SOLAR CONVERTERS AND DEVICES TO GAIN THERMAL ENERGY AND POWER

Principles, Design, Details and Examples

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SOLAR COLLECTORS

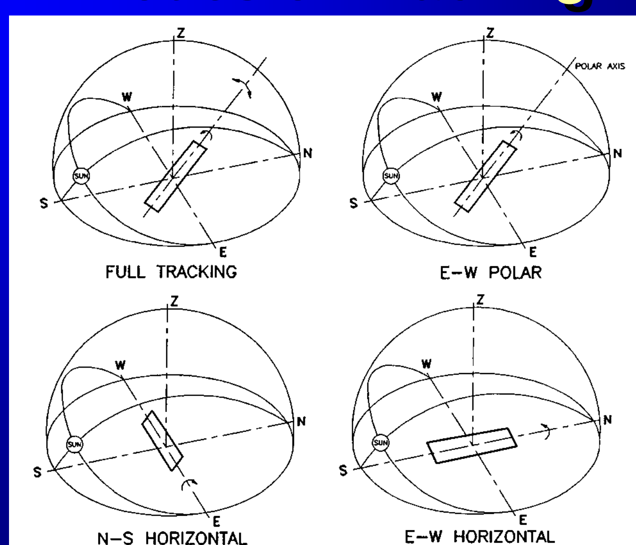
- Types of collectors
  - Stationary
  - Sun tracking
- Thermal analysis of collectors
- Performance
- Applications
  - Solar water heating
  - Solar space heating and cooling
  - Refrigeration
  - Industrial process heat
  - Solar thermal power systems

Types of solar collectors

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30-80
	Evacuated tube collector (ETC)	Flat	1	50-200
	Compound parabolic collector (CPC)	Tubular	1-5	60-240
Single-axis tracking			5-15	60-300
	Linear Fresnel reflector (LFR)	Tubular	10-40	60-250
	Parabolic trough collector (PTC)	Tubular	15-45	60-300
	Cylindrical trough collector (CTC)	Tubular	10-50	60-300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100-1000	100-500
	Heliostat field collector (HFC)	Point	100-1500	150-2000

Note: Concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.

Modes of Tracking



Comparison of energy absorbed for various modes of tracking

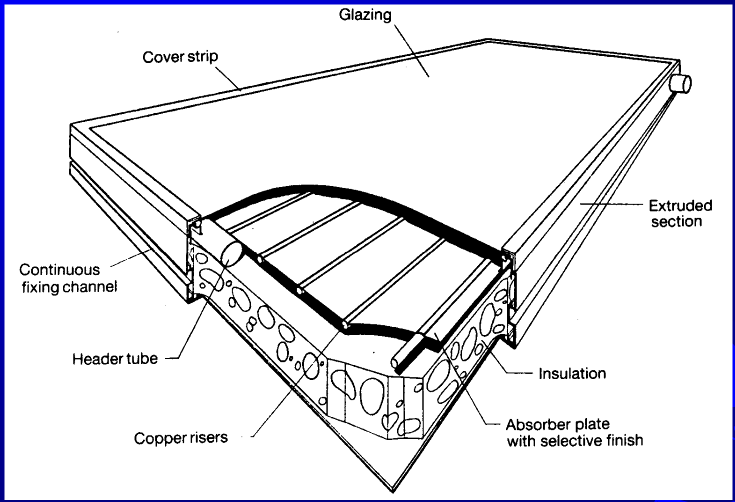
Tracking mode	Solar energy (kWh/m^2)			Percent to full tracking		
	E	SS	WS	E	SS	WS
Full tracking	8.43	10.60	5.70	100.0	100.0	100.0
E-W Polar	8.43	9.73	5.23	100.0	91.7	91.7
N-S Horizontal	6.22	7.85	4.91	73.8	74.0	86.2
E-W Horizontal	7.51	10.36	4.47	89.1	97.7	60.9

Note: E - Equinoxes, SS - Summer Solstice, WS - Winter Solstice

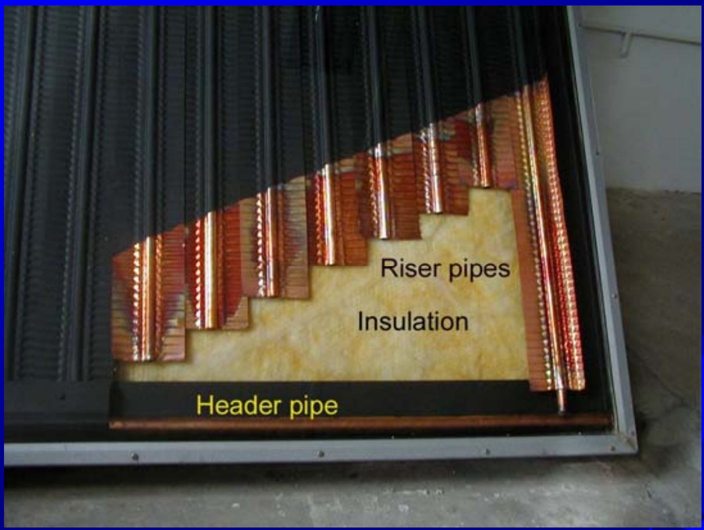
Stationary collectors

No concentration

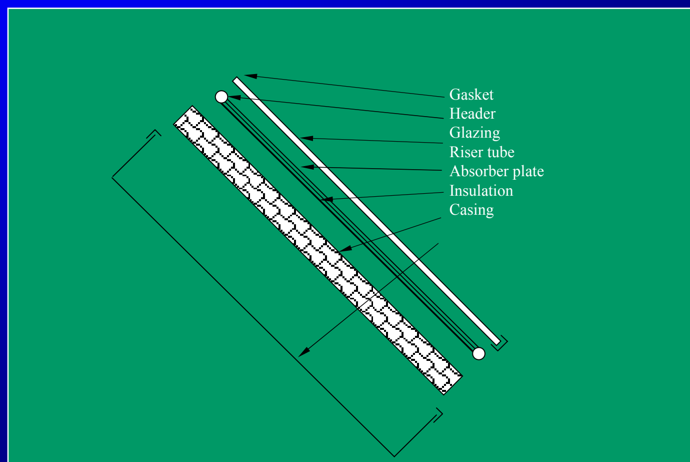
Flat-plate collector



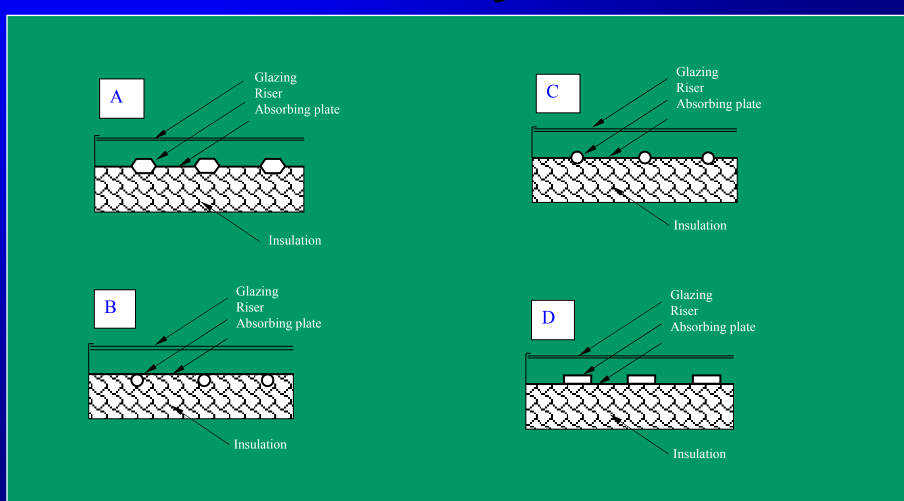
Flat-plate Collectors



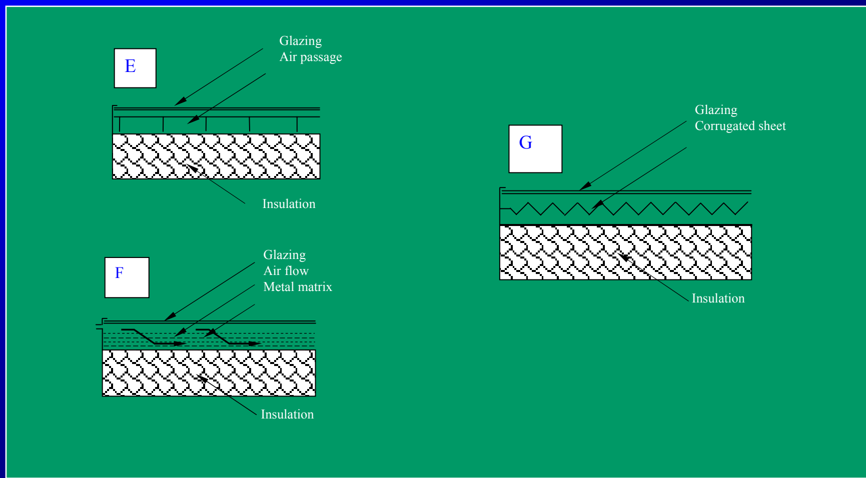
Exploded view of a flat-plate collector



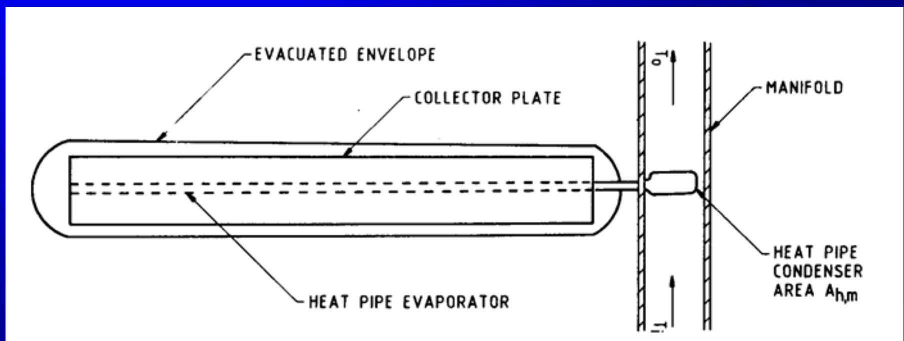
Types of flat-plate collectors Water systems



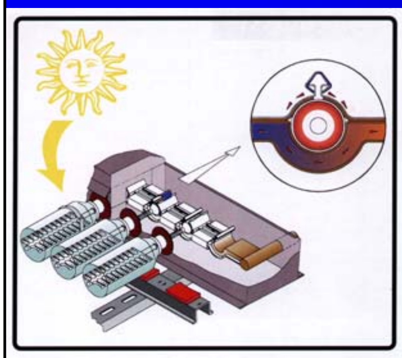
Types of flat-plate collectors
Air systems



Schematic diagram of an evacuated tube collector



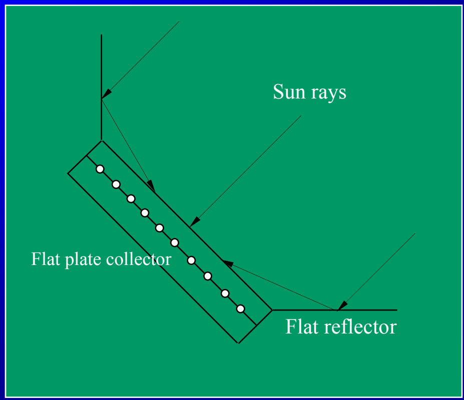
Evacuated tube collectors



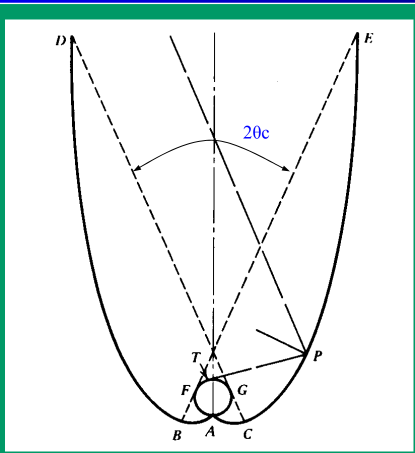
Stationary collectors

Concentrating

Flat plate collector with flat reflectors



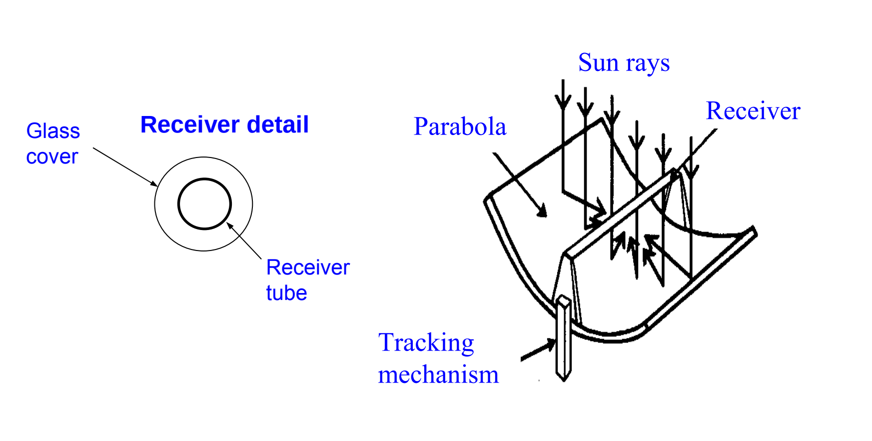
Schematic diagram of a CPC collector



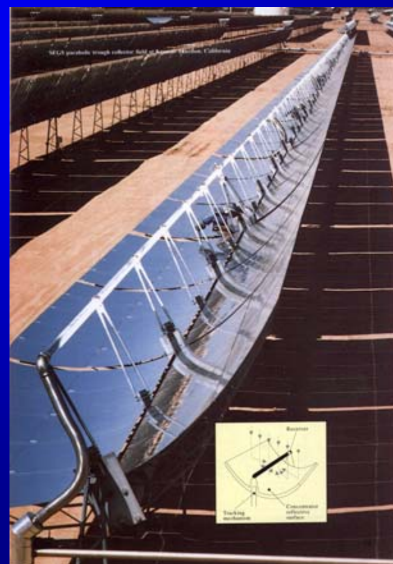
Sun tracking collectors

Concentrating

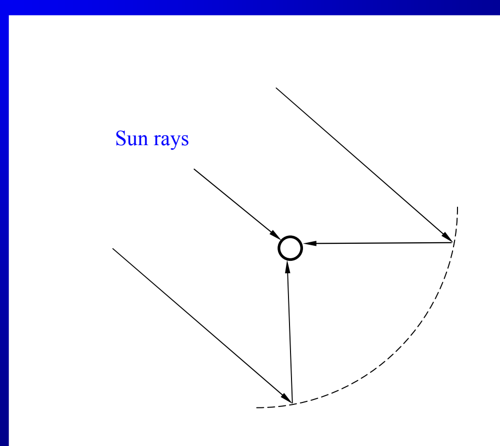
Schematic of a parabolic trough collector



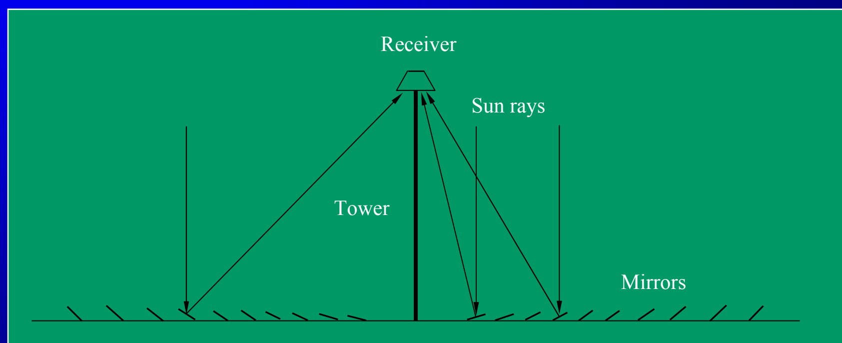
Parabolic trough collectors



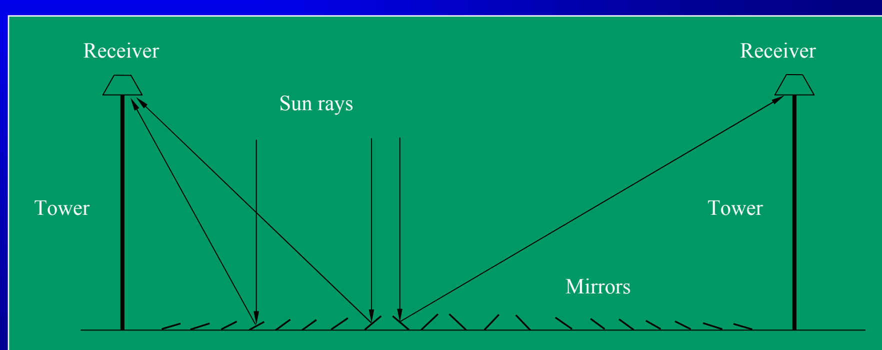
Fresnel type parabolic trough collector



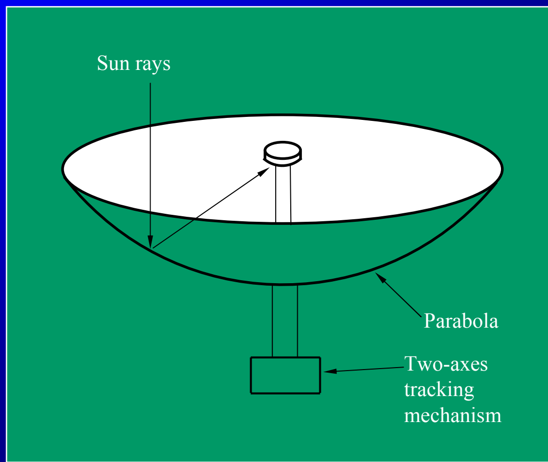
Schematic diagram of a downward facing receiver illuminated from a Linear Fresnel Reflector (LFR) field



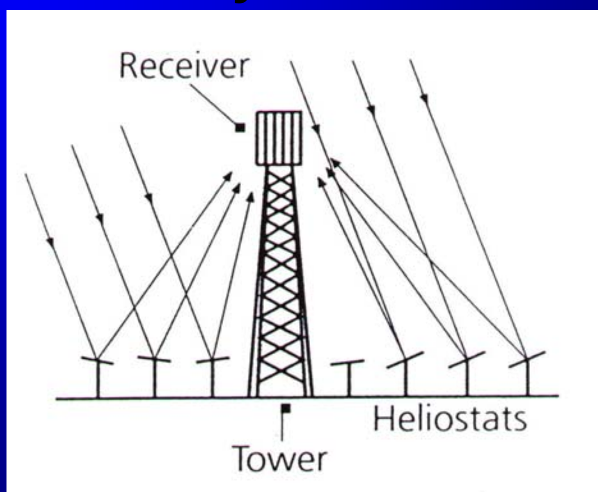
Schematic diagram showing interleaving of mirrors in a CLFR with reduced shading between mirrors



Schematic of a parabolic dish collector



Schematic of central receiver system



Thermal analysis of collectors

Useful energy collected from a collector-Flat plate

- General formula:

$$q_u = A_c\left[G_t(\tau\alpha) - U_L\left(T_p - T_a\right)\right] = mc_p\left[T_o - T_i\right]$$

- by substituting inlet fluid temperature (T_i) for the average plate temperature (T_p):

$$q_u = A_c F_R\left[G_t(\tau\alpha) - U_L\left(T_i - T_a\right)\right]$$

  - Where F_R is the heat removal factor

Collector efficiency

- Finally, the collector efficiency can be obtained by dividing q_u by $(G_t A_c)$. Therefore:

$$n = F_R \left[(\tau\alpha) - \frac{U_L (T_i - T_a)}{G_t} \right]$$

Concentration

- The concentration ratio (C) is defined as the ratio of the aperture area to the receiver/absorber area, i.e.:

$$C = \frac{A_a}{A_r}$$

- For flat-plate collectors with no reflectors, C=1. For concentrators C is always greater than 1. For a single axis tracking collector the maximum possible concentration is given by:

$$C_{max} = \frac{1}{\sin(\theta_m)}$$

- and for two-axes tracking collector:

$$C_{max} = \frac{1}{\sin^2(\theta_m)}$$

where θ_m is the half acceptance angle limited by the size of the sun's disk, small scale errors and irregularities of the reflector surface and tracking errors.

Maximum concentration

- For a perfect collector and tracking system C_{max} depends only on the sun's disk which has a width of 0.53° (32´). Therefore:
- For single axis tracking:

  C_{max} = 1/sin(16´) = 216
- For full tracking:

  C_{max} = 1/sin2(16´) = 46,747

Concentrating collectors

- The useful energy delivered from a concentrator is:

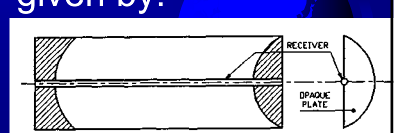
$$q_u = G_b n_o A_a - A_r U_L (T_r - T_a)$$

- Where n_o is the optical efficiency given by:

$$n_o = \rho\tau\alpha\gamma\left[\left(1 - A_f \tan(\theta)\right)\cos(\theta)\right]$$

- And A_f is the geometric factor given by:

$$A_f = \frac{2}{3} W_a h_p + f W_a \left[1 + \frac{W_a^2}{48 f^2}\right]$$



Concentrating collectors efficiency

- Similarly as for the flat-plate collector the heat removal factor can be used:

$$q_u = F_R\left[G_b n_o A_a - A_r U_L\left(T_i - T_a\right)\right]$$

- And the collector efficiency can be obtained by dividing q_u by $(G_b A_a)$:

$$n = F_R\left[n_o - U_L\left(\frac{T_i - T_a}{G_b C}\right)\right]$$

Note C in the denominator

PERFORMANCE OF SOLAR COLLECTORS

- The thermal performance of the solar collector is determined by obtaining:
  - values of instantaneous efficiency for different combinations of incident radiation, ambient temperature, and inlet fluid temperature.
  - the transient thermal response characteristics of the collector (time constant).
  - the variation of steady-state thermal efficiency with incident angles between the direct beam and the normal to collector aperture area at various sun and collector positions (incidence angle modifier).

1. Collector Thermal Efficiency

- In reality the heat loss coefficient U_L in previous equations is not constant but is a function of collector inlet and ambient temperatures. Therefore:

$$F_R U_L = c_1 + c_2 (T_i - T_a)$$

- Applying above equation we have:

For flat-plate collectors:

$$q_u = A_a F_R \left[(\tau\alpha) G_t - c_1 (T_i - T_a) - c_2 (T_i - T_a)^2 \right]$$

and for concentrating collectors:

$$q_u = F_R \left[G_b n_o A_a - A_r c_1 (T_i - T_a) - A_r c_2 (T_i - T_a)^2 \right]$$

Flat plate collector efficiency

- Therefore for flat-plate collectors the efficiency can be written as:

$$n = F_R (\tau\alpha) - c_1 \frac{(T_i - T_a)}{G_t} - c_2 \frac{(T_i - T_a)^2}{G_t}$$

- and if we denote $c_o = F_R(\tau\alpha)$ and $x = (T_i - T_a)/G_t$ then:

$$n = c_o - c_1 x - c_2 G_t x^2$$

Concentrating collector efficiency

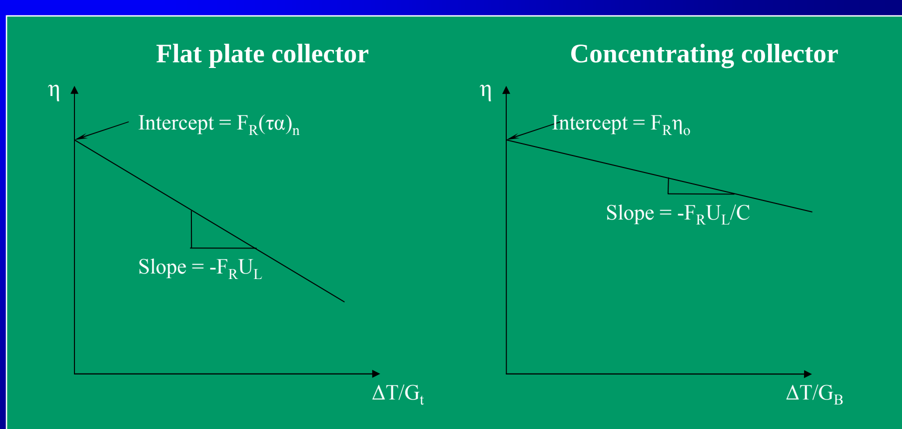
- For concentrating collectors the efficiency can be written as:

$$n = F_R n_o - \frac{c_1 (T_i - T_a)}{CG_b} - \frac{c_2 (T_i - T_a)^2}{CG_b}$$

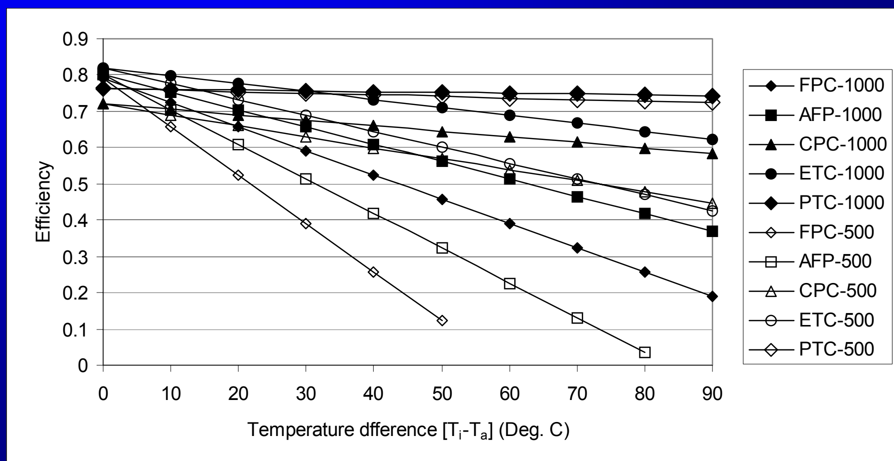
- and if we denote $k_o = F_R n_o$, $k_1 = c_1/C$, $k_2 = c_2/C$ and $y = (T_i - T_a)/G_b$ then:

$$n = k_o - k_1 y - k_2 G_b y^2$$

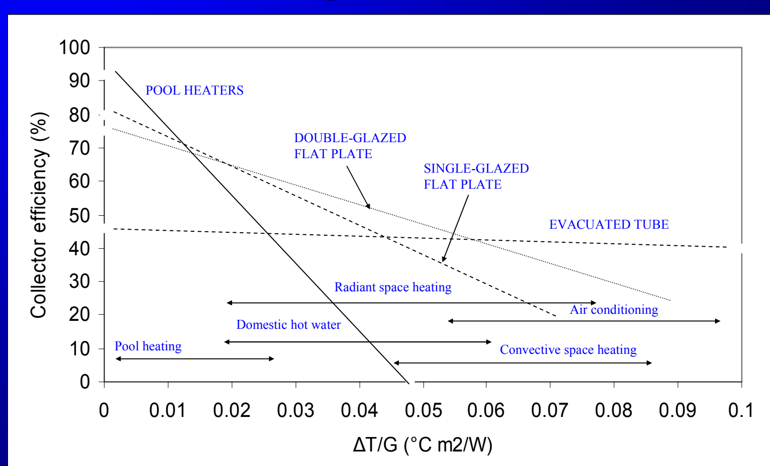
Efficiency plots



Comparison of the efficiency of various collectors at two irradiation levels, 500 and 1000 W/m²



Collector efficiencies of various liquid collectors



Incidence Angle Modifier Flat-plate collectors

- The above performance equations assume that the sun is perpendicular to the plane of the collector, which rarely occurs.
- For the glass cover plates of a flat-plate collector, specular reflection of radiation occurs thereby reducing the (τα) product.
- The incident angle modifier is defined as the ratio of τα at some incident angle θ to τα at normal radiation $(\tau\alpha)_n$:

$$k_{\alpha\tau} = 1 - b_o\left(\frac{1}{\cos(\theta)} - 1\right) - b_1\left(\frac{1}{\cos(\theta)} - 1\right)^2$$

- For single glass cover, a single-order equation can be used with b_o equal to -0.1 and b_1=0

Efficiency equation by considering incidence angle modifier

- With the incidence angle modifier the collector efficiency equation can be modified as:

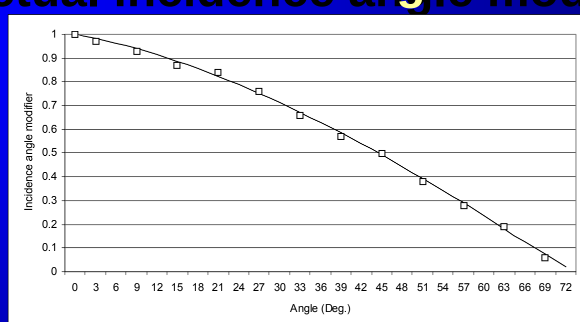
$$n = F_R(\tau\alpha)_n k_{\alpha\tau} - c_1\frac{(T_i - T_a)}{G_t} - c_2\frac{(T_i - T_a)^2}{G_t}$$

Incidence Angle Modifier Concentrating collectors

- For off-normal incidence angles, the optical efficiency term (n_o) is often difficult to be described analytically because it depends on the actual concentrator geometry, concentrator optics, receiver geometry and receiver optics which may differ significantly.
- Fortunately, the combined effect of these three parameters at different incident angles can be accounted for with the incident angle modifier. It describes how the optical efficiency of the collector changes as the incident angle changes. Thus performance equation becomes:

$$n = F_R K_{\alpha\tau} n_o - \frac{c_1(T_i - T_a)}{CG_b} - \frac{c_2(T_i - T_a)^2}{CG_b}$$

Actual incidence angle modifier

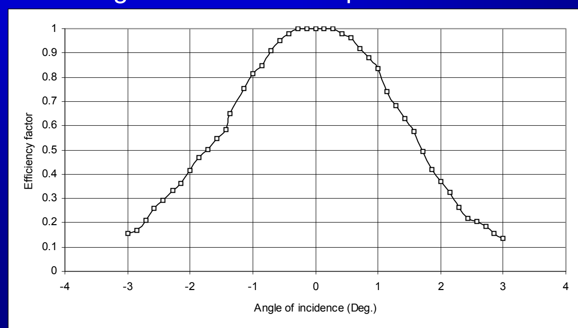


- By using a curve fitting method (second order polynomial fit), the curve that best fits the points can be obtained:

$$K_{\alpha\tau} = 1 - 0.00384(\theta) - 0.000143(\theta)^2$$

Concentrating Collector Acceptance Angle

- Another test required for the concentrating collectors is the determination of the collector acceptance angle, which characterises the effect of errors in the tracking mechanism angular orientation.
- This can be found with the tracking mechanism disengaged and measuring the efficiency at various out of focus angles as the sun is travelling over the collector plane.



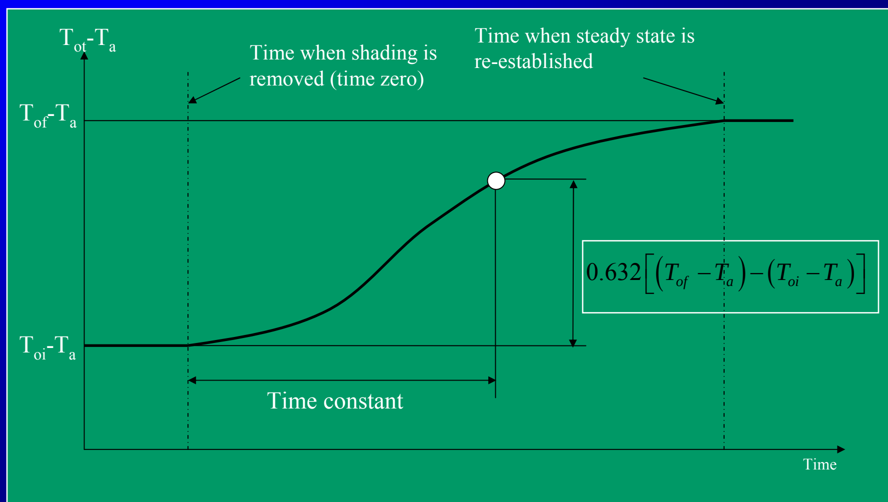
Collector Time Constant

- A last aspect of collector testing is the determination of the heat capacity of a collector in terms of a time constant.
- Whenever transient conditions exist, performance equations given before do not govern the thermal performance of the collector since part of the absorbed solar energy is used for heating up the collector and its components.
- The time constant of a collector is the time required for the fluid leaving the collector to reach 63% of its ultimate steady value after a step change in incident radiation. The collector time constant is a measure of the time required for the following relationship to apply:

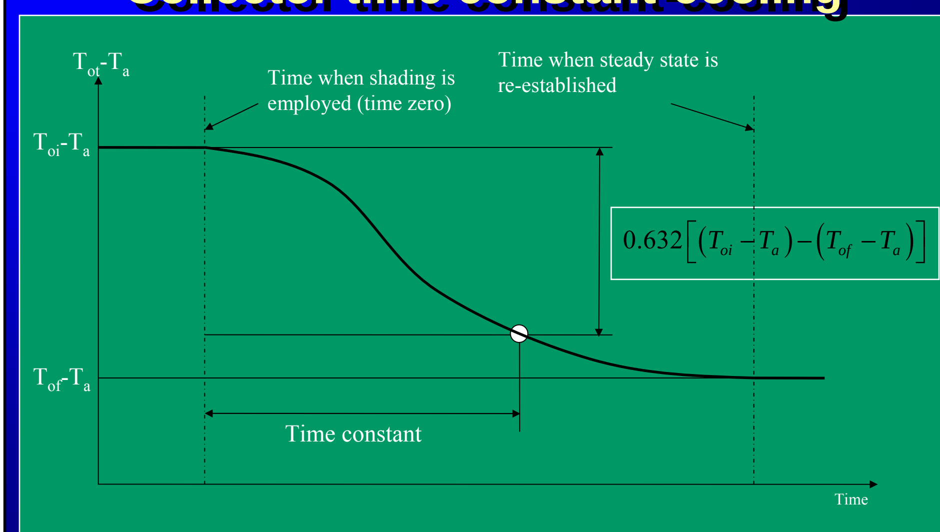
$$\frac{T_{ot} - T_i}{T_{oi} - T_i} = \frac{1}{e} = 0.368$$

- T_{ot} = Collector outlet water temperature after time t (°C)
- T_{oi} = Collector outlet initial water temperature (°C)
- T_i = Collector inlet water temperature (°C)

Collector time constant-heating



Collector time constant-cooling



SOLAR COLLECTOR APPLICATIONS

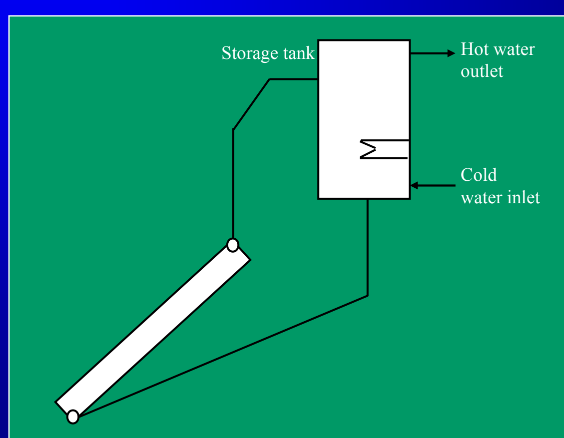
Solar Water Heating Systems

Thermosyphon systems
Integrated collector storage systems
Direct circulation systems
Indirect water heating systems
Air systems

Thermosyphon systems (passive)

- Thermosyphon systems heat potable water or heat transfer fluid and use natural convection to transport it from the collector to storage.
- The water in the collector expands becoming less dense as the sun heats it and rises through the collector into the top of the storage tank.
- There it is replaced by the cooler water that has sunk to the bottom of the tank, from which it flows down the collector.
- The circulation continuous as long as there is sunshine.
- Since the driving force is only a small density difference larger than normal pipe sizes must be used to minimise pipe friction.
- Connecting lines must be well insulated to prevent heat losses and sloped to prevent formation of air pockets which would stop circulation.

Schematic diagram of a thermosyphon solar water heater



Typical thermosyphon solar water heater

Laboratory model

Application on inclined roof-1

Application on inclined roof-2

Application on inclined roof-3

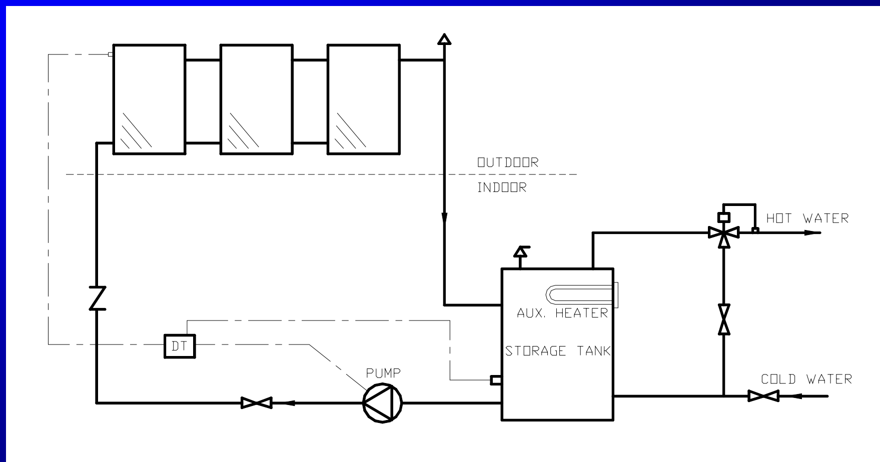
Multi-residential application

Pressurized system on inclined roof

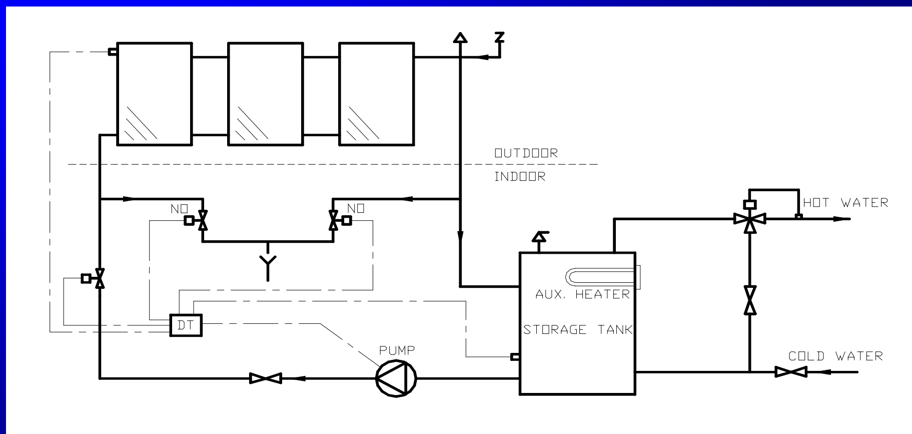
Direct circulation systems (active)

- In direct circulation systems a pump is used to circulate potable water from storage to the collectors when there is enough available solar energy to increase its temperature and then return the heated water to the storage tank until it is needed.
- As a pump circulates the water, the collectors can be mounted either above or below the storage tank.

Direct circulation system



Drain-down system



When a freezing condition or a power failure occurs, the system drains automatically by isolating the collector array and exterior piping from the make-up water supply and draining it using the two normally open (NO) valves

Direct of force circulation type SWH

- In this system only the solar panels are visible on the roof.
- The hot water storage tank is located indoors in a plantroom.
  - The system is completed with piping, pump and a differential thermostat.
- This type of system is more appealing mainly due to architectural and aesthetic reasons but also more expensive.

Force circulation system-1

Force circulation system-2

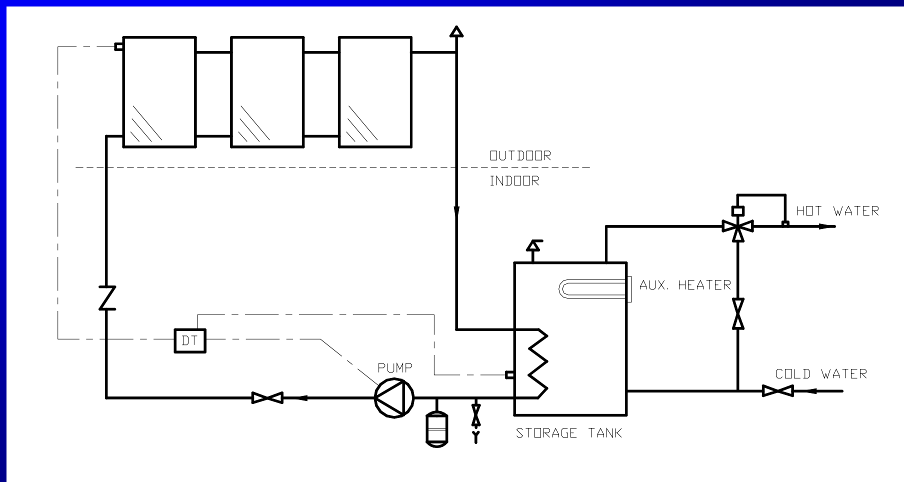
Large solar water heating system

Swimming pool heating

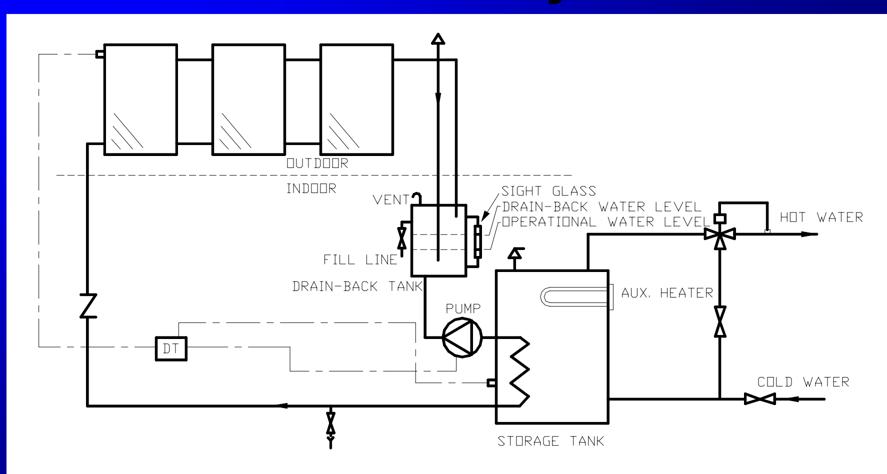
Indirect water heating systems (active)

- Indirect water heating systems circulate a heat transfer fluid through the closed collector loop to a heat exchanger, where its heat is transferred to the potable water.
- The most commonly used heat transfer fluids are water/ethylene glycol solutions, although other heat transfer fluids such as silicone oils and refrigerants can also be used.
- The heat exchanger can be located inside the storage tank, around the storage tank (tank mantle) or can be external.
- It should be noted that the collector loop is closed and therefore an expansion tank and a pressure relief valve are required.

Indirect water heating system



Drain-back system

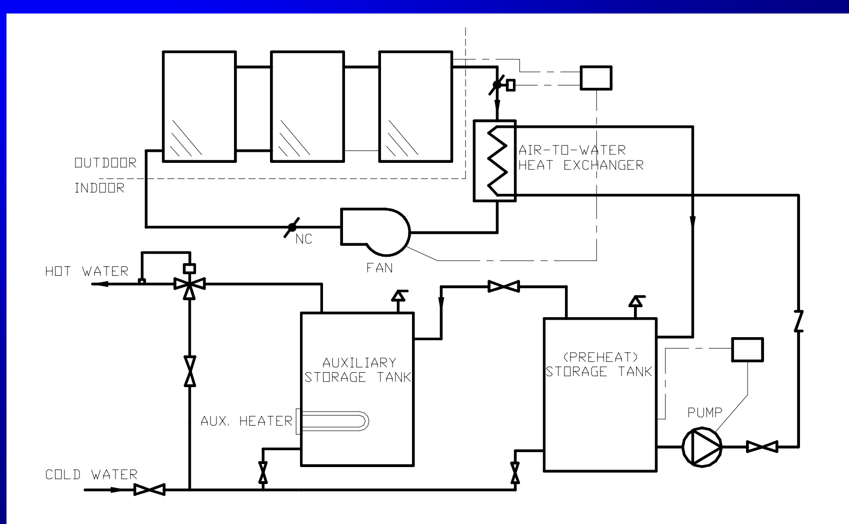


Circulation continues as long as usable energy is available. When the circulation pump stops the collector fluid drains by gravity to a drain-back tank.

Air systems

- Air systems are indirect water heating systems that circulate air via ductwork through the collectors to an air-to-liquid heat exchanger. In the heat exchanger, heat is transferred to the potable water, which is also circulated through the heat exchanger and returned to the storage tank.
- The main advantage of the system is that air does not need to be protected from freezing or boiling, is non-corrosive, and is free.
- The disadvantages are that air handling equipment (ducts and fans) need more space than piping and pumps, air leaks are difficult to detect, and parasitic power consumption is generally higher than that of liquid systems.

Air system



Solar Space Heating and Cooling

Space Heating and Service Hot Water

Air systems

Water systems

Solar Space Heating and Cooling

- The components and subsystems discussed so far may be combined to create a wide variety of building solar heating and cooling systems.
- Active solar space systems use collectors to heat a fluid, storage units to store solar energy until needed, and distribution equipment to provide the solar energy to the heated spaces in a controlled manner.
- The load can be space cooling, heating, or a combination of these two with hot water supply.
- In combination with conventional heating equipment solar heating provides the same levels of comfort, temperature stability, and reliability as conventional systems.

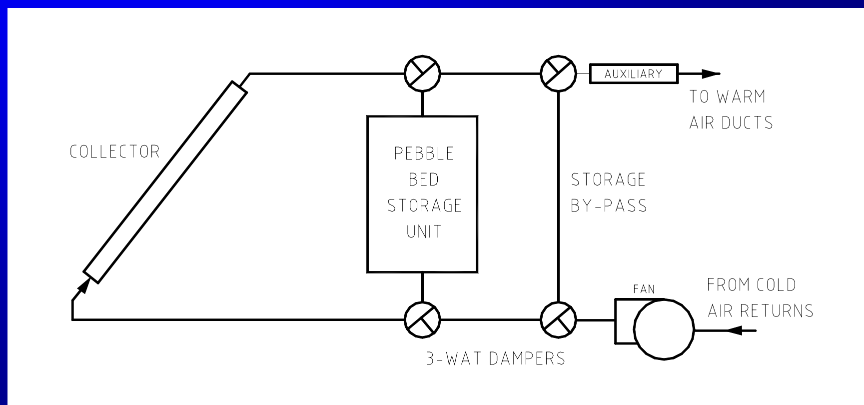
Space Heating and Service Hot Water

- It is useful to consider solar systems as having five basic modes of operation, depending on the conditions that exist in the system at a particular time:
  - If solar energy is available and heat is not needed in the building, energy gain from the collector is added to storage.
  - If solar energy is available and heat is needed in the building, energy gain from the collector is used to supply the building need.
  - If solar energy is not available, heat is needed in the building, and the storage unit has stored energy in it, the stored energy is used to supply the building need.
  - If solar energy is not available, heat is needed in the building, and the storage unit has been depleted, auxiliary energy is used to supply the building need.
  - The storage unit is fully heated, there are no loads to met, and the collector is absorbing heat.

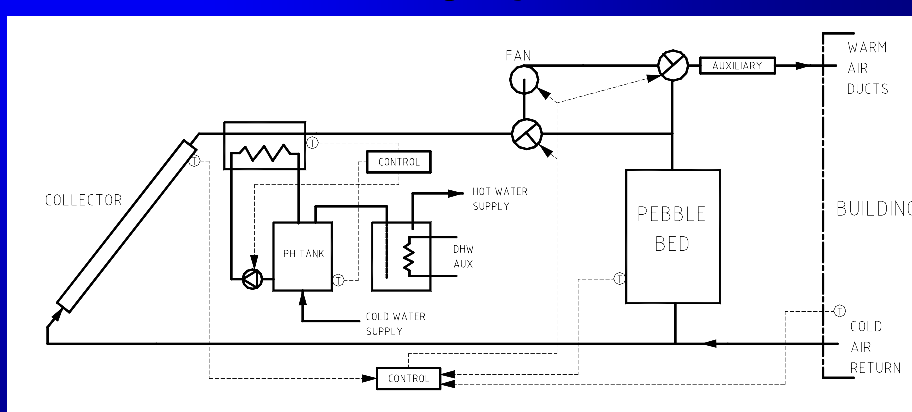
Air systems

- The usual type of storage used for air systems is pebble bed. This is a concrete container usually located below the house.
- Auxiliary energy can be combined with energy supplied from collector or storage to top-up the air temperature in order to cover the building load.
- It is possible to bypass the collector and storage unit when auxiliary alone is being used to provide heat.

Schematic of basic hot air system



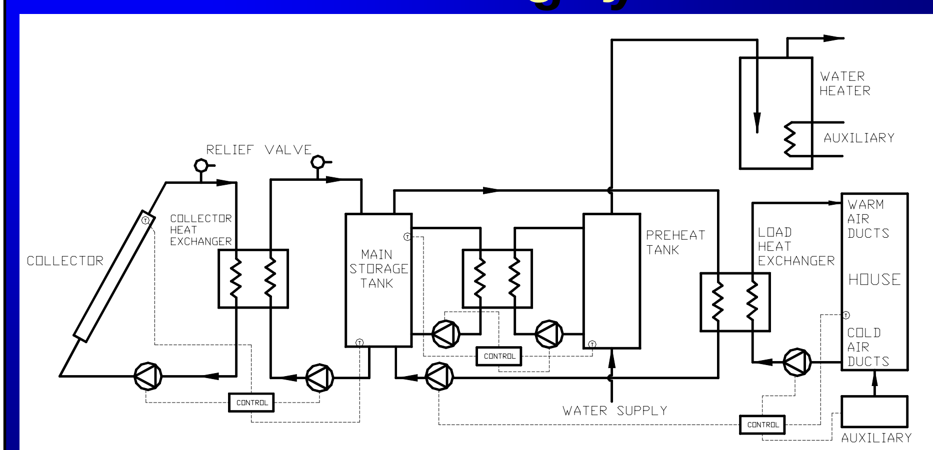
Detail schematic of a solar air heating system



Water systems

- When used for both space and hot water production this system allows independent control of the solar collector-storage and storage-auxiliary-load loops as solar-heated water can be added to storage at the same time that hot water is removed from storage to meet building loads.
- Usually, a bypass is provided around the storage tank to avoid heating the storage tank, which can be of considerable size, with auxiliary energy.

Detail schematic of a solar water heating system



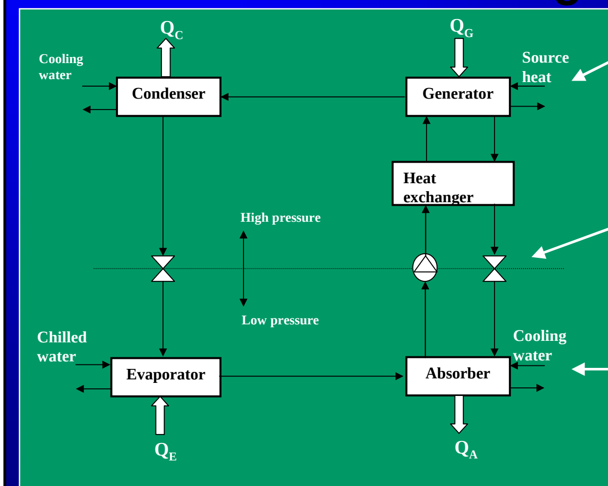
Solar Refrigeration

- Solar cooling can be considered for two related processes;
  - to provide refrigeration for food and medicine preservation and
  - to provide comfort cooling.
- Two types of cycles are available - Adsorption and Absorption
- More on special lecture on solar cooling.

Absorption systems

- Absorption systems are similar to vapour-compression air conditioning systems but differ in the pressurisation stage.
- In general an absorbent, on the low-pressure side, absorbs an evaporating refrigerant.
- The most usual combinations of fluids include lithium bromide-water ($LiBr\text{-}H_2O$) where water vapour is the refrigerant and ammonia-water ($NH_3\text{-}H_2O$) systems where ammonia is the refrigerant.

Basic principle of the absorption air conditioning system



In the generator heat is used to separate the low-boiling refrigerant from the solution

The solution is pumped to a high pressure with an ordinary liquid pump

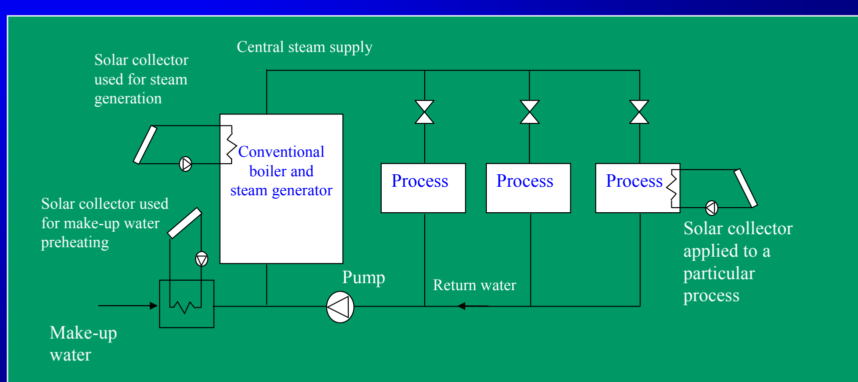
In the absorber the refrigerant is dissolved

Industrial Process Heat

Industrial Process Heat

- The central system for heat supply in most factories uses hot water or steam at a pressure corresponding to the highest temperature needed in the different processes.
- Hot water or low pressure steam at medium temperatures (<150ºC) can be used either for preheating of water (or other fluids) used for processes (washing, dyeing, etc.) or for steam generation or by direct coupling of the solar system to an individual process working at temperatures lower than that of the central steam supply (see next Fig.).
- In the case of water preheating, higher efficiencies are obtained due to the low input temperature to the solar system, thus low-technology collectors can work effectively and the required load supply temperature has no or little effect on the performance of the solar system.

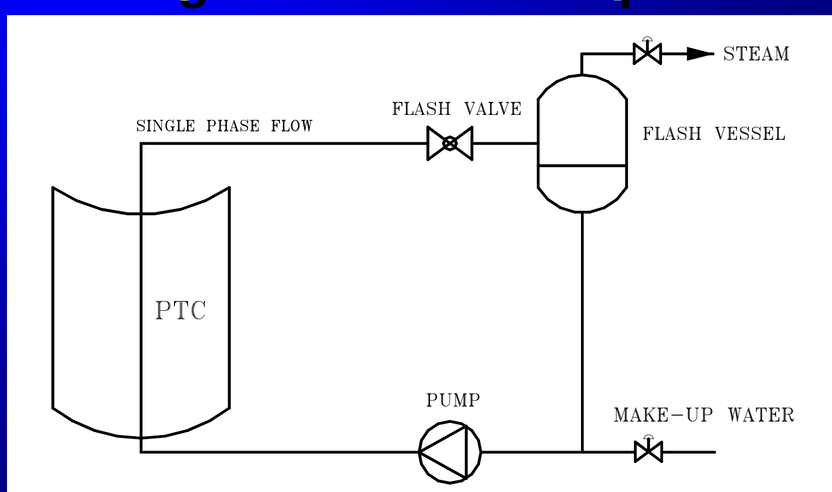
Possibilities of combining the solar system with the existing heat supply



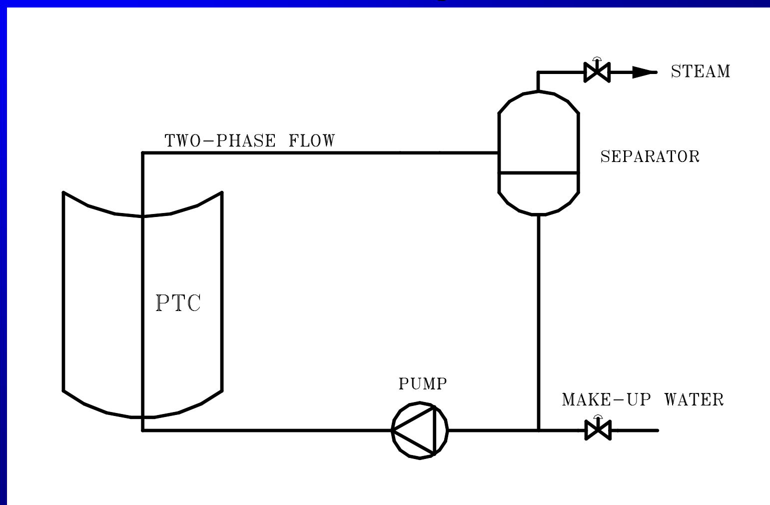
Solar steam generation systems

- Parabolic trough collectors are frequently employed for solar steam generation because relatively high temperatures can be obtained without any serious degradation in the collector efficiency.
- Low temperature steam can be used in industrial applications, sterilisation, and for powering desalination evaporators.
- Three methods have been employed to generate steam using parabolic trough collectors:
  - The **steam-flash concept**, in which pressurised water is heated in the collector and then flashed to steam in a separate vessel.
  - The **direct or in-situ concept**, in which two phase flow is allowed in the collector receiver so that steam is generated directly.
  - The **unfired-boiler concept**, in which a heat-transfer fluid is circulated through the collector and steam is generated via heat-exchange in an unfired boiler.

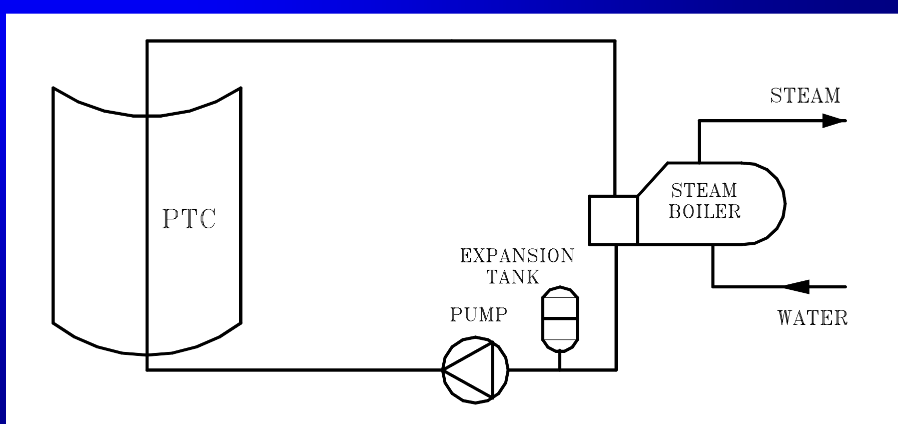
The steam-flash steam generation concept



The direct steam generation concept



The unfired-boiler steam generation concept

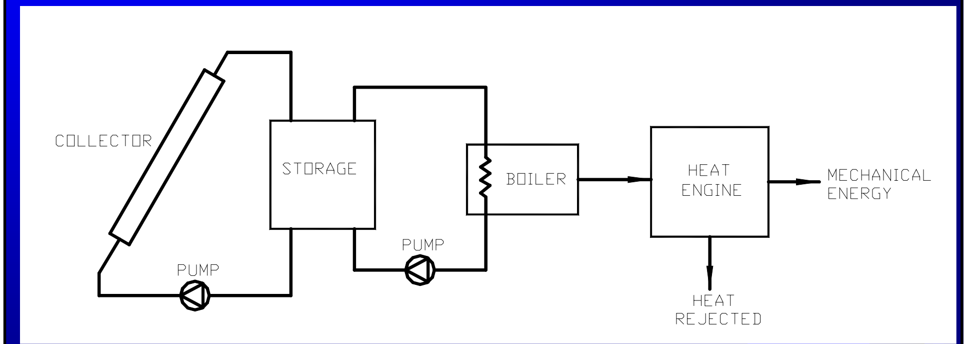


Solar Power systems

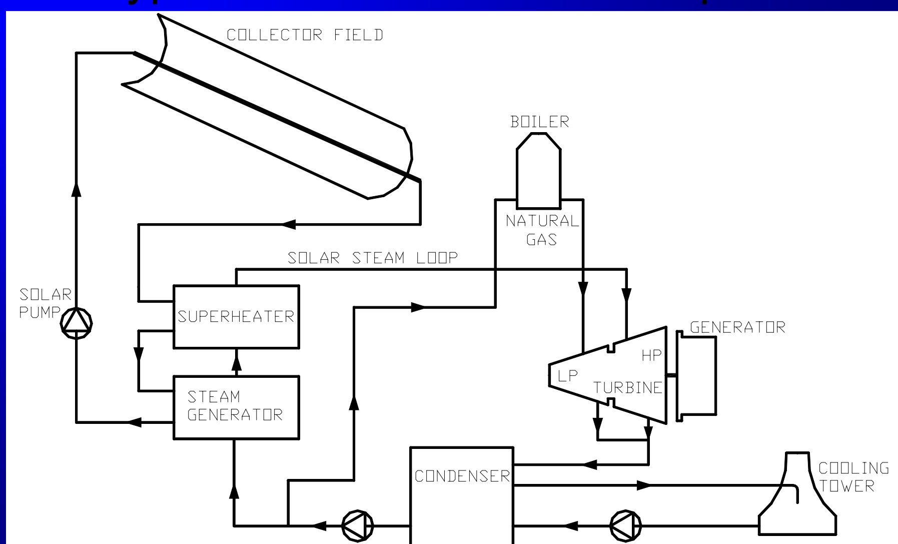
Solar Thermal Power

- Three types of systems belong to this category:
  - Parabolic trough collector system
  - Central receiver system
  - Dish collector system
- The process of conversion of solar to mechanical and electrical energy by thermal means is fundamentally similar to the traditional thermal processes.
- The solar systems differ from the ones considered so far as these operate at much higher temperatures.

Schematic of a solar-thermal conversion system



Typical Schematic of SEGS plants



Parabolic Trough System

Parabolic trough collectors

Parabola detail

Receiver detail

Central receiver system

Tower detail

Heliostat detail

Central Receiver systems

- Suitable for decentralised applications
- Sizes 5-25 kW each
- In most frequent applications the system is equipped with a Stirling engine and produce electricity directly
- For large applications a number of units can be used.

Central receiver-1

Central receiver-2

Central receiver-3

Central receiver-4

Central receiver-5

Eurodish

Solar energy should be given a chance if we want to protect the environment.

We own it to our children, our grandchildren and the generations to come.

Thank you for your attention,

any questions please….