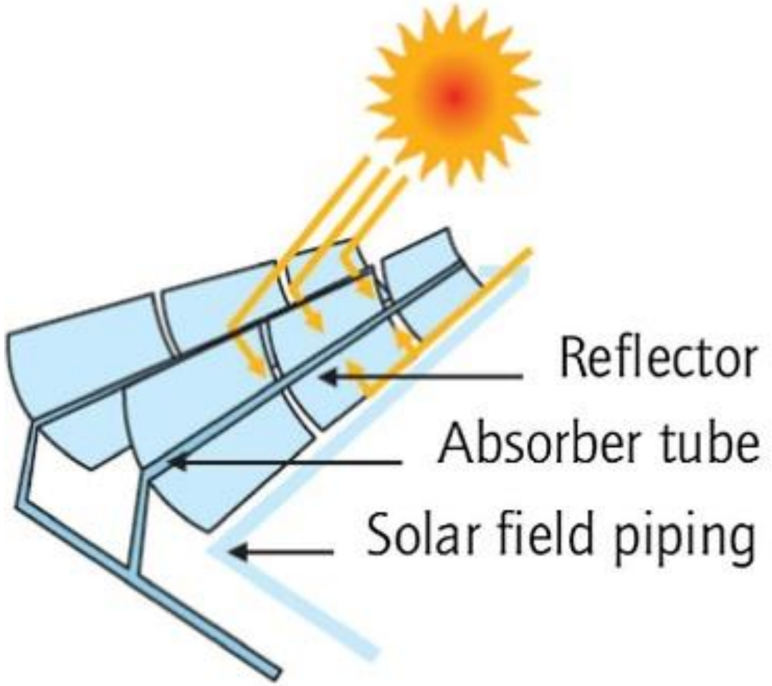
Domestic/ Small Scale

- ✓ Hot Water Collector
- ✓ Solar HVAC
- ✓ Solar Steam Cooking
- ✓ Solar Ovens/Cookers
- ✓ Solar Food Dryers

Concentrating Solar Power (CSP) technology analysis

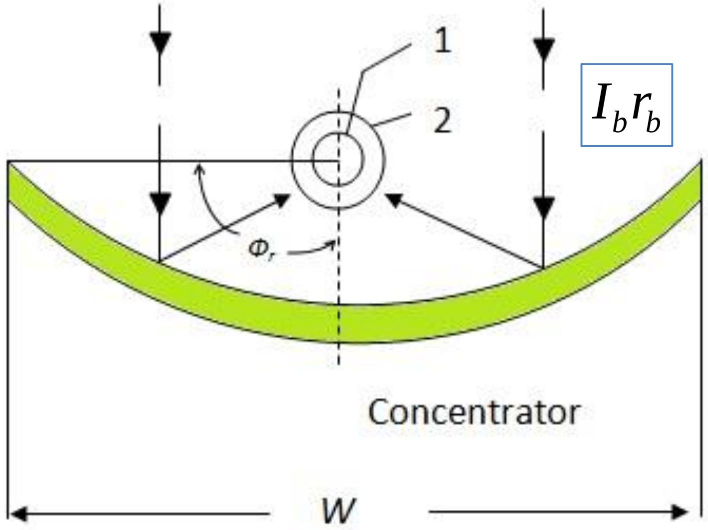
CSP Technology	Relative cost	Land occupancy	Thermodynamic efficiency	Operating Temperature range (°C)	Solar concentration ratio	Improvement potential
Parabolic trough collector (PTC)	Low	Large	Low	20–400	15–45	Limited
Solar Power Tower (SPT)	High	Medium	High	300–565	150–1500	Very significant
Linear Fresnel Reflector (LFR)	Very low	Medium	Low	50–300	10–40	Significant
Parabolic Dish (PD)	Very high	Small	High	120–1500	100–1000	High potential

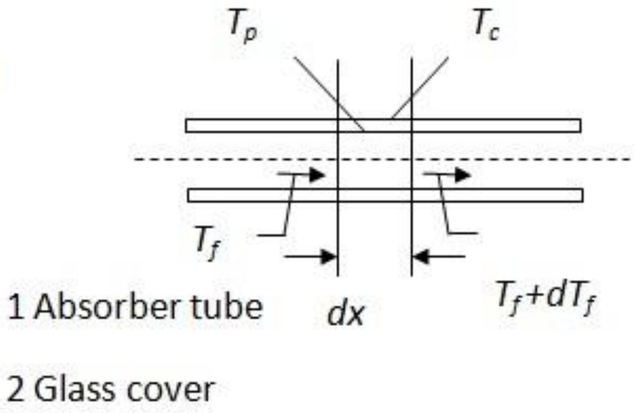
Analysis of Parabolic Trough Collector



Assumption

- ✓ Radiation flux is same along the length
- ✓ Temperature drops across the absorber tube and the glass cover are neglected





$$\boxed{C = \frac{\text{Effective aperture area}}{\text{Absorber tube area}} = \frac{(W - D_o)L}{\pi D_o L} = \frac{(W - D_o)}{\pi D_o}}$$

- ➢ Aperture of the concentrator: *W*
- ➢ *Length L* ϕ_r
- ➢ *Rim angle:*

- ✓ *Absorber inner Dia: D_i,*
- ✓ *outer diameter D_o,*
- ✓ *Concentric glass cover of inner dia D_{ci}, outer dia D_{co},*

- ✓ *Fluid being heated has a mass flow rate* $\dot{m}$
- ✓ *Fluid inlet temperature , T_{fi}*
- ✓ *Fluid outlet temperature , T_{fo}*

Analysis of Parabolic trough collector

An energy balance on an elementary slice *dx* *of the absorber tube at a distance x from the inlet, yields the steady state equation*

$$dq_u = \left[I_b r_b (W - D_o) \rho\gamma(\tau\alpha)_b + I_b r_b D_o (\tau\alpha)_b - U_l \pi D_o (T_p - T_a) \right] dx \quad \text{(A)}$$

Incident beam radiation absorbed in the absorber tube after reflection

Absorbed incident beam radiation which fall directly on the absorber tube

Loss by convection and reradiation

Absorbed solar flux:

$$S = I_b r_b \rho\gamma(\tau\alpha)_b + I_b r_b (\tau\alpha)_b \left(\frac{D_o}{W - D_o} \right) \quad \text{(B)}$$

Using eq.(B) in eq.(A)

$$dq_u = \left[s - \frac{U_l}{C}(T_p - T_a) \right] (W - D_o) dx \quad \text{(C)}$$

Useful heat gain rate

$$dq_u = h_f \pi D_i (T_p - T_f) dx \quad \text{(D)}$$

$$dq_u = \dot{m} C_p dT_f \quad \text{(E)}$$

Combining eq. (C) and (D)

$$dq_u = F' \left[s - \frac{U_l}{C}(T_p - T_a) \right] (W - D_o) dx \quad \text{(F)}$$

Collector efficiency factor

$$F' = \frac{1}{U_l \left[\frac{1}{U_l} + \frac{D_o}{D_i h_f} \right]} \quad \text{(G)}$$

Combining eq.(E) and (F)

$$\frac{dT_f}{dx} = \frac{F' \pi D_o U_l}{\dot{m} C_p} \left[\frac{CS}{U_l} - (T_f - T_a) \right] \quad \text{(H)}$$

Integrating and using the initial conditions:

$$x = 0, T_f = T_{fi}$$

Temperature distribution:

$$\frac{\left(\frac{CS}{U_l}+T_a\right)-T_f}{\left(\frac{CS}{U_l}+T_a\right)-T_{fi}}=\exp\left\{-\frac{F'\pi D_o U_l x}{\dot{m}C_p}\right\}$$

Fluid temperature is obtained by putting $T_f = T_{fi}$ and $x = L$

$$\frac{T_{fo}-T_{fi}}{\frac{CS}{U_l}+T_a-T_{fi}}=1-\exp\left\{-\frac{F'\pi D_o U_l L}{\dot{m}C_p}\right\}$$

Useful heat gain rate,

$$q_u=\dot{m}C_p\left(T_{fo}-T_{fi}\right)=\dot{m}C_p\left[\frac{CS}{U_l}+T_a-T_{fi}\right]\left[1-\exp\left\{-\frac{F'\pi D_o U_l L}{\dot{m}C_p}\right\}\right]$$

$$q_u=F_R\left(W-D_o\right)L\left[1-\exp\left\{-\frac{F'\pi D_o U_l L}{\dot{m}C_p}\right\}\right]$$

Collector Heat removal factor,

$$F_R=\frac{\dot{m}C_p}{\pi D_o L U_l}\left[1-\exp\left\{-\frac{F'\pi D_o U_l L}{\dot{m}C_p}\right\}\right]$$

Instantaneous collector efficiency

$$\eta_i=\frac{q_u}{\left(I_b r_b+I_d r_d\right)WL}$$

If the ground reflected radiation is neglected

$$\Rightarrow \quad \eta_i=\frac{q_u}{I_b r_b WL}$$

Overall loss coefficient and heat transfer correlations

$$\frac{q_l}{L} = h_{p-c}\left(T_{pm} - T_c\right)\pi D_o + \frac{\sigma \pi D_o\left(T_{pm}^4 - T_c^4\right)}{\left\{\frac{1}{\varepsilon_p} + \frac{D_o}{D_{ci}}\left(\frac{1}{\varepsilon_c} - 1\right)\right\}}$$

$$= h_w\left(T_c - T_a\right)\pi D_{co} + \sigma \pi D_{co} \varepsilon_c\left(T_c^4 - T_{sky}^4\right)$$

Heat Transfer coefficient between the absorber tube and the cover

$$\frac{k_{eff}}{k} = 0.317\left(Ra*\right)^{1/4} \qquad \left(Ra*\right)^{1/4} = \frac{\ln\left(D_{ci}/D_o\right)}{b^{3/4}\left(\frac{1}{D_o^{3/5}} + \frac{1}{D_{ci}^{3/5}}\right)^{5/4}} Ra^{1/4}$$

$$\frac{2\pi k_{eff}}{\ln\left(D_{ci}/D_o\right)}\left(T_{pm} - T_c\right) = h_{p-c}\pi D_o\left(T_{pm} - T_c\right)$$

$$\boxed{h_{p-c} = \frac{2\pi k_{eff}}{D_o \ln\left(D_{ci}/D_o\right)}}$$

Heat Transfer coefficient on the outside surface of the cover

Hilpert's correlation $Nu = C_1 \mathrm{Re}^n$

$40 < \mathrm{Re} < 4000, C_1 = 0.615, n = 0.466$

$4000 < \mathrm{Re} < 40000, C_1 = 0.174, n = 0.618$

$40000 < \mathrm{Re} < 400000, C_1 = 0.0239, n = 0.805$

Churchili and Bernstein : Valid upto Re = 10^7

$$\mathrm{Nu} = 0.3 + \frac{0.62\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}}{\left[1 + \left(0.4/\mathrm{Pr}\right)^{2/3}\right]^{1/4}}\left[1 + \left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right]^{4/5}$$

For 20000<Re<400000

$$\mathrm{Nu} = 0.3 + \frac{0.62\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}}{\left[1 + \left(0.4/\mathrm{Pr}\right)^{2/3}\right]^{1/4}}\left[1 + \frac{\mathrm{Re}}{282000}\right]^{1/2}$$

Heat Transfer coefficient on the inside surface of the absorber tube

$$\mathrm{Nu} = 3.66$$ For laminar flow Re < 2000

Assumption:
Flow is fully developed as L/D_i is grater than 20

For turbulent flow Re > 2000

Dittus-Boelter equation:

$$\mathrm{Nu} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

Hong and Bergles

$$Nu = 5.172\left[1 + 0.005484\left\{\mathrm{Pr}(\mathrm{Re}/X)^{1.78}\right\}^{0.7}\right]^{0.5}$$

$$X = \frac{H}{D_i} = \text{tape twist ratio}$$

$$H = \text{length over which the tape is twisted through } 180^o$$

Pressure drop (Date and Singham)

$$f\,\mathrm{Re} = 38.4(\mathrm{Re}/X)^{0.05} \quad 6.7 \le (\mathrm{Re}/X) \le 100$$
$$= C_2(\mathrm{Re}/X)^{0.3} \quad (\mathrm{Re}/X) > 100$$

$$f = \text{friction factor}$$
$$C_2 = 8.8201\,X - 2.1193\,X^2 + 0.2108\,X^3 - 0.0069\,X^4$$

Summary

- Fundamentals of concencetrating collectors
- Classification based on
  - Reflecting type utilizing mirrors
  - Refracting type utilizing Fresnel lenses
  - Imaging (point focus and line focus)
  - Concentration ratio (operating temperature)
  - Tracking
- Basic Energy Balance $$q_u = A_a\left[S - \frac{U_l}{C}\left(T_{pm} - T_a\right)\right]$$
- Analysis of Parabolic Trough Collector and heat transfer coefficient