Module I

Solar Radiation and Measurement

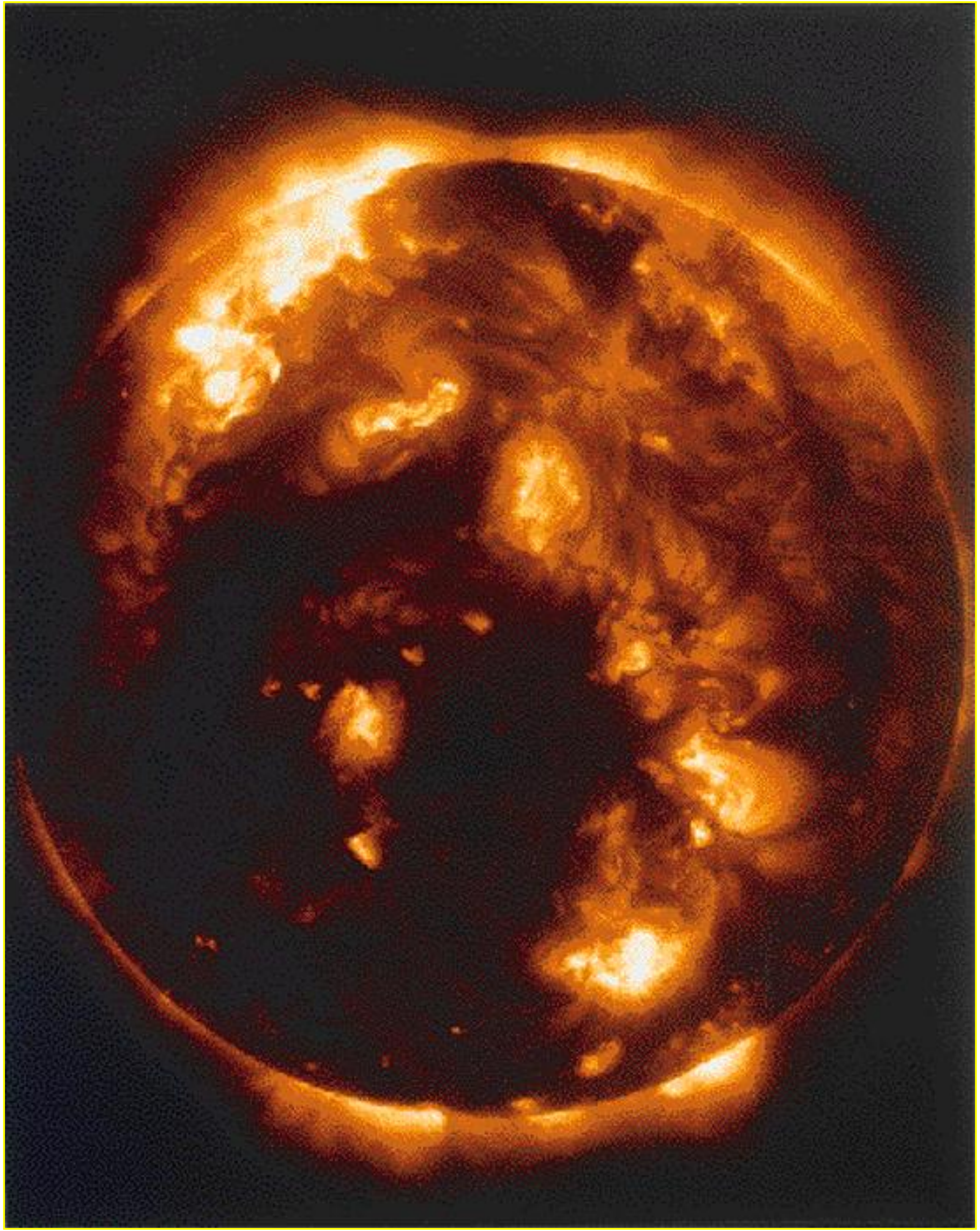
Sun

Radius - 70,0000 km

Mass - 2.0 x 10^{30} kg

Temperature - 5500 C

Distance between sun and earth – 150 million km



Modes of heat transfer

- Conduction
- Convection
- Radiation

Stefan–Boltzmann law

Total energy emitted by a black body

$$E = \sigma T^4$$

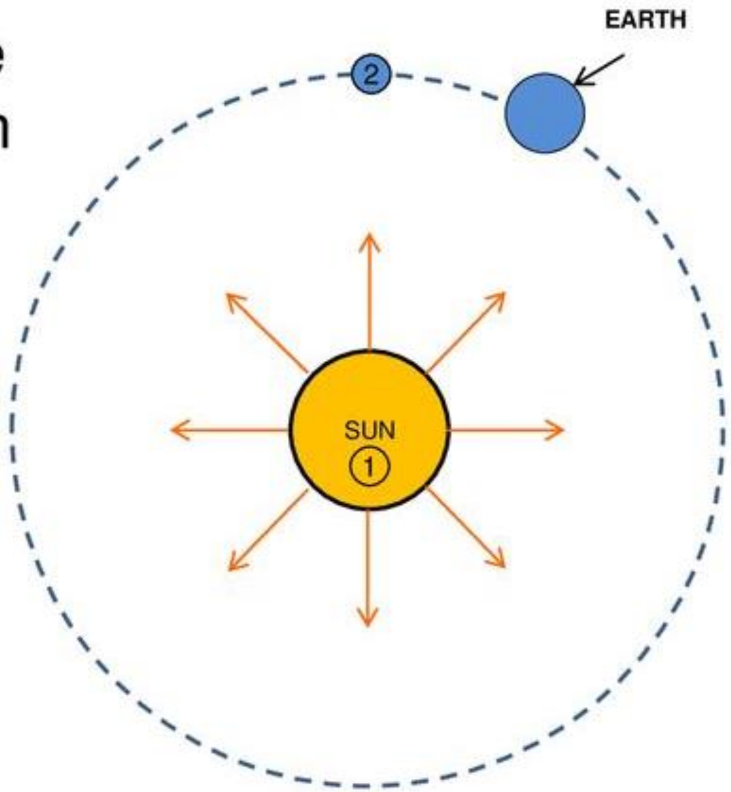
$$\sigma = 5.67 \times 10^{-8} W / m^2 k^4$$

Radiation from sun

- The net radiation heat transfer between the sun's surface (1) and the surface of the sphere containing earth (2) is given by:

$$\dot{Q}_{1\rightarrow 2} = A_1 F_{1\rightarrow 2}\, \sigma(T_1^4 - T_2^4)$$

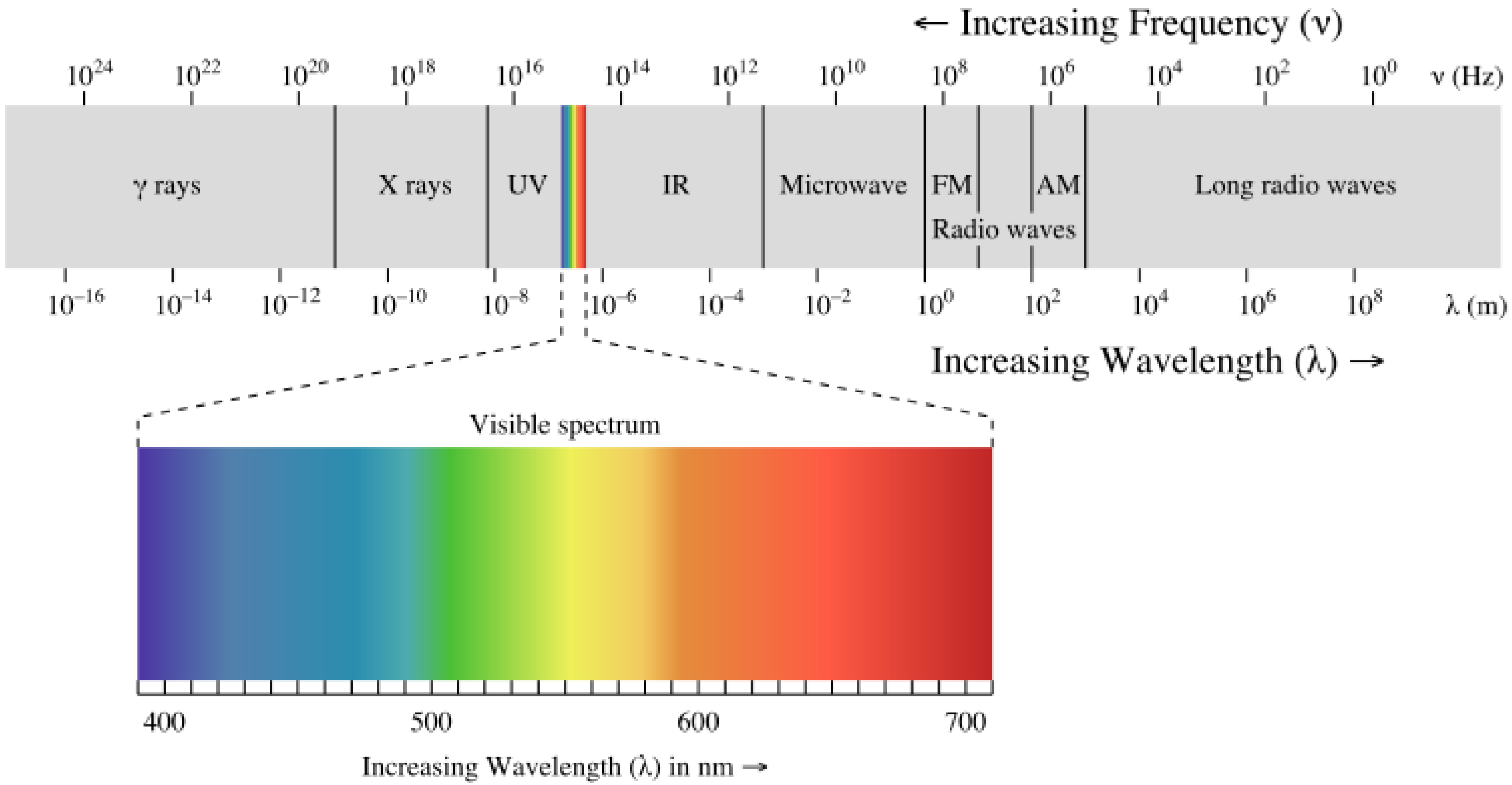
- $F_{1\rightarrow 2} = 1$
- $A_1 = 4\pi r_1^2$, where r_1 is the radius of the sun (6.955×10^8 m)
- T_2 is negligible
- The total rate of heat transfer leaving the sun's surface and reaching Surface 2 is: 3.84×10^{26} W.



Two Categories of Solar Energy

- **<u>Active Solar</u>**: A method specifically designed to acquire energy from sun and move it to where needed, including:
  - photovoltaic electric power generation
  - solar thermal electric power generation
  - active solar heating using solar collectors
- **<u>Passive Solar</u>**: a design (usually of buildings) that inherently takes advantage of the sun for daylighting and winter heating, and avoids solar gain in summer to minimize need for cooling.

Electro magnetic spectrum

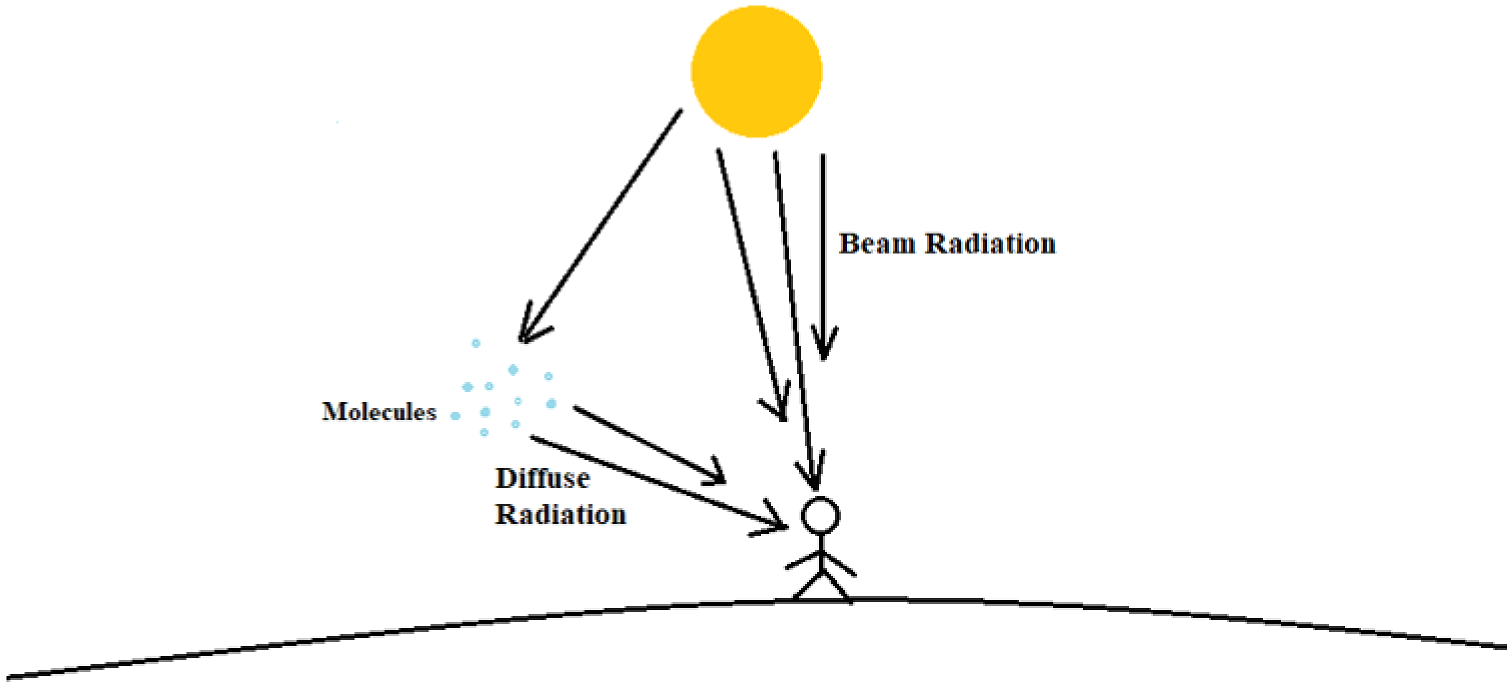


Solar constant

Average solar energy received per unit area at earth's atmosphere.

Solar constant – 1361 W/m^2

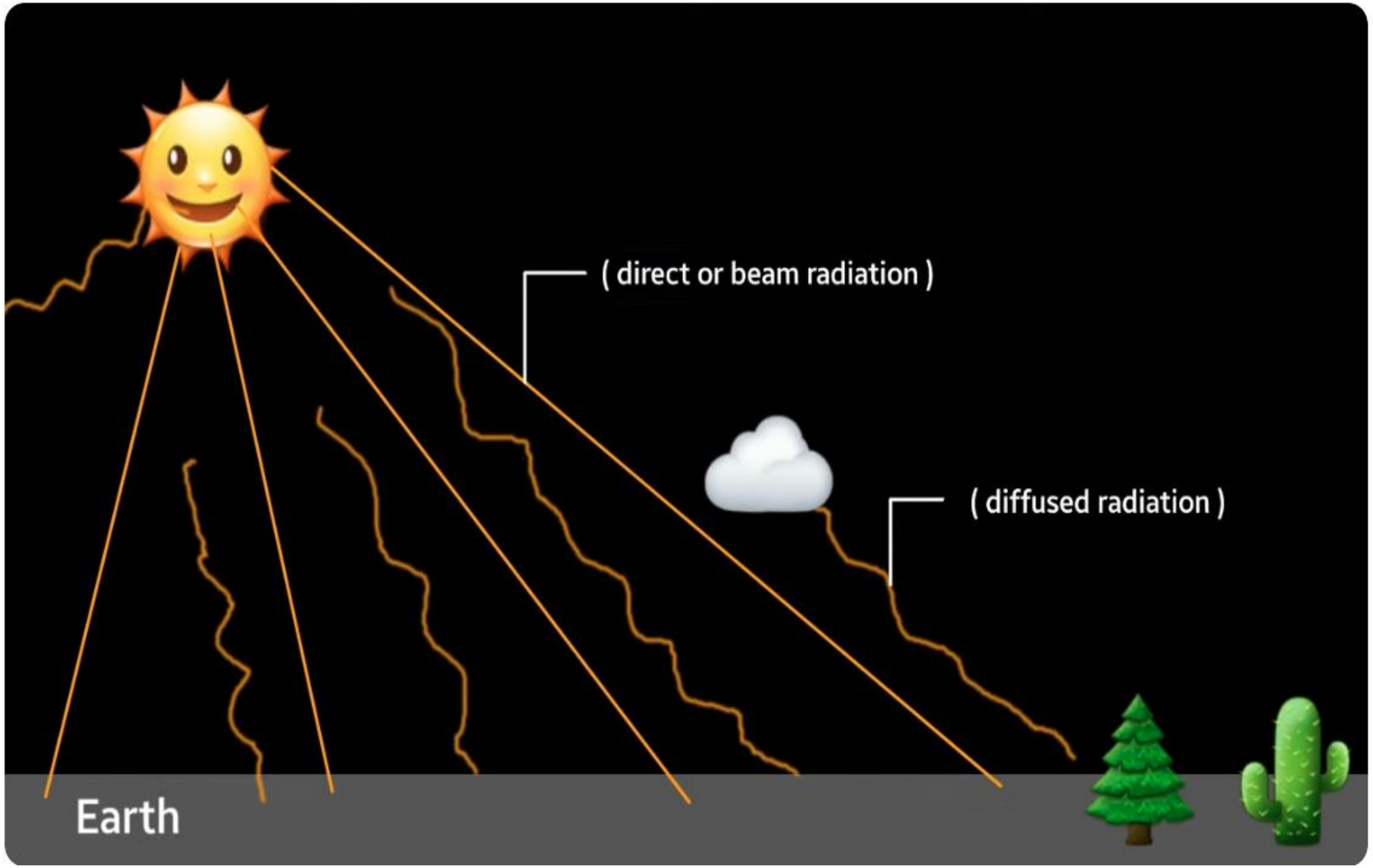
Solar Radiation measurement



Beam Radiation

Diffuse radiation

Global or total radiation

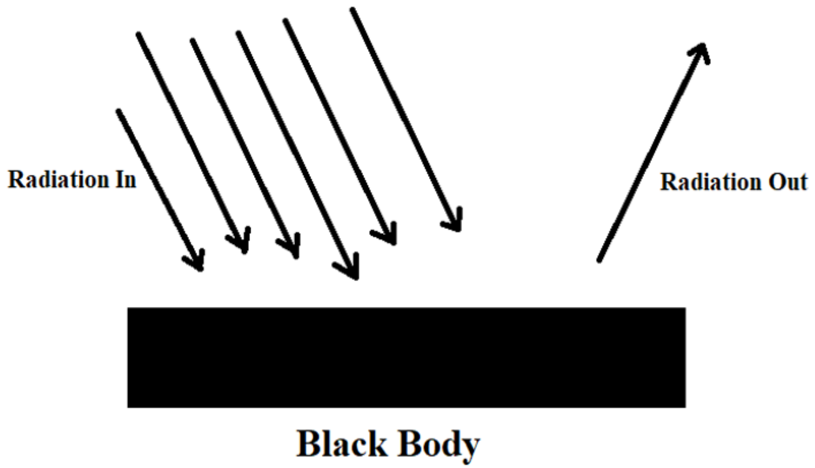

(direct or beam radiation)
(diffused radiation)
Earth

Solar Radiation measurement

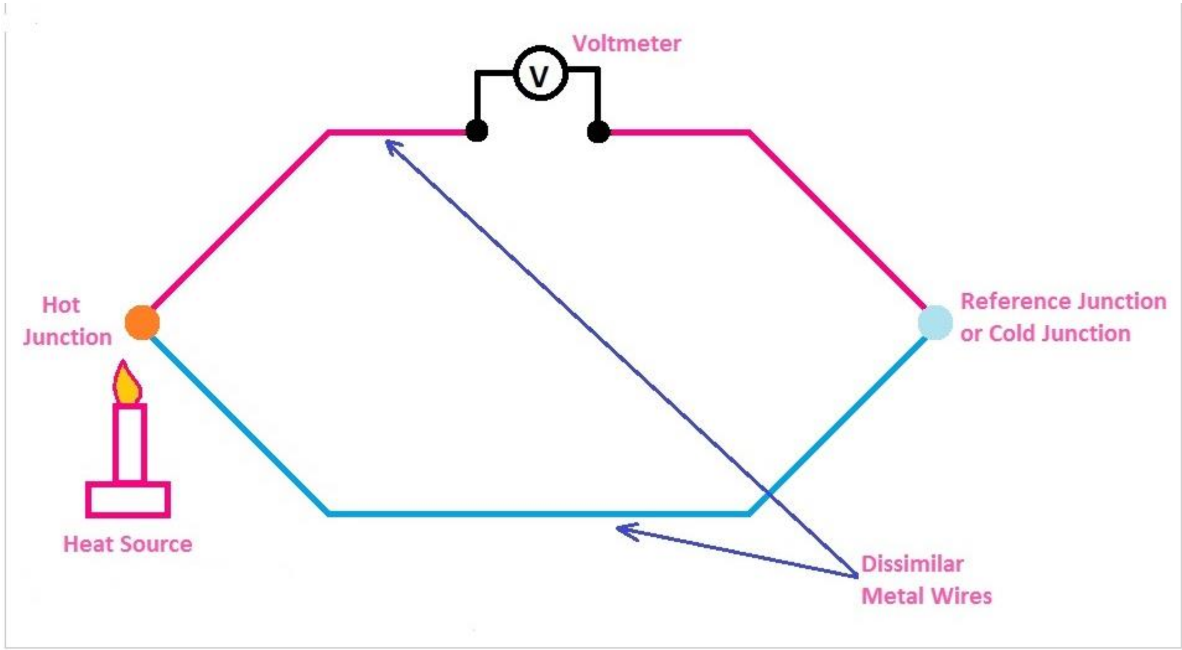
- Pyranometer - Beam and diffuse radiation
- Pyrheliometer - Beam Radiation

Solar Radiation measurement

Black body radiation

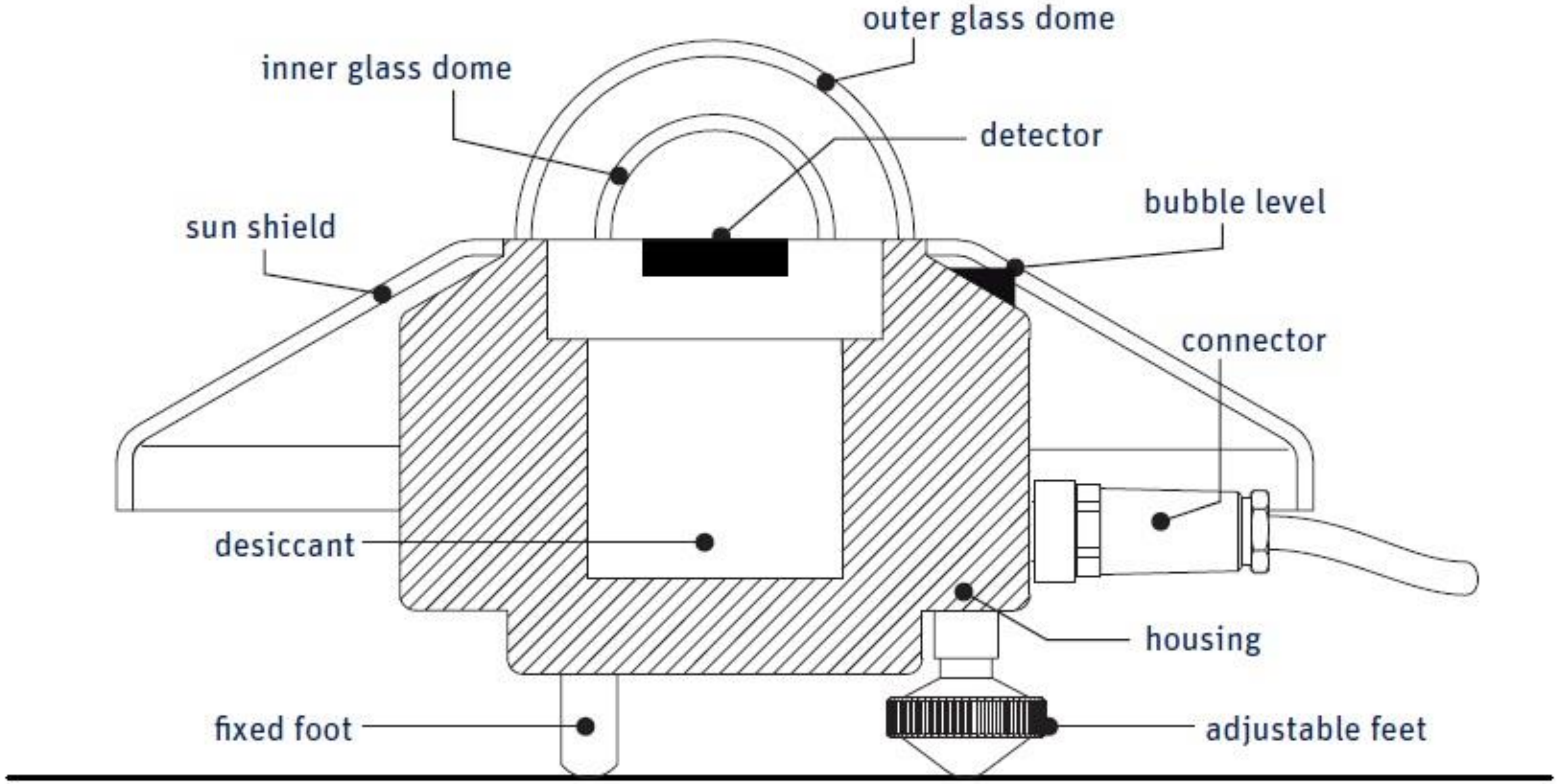


Principle of thermocouple



$V \propto \Delta T$

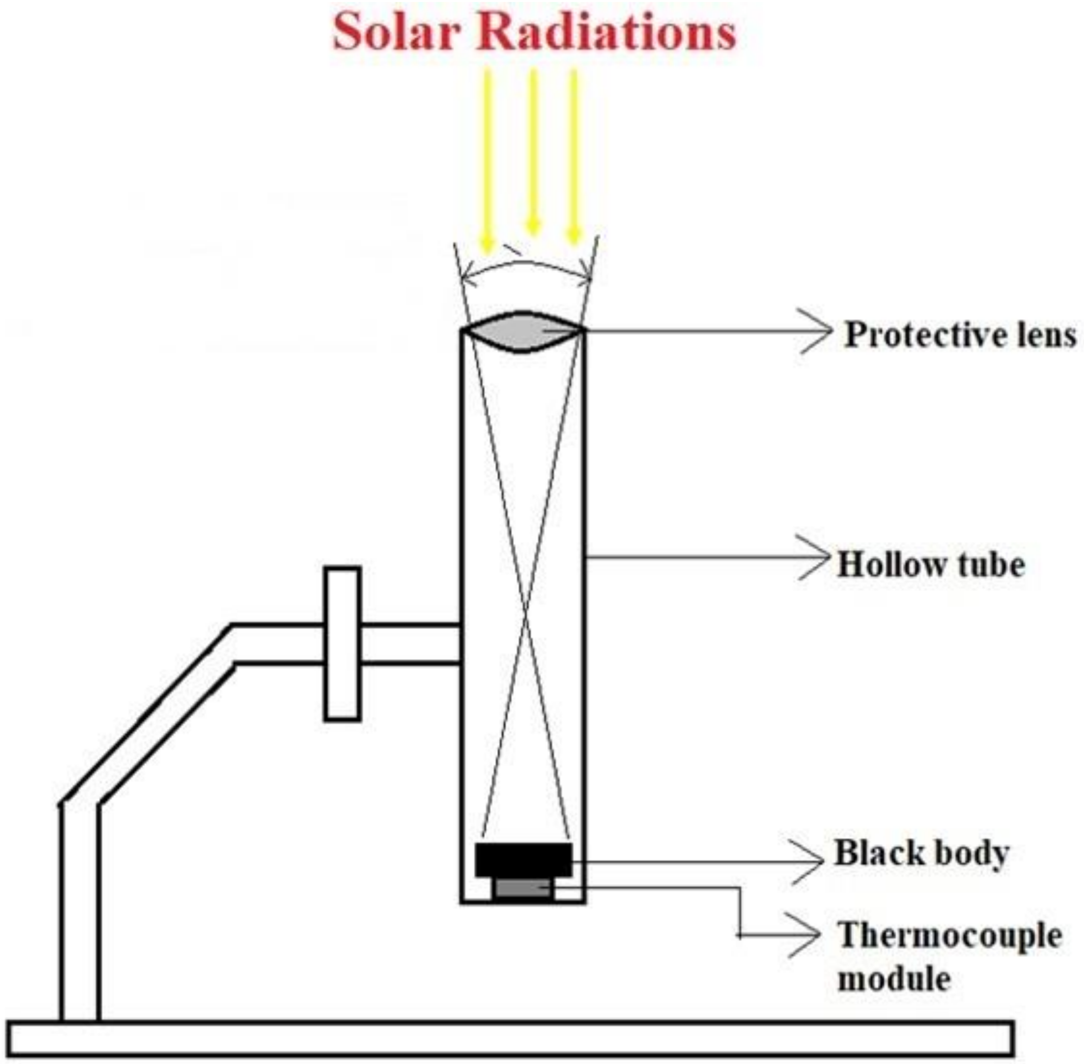
Pyranometer



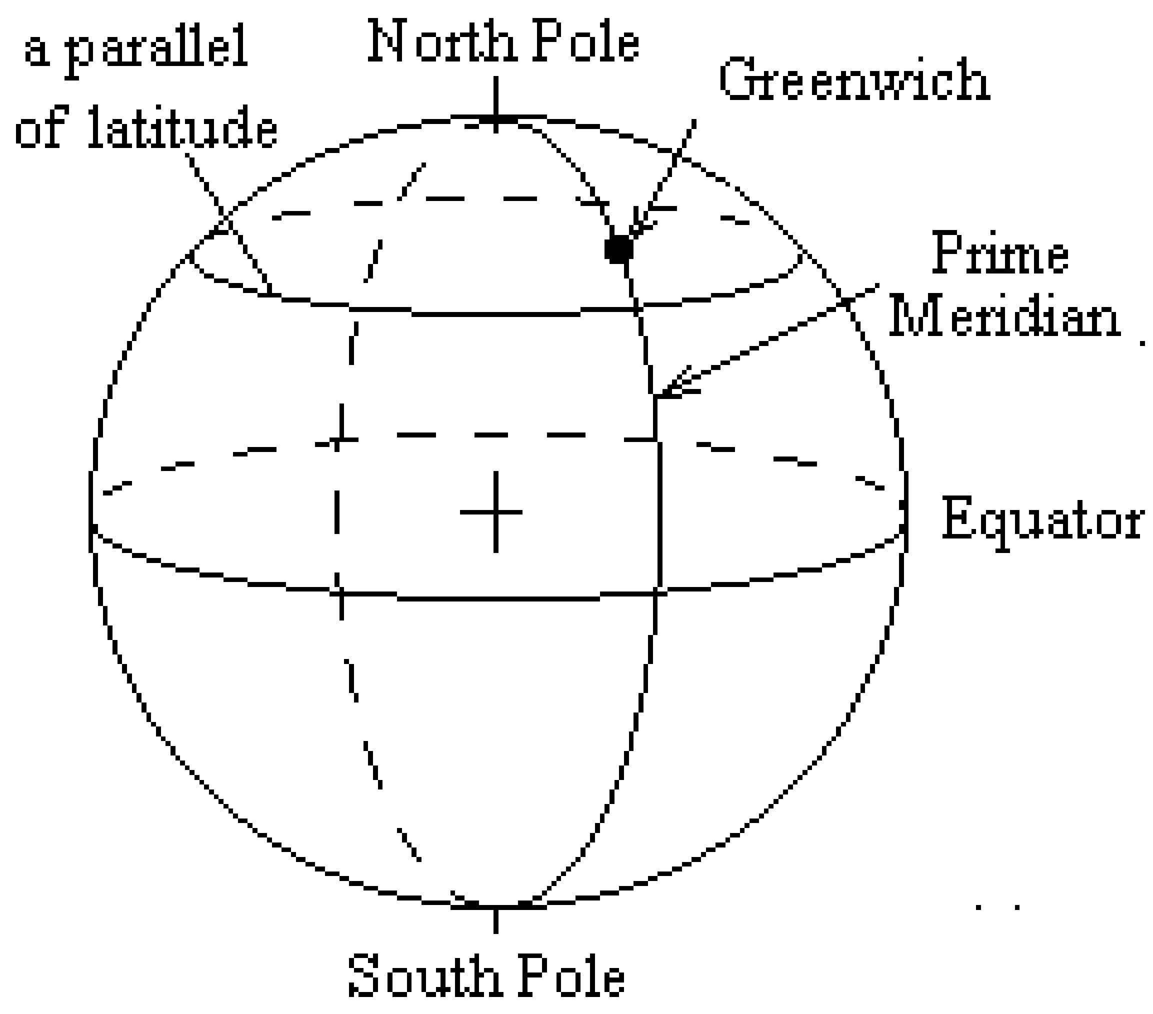
Wavelength Range Measured

Region	**Approximate Wavelength**	**Frequency (Hz)**
Ultraviolet (UV)	300 – 400 nm	~10^{15} Hz
Visible Light	400 – 700 nm	~4.3×10^{14} to 7.5×10^{14} Hz
Near Infrared (NIR)	700 – 2800 nm	~10^{14} Hz

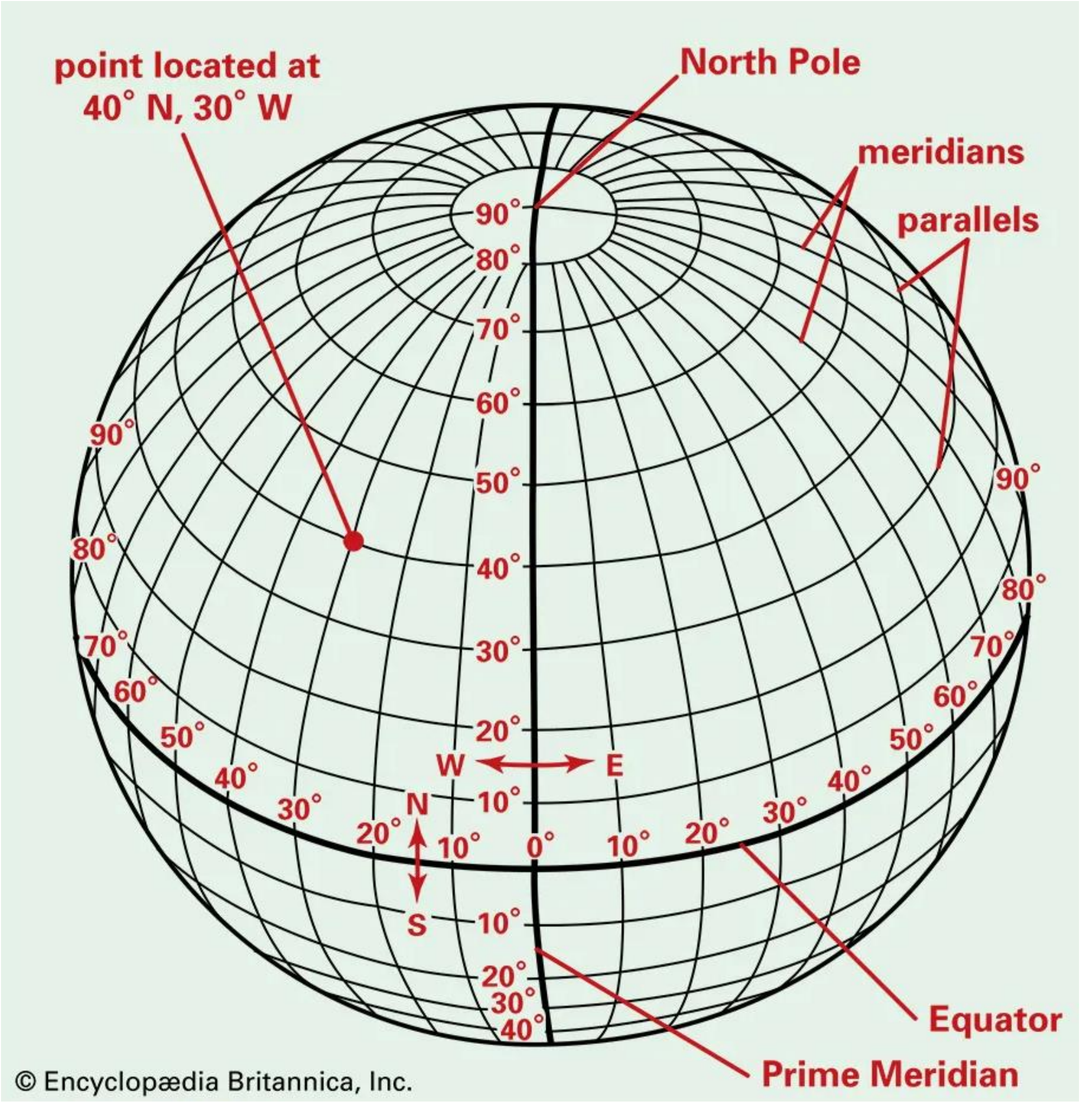
Pyrheliometer

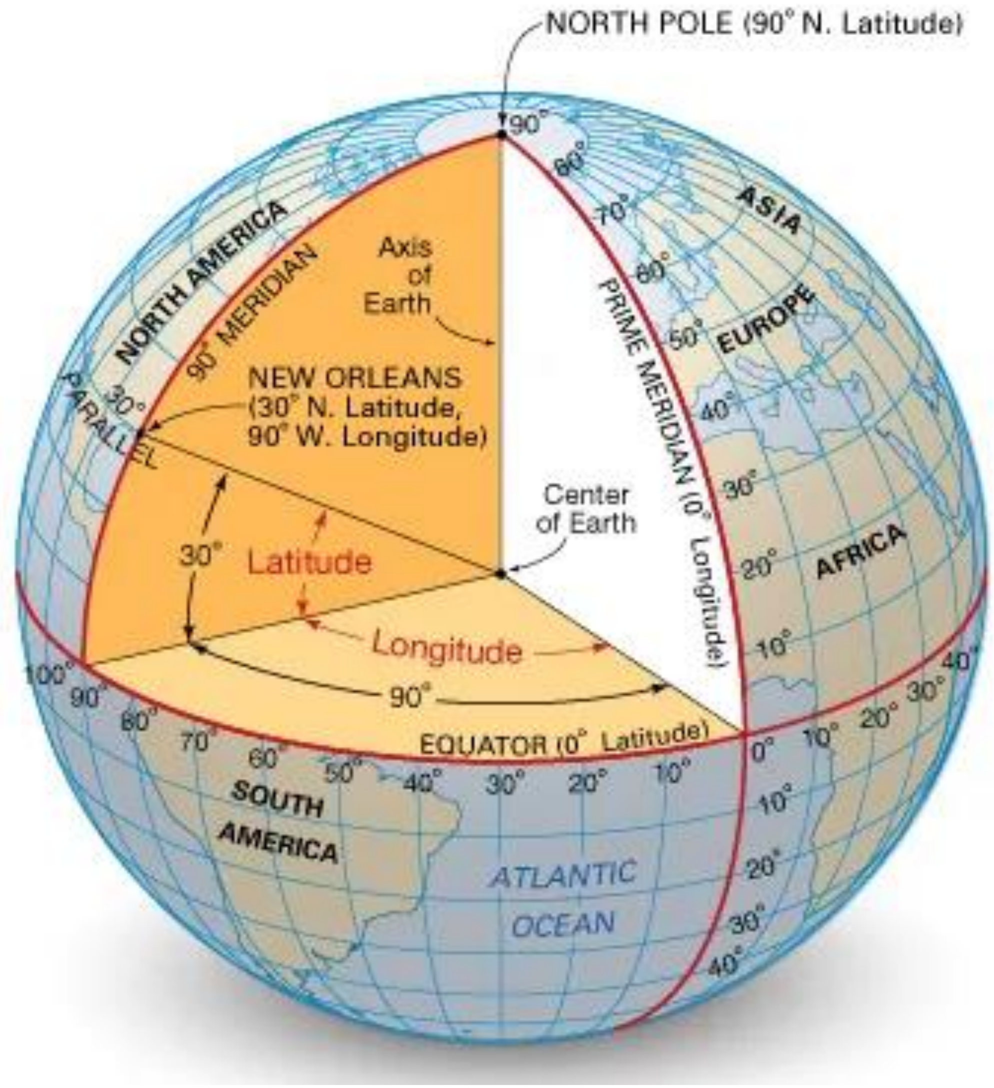


Coordinates of Earth



Coordinates of Earth





Basic Earth Sun angles

Latitude (∅)

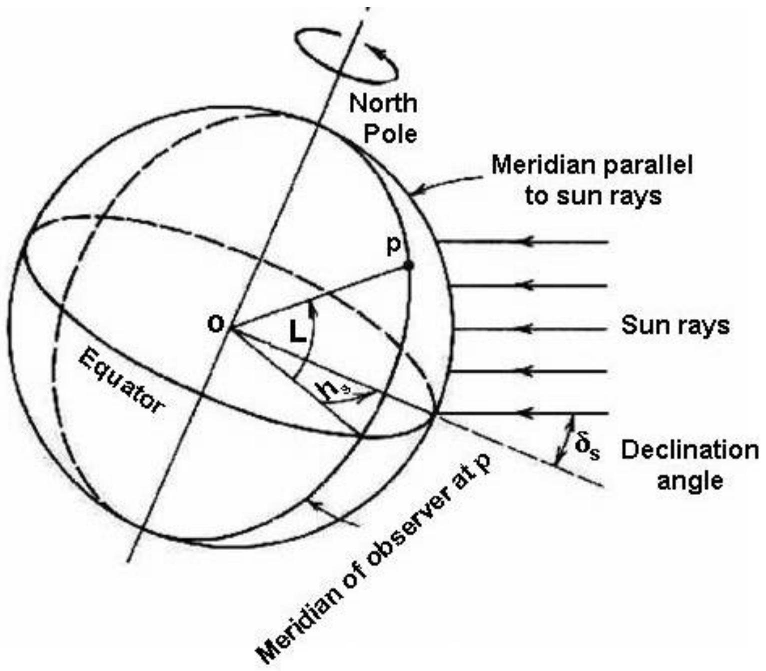
- The angular distance of a location on Earth north or south of the equator measured in degrees

Declination angle (δ)

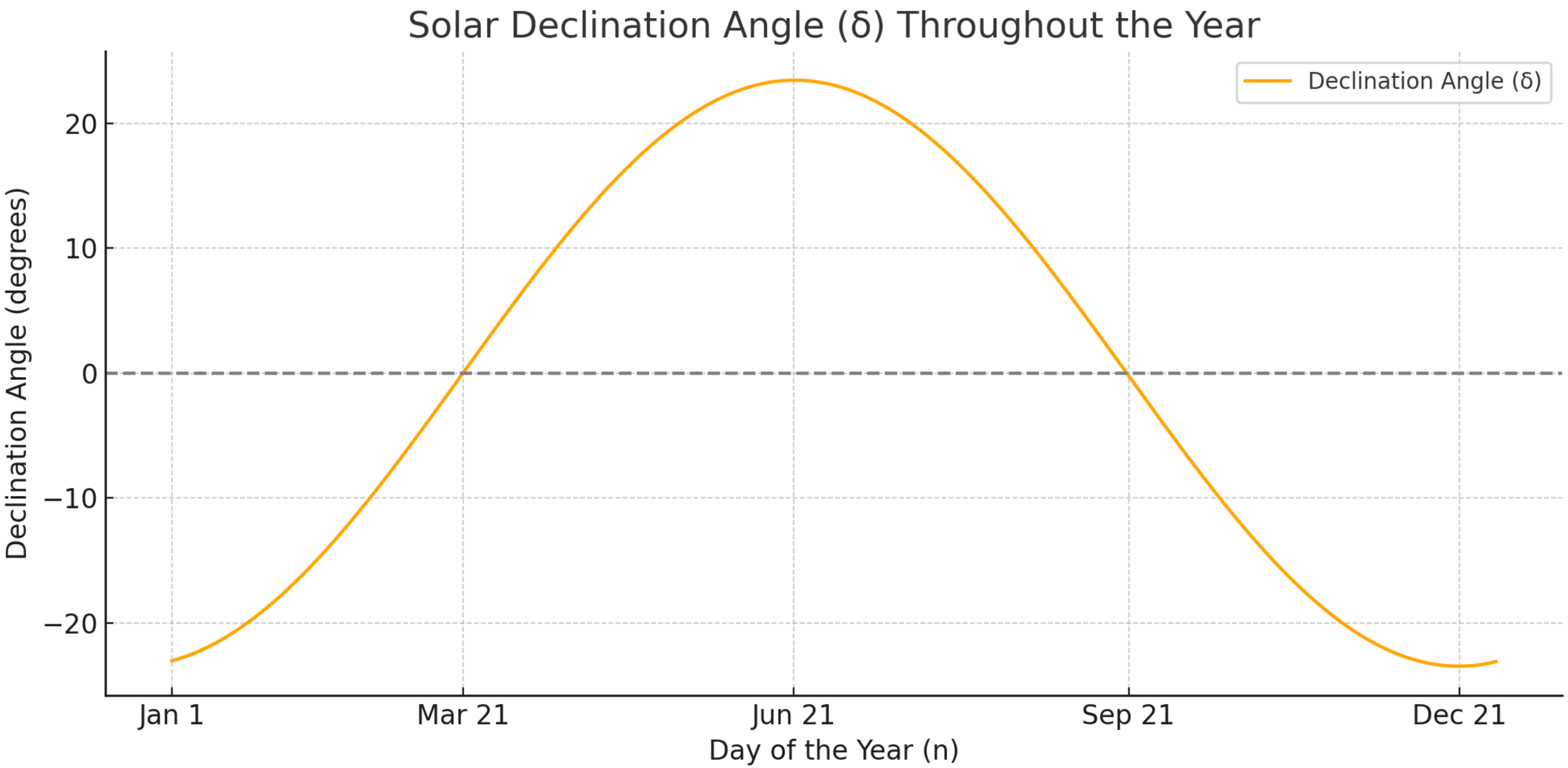
- The angle between the rays of the Sun and the equatorial plane of earth
- It determines the season and changes throughout the year as Earth revolves around the Sun.

$$\delta = 23.45 \ \sin\left[\frac{(n-81)}{365} x \, 360\right]$$

n – day number of the year



Declination angle



Derived solar angles

Zenith angle (θ)

- The zenith angle is the angle between the Sun rays and the vertical direction directly overhead.
- Used in solar radiation models to calculate the intensity of sunlight on inclined surfaces.
- A smaller zenith angle means stronger solar intensity.

$$\cos\theta = \cos\emptyset\ \cos\omega\ \cos\delta + \sin\emptyset\ \sin\delta$$

Altitude angle (α)

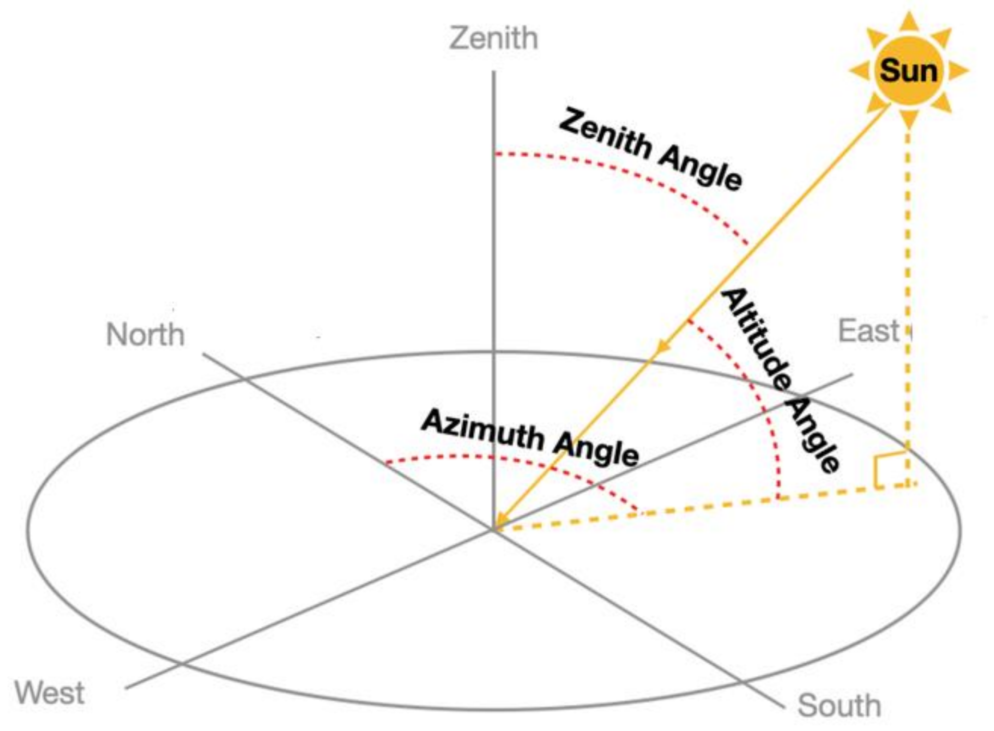
- The altitude angle is the angle between the Sun rays and the horizontal plane at a given location. It ranges from 0° (at sunrise/sunset) to 90° (when the Sun is directly overhead).
- Determines the height of the Sun in the sky.

$$\sin\alpha = \cos\emptyset\ \cos\omega\ \cos\delta + \sin\emptyset\ \sin\delta$$

Azimuth angle (γ)

- The solar azimuth angle is the compass direction from which the sunlight is coming, measured clockwise from true north.
- In the context of measuring the solar azimuth angle, a compass direction refers to the cardinal direction (North, East, South, West) and the degrees of rotation around the horizon used to indicate where the sunlight is coming from.

$$\cos\gamma = \sec\alpha\ (\cos\emptyset\ \sin\delta - \cos\delta\ \sin\emptyset\ \cos\omega)$$



- **Hour angle** $(\boldsymbol{\omega})$

The angular distance the Earth has rotated since solar noon measured in degrees.

$$\cos\theta = \cos\emptyset \ \cos\omega \ \cos\delta + \sin\emptyset \ \sin\delta$$

The zenith angle $\theta = 90$ at sun rise and sun set

$$\cos 90 = \cos\emptyset \ \cos\omega \ \cos\delta + \sin\emptyset \ \sin\delta$$

$$0 = \cos\emptyset \ \cos\omega \ \cos\delta + \sin\emptyset \ \sin\delta$$

$$-\sin\emptyset \ \sin\delta = \cos\emptyset \ \cos\omega \ \cos\delta$$

$$\cos\omega = -\frac{\sin\emptyset \ \sin\delta}{\cos\emptyset \cos\delta}$$

$$cos\ \omega = -\ tan\ \emptyset\ tan\ \delta$$

$$\boldsymbol{\omega = cos^{-1}\ (-\ tan\ \emptyset\ tan\ \delta)}$$

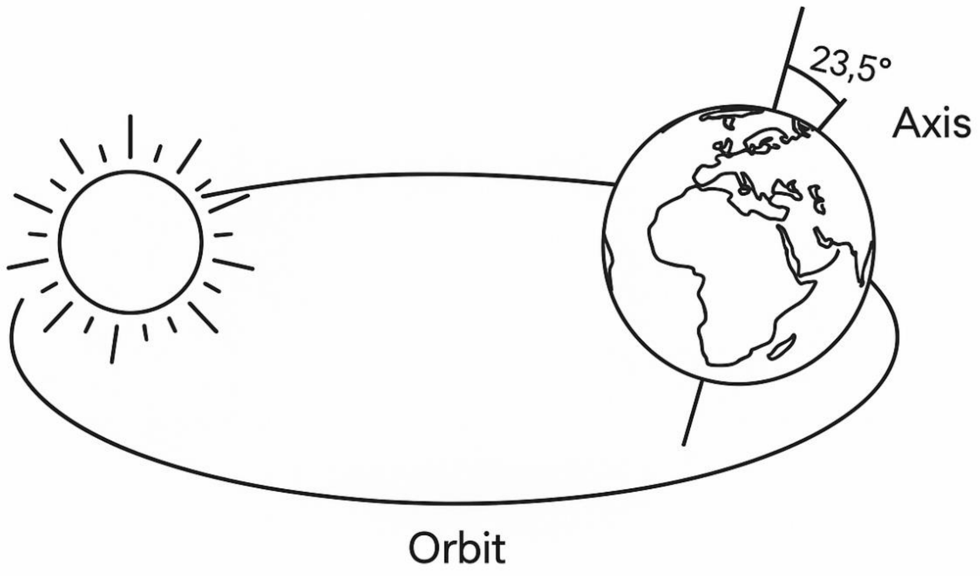
Day length (T_d)

The time interval between sunrise and sunset during which solar radiation reaches the surface of the earth.

It depends on both the latitude of the location and the solar declination angle which changes throughout the year due to the axial tilt of the earth and orbit around the sun.

$$T_d = \frac{2}{15}\,\omega$$

$$\boldsymbol{T_d = \frac{2}{15}\,cos^{-1}\,(-\,tan\,\theta\,tan\,\delta)}$$



Module II
Non Concentrating Collectors

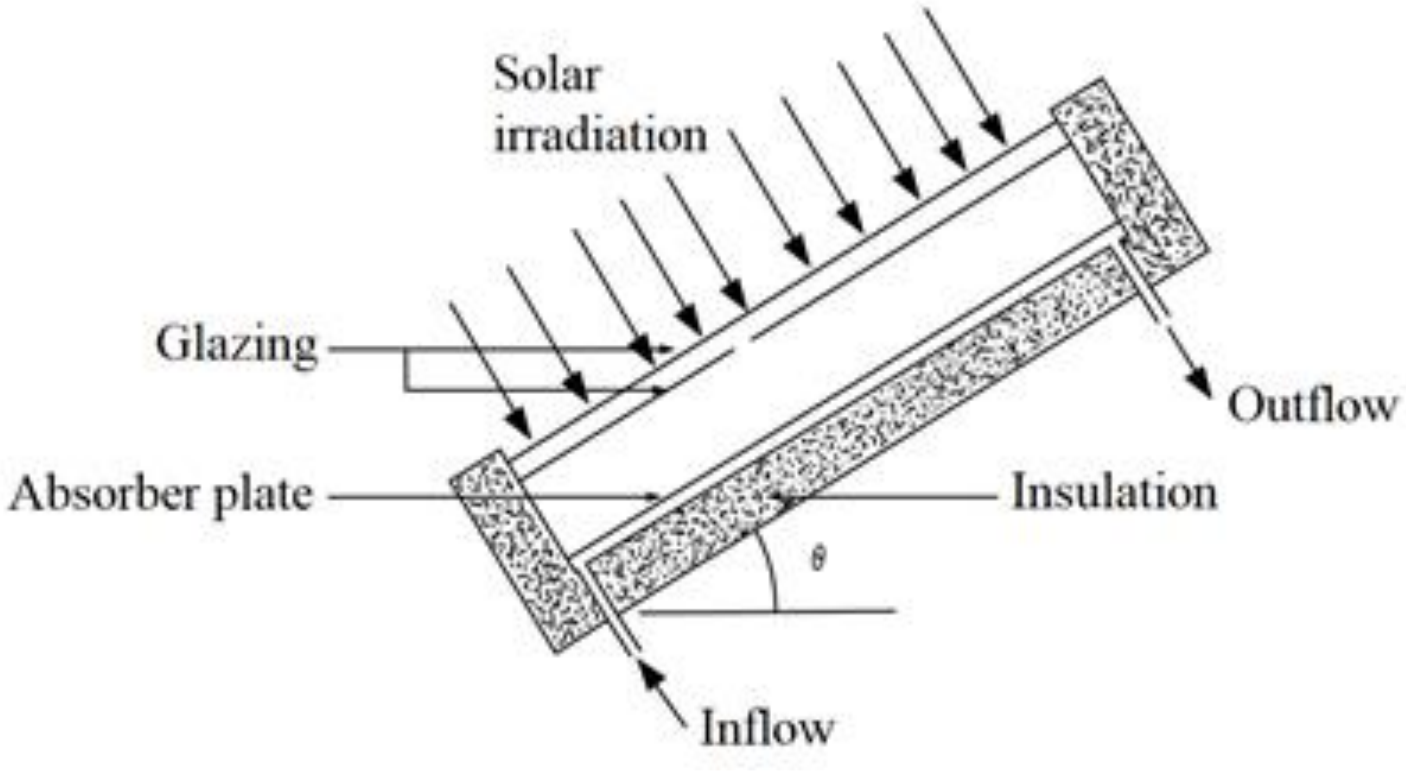
Types of collectors

- Low temperature cycle using Flat plate collectors (50 C – 90 C)
- Concentrator collector for medium temperature (150 – 400 C)
- Power tower concept for high temperature (600 C – 900 C)

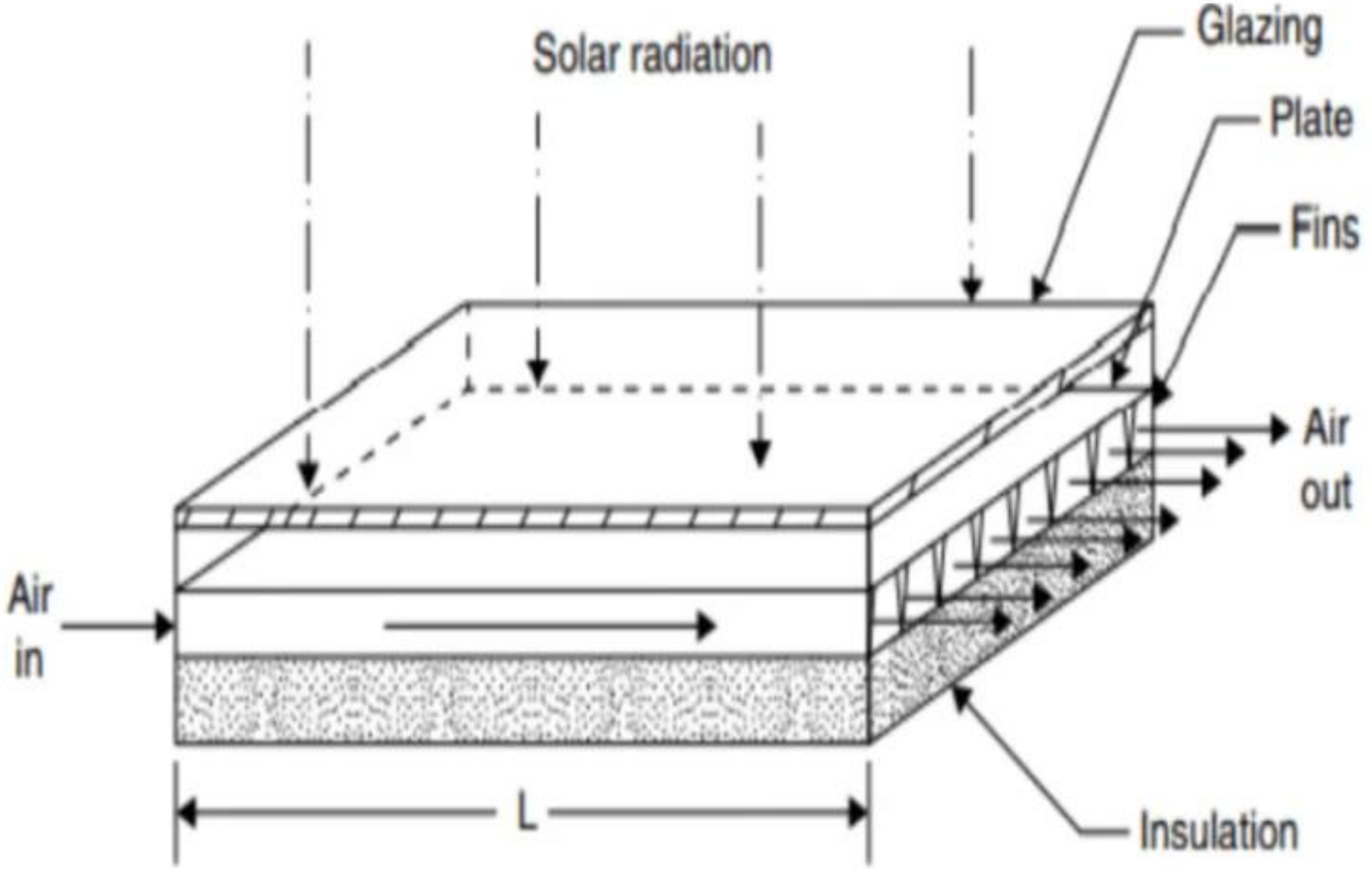
Non concentrating collector (Flat Plate collectors)

- Liquid Flat plate collector
- Air flat plate collector

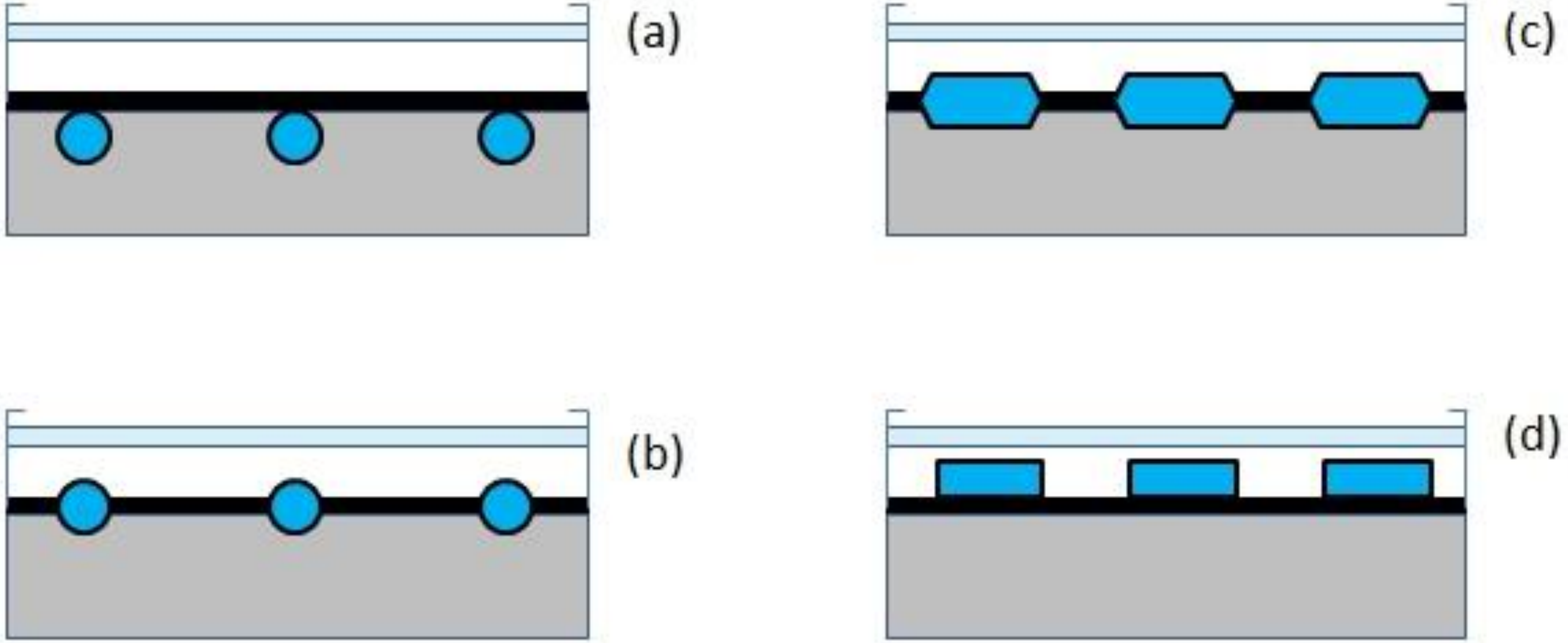
Liquid Flat plate collector



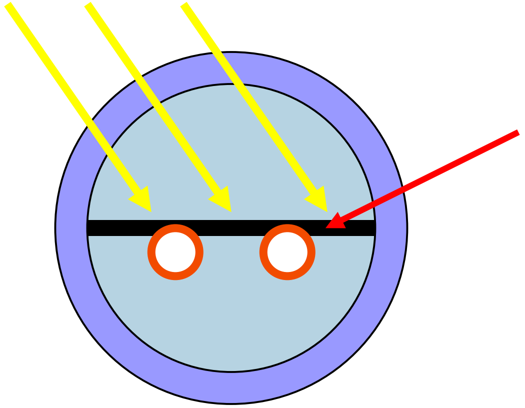
Air Flat plate collector



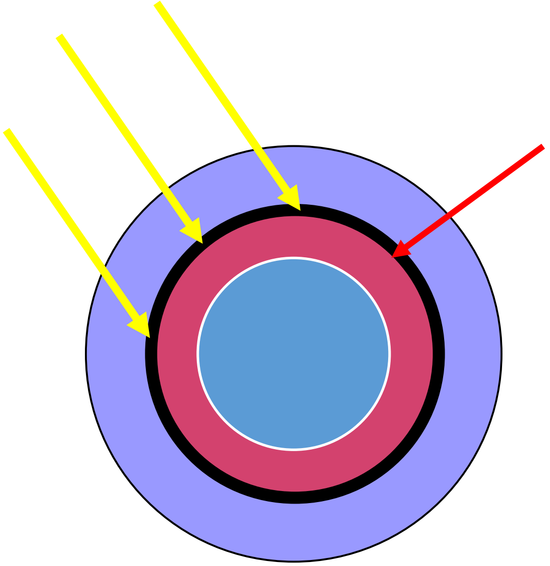
Collector tube construction



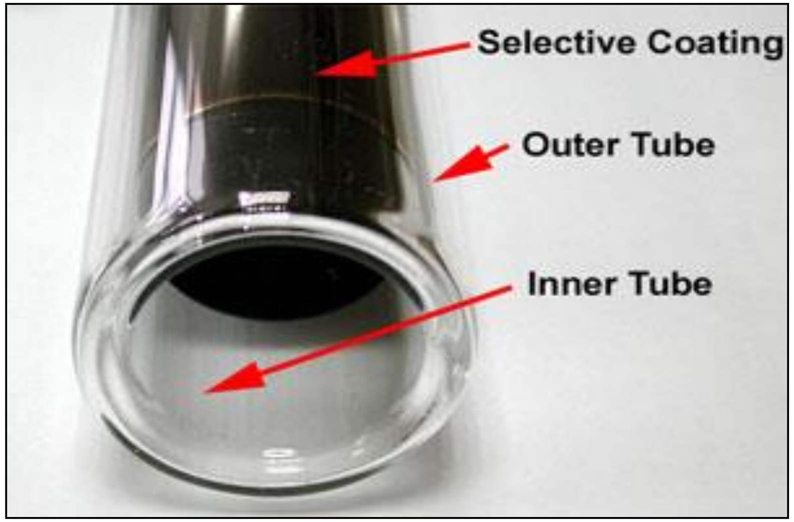
Evacuated collector



Flat plate collector

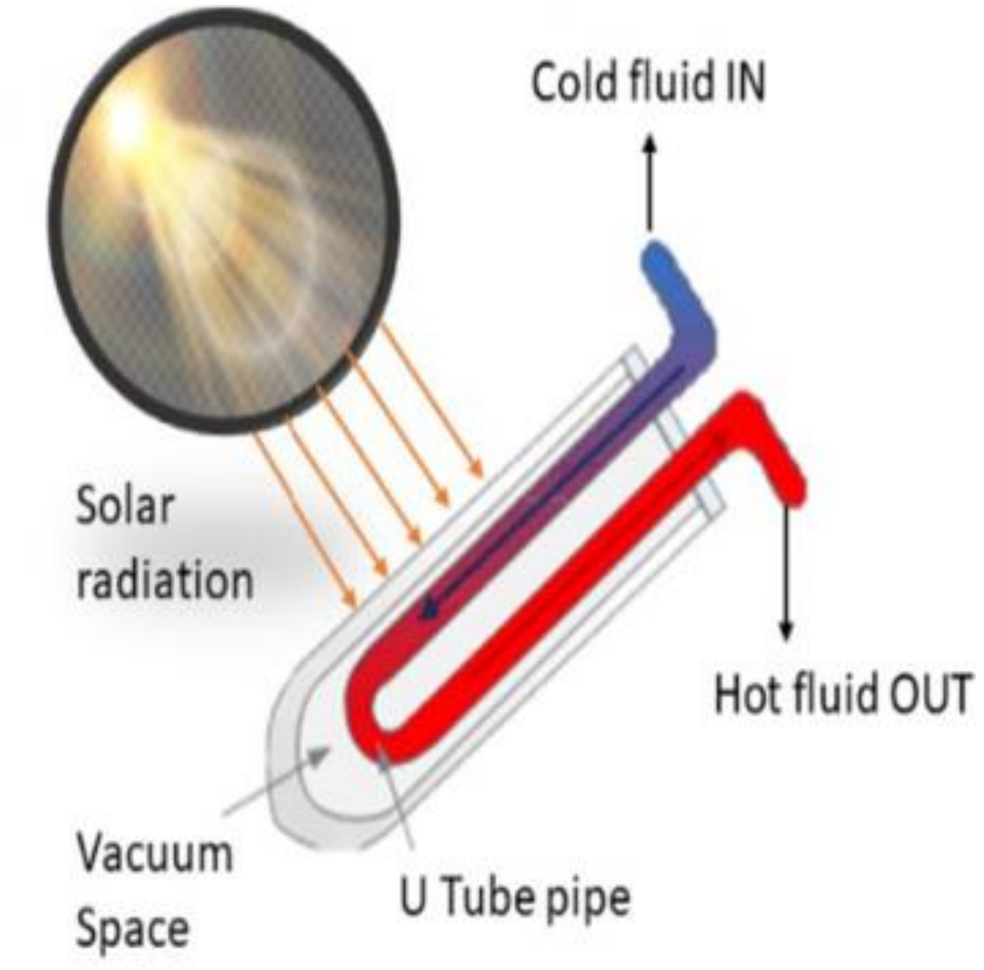


Evacuated collector

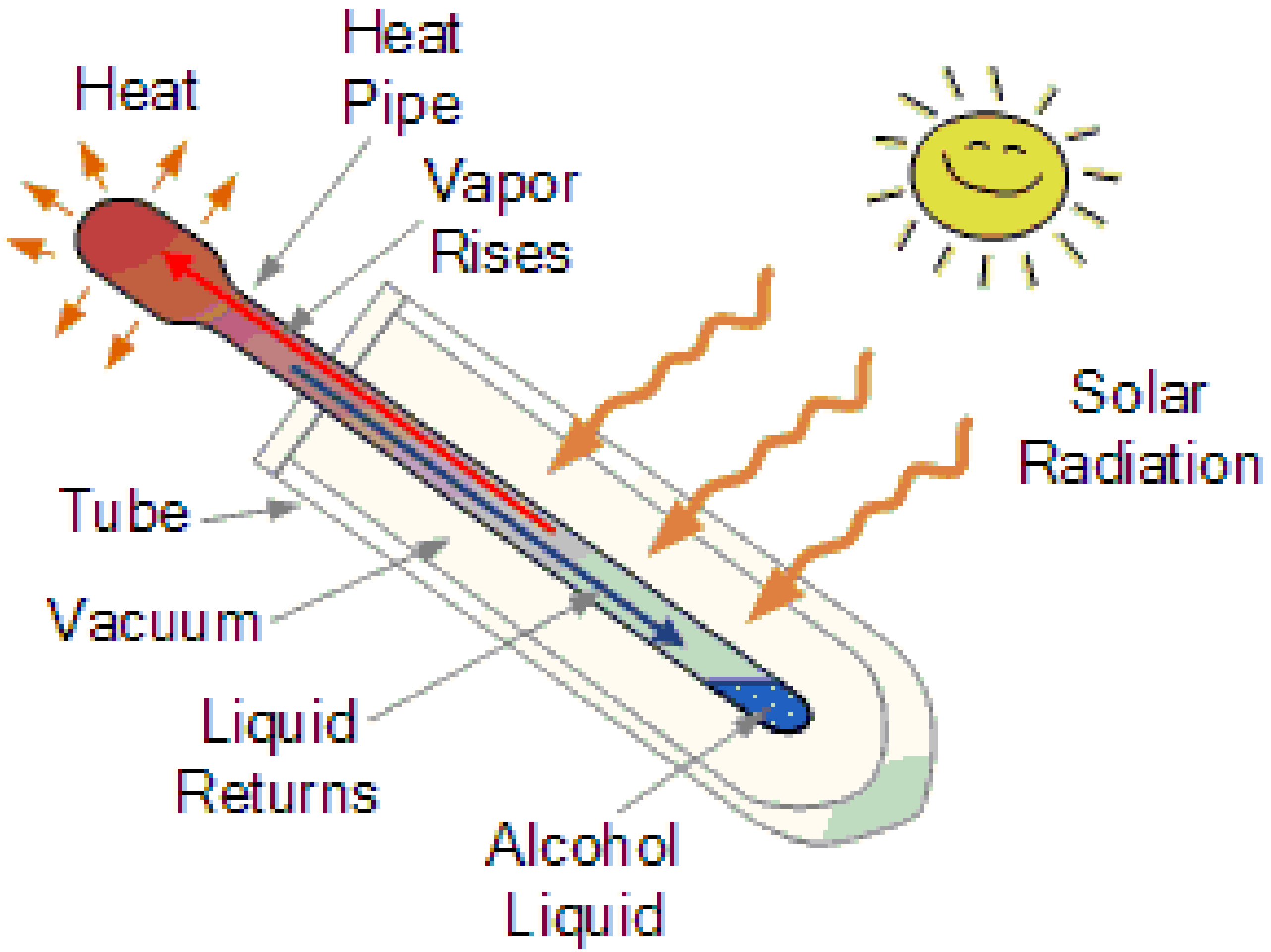


Evacuated tube collector

Direct Flow Evacuated Tube Collector



Heat Pipe Evacuated Tube Collectors



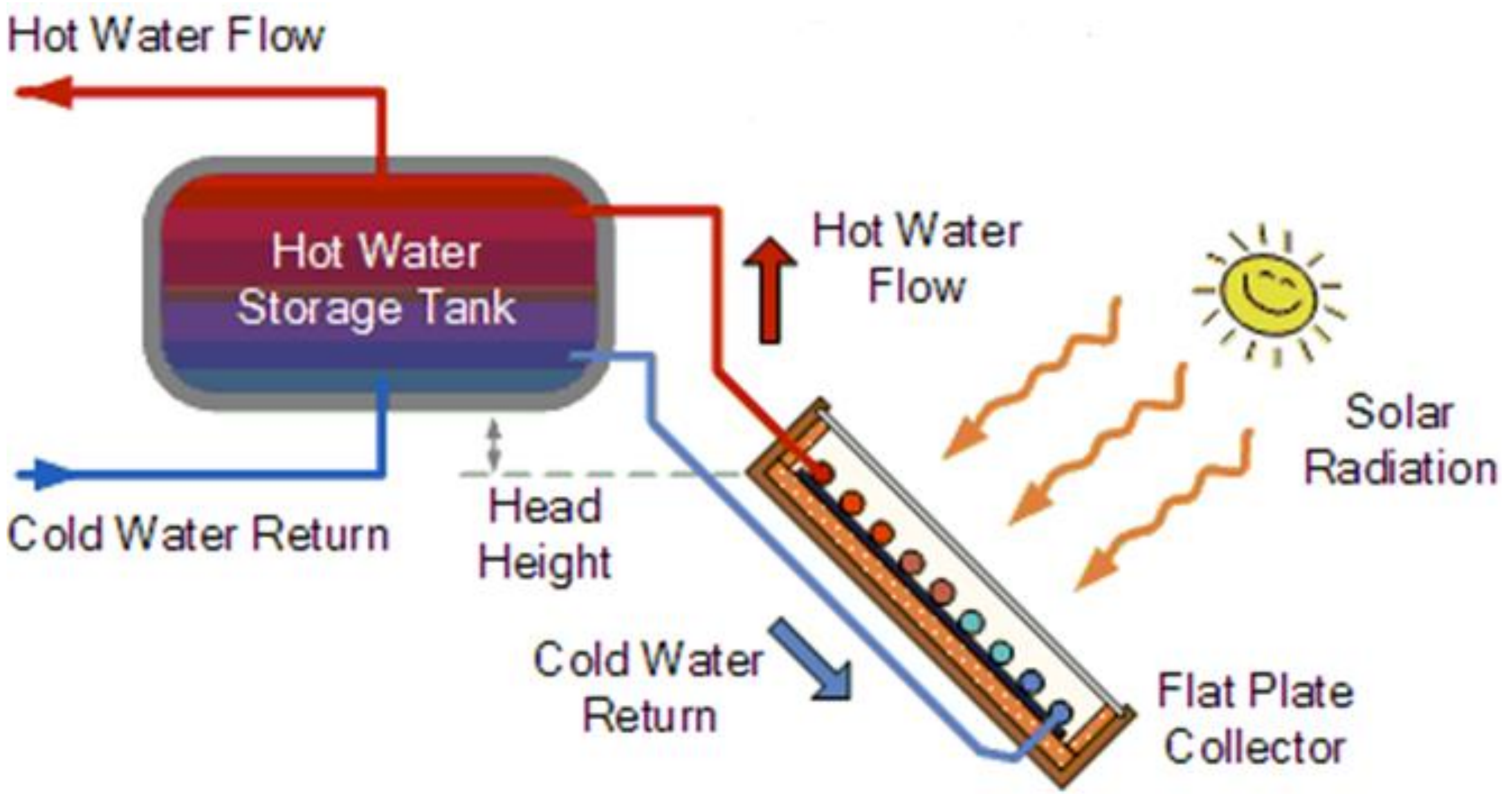
Collector: comparison

System	Useful radiation	Temperature range (^oC)	Efficiency (%)
Flate plate hot water heating	Global	40 to 60	40
Evacuated tube water heating	Global	50 to 80	50

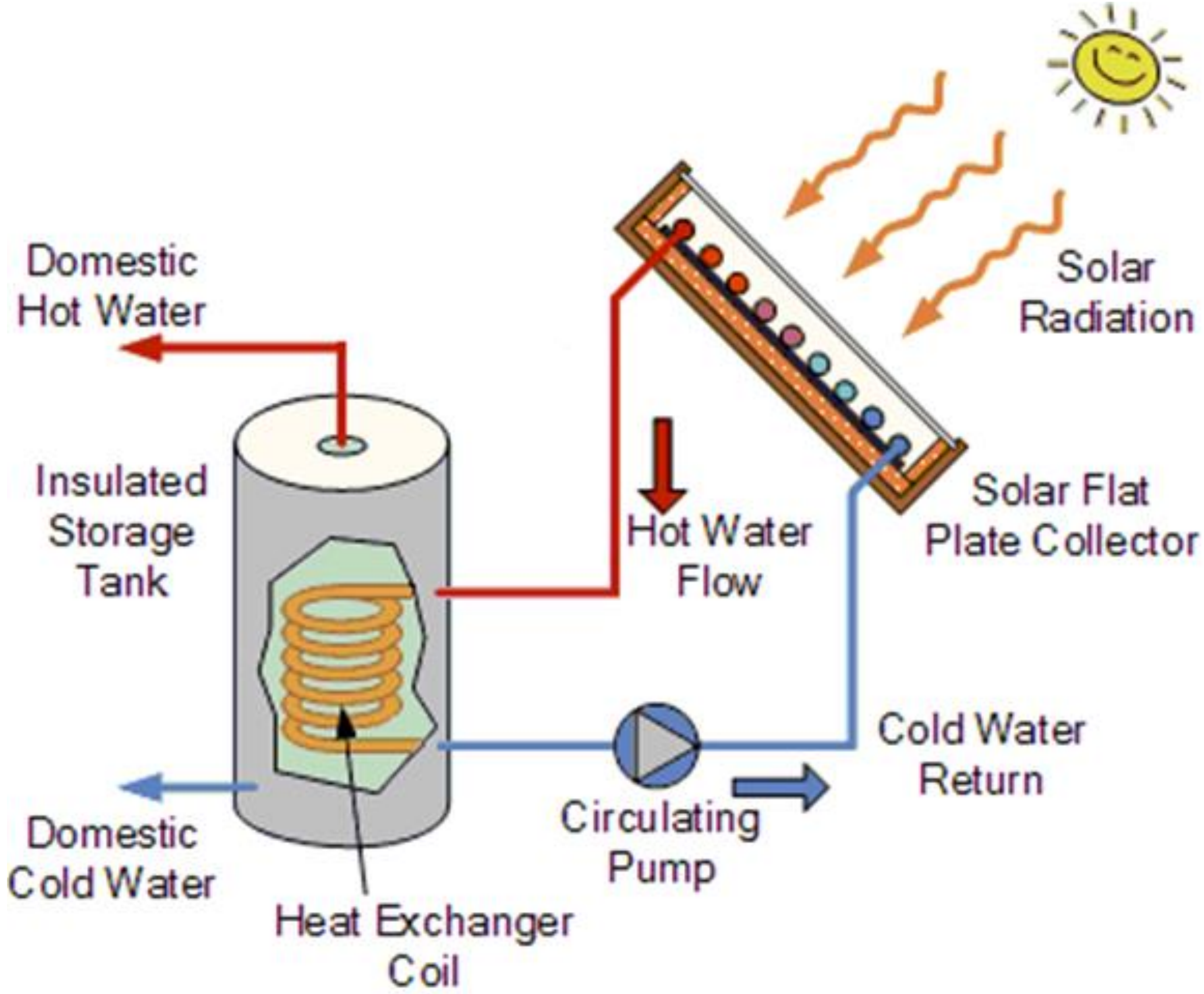
Solar Water Heater

Applications of flat plate collector

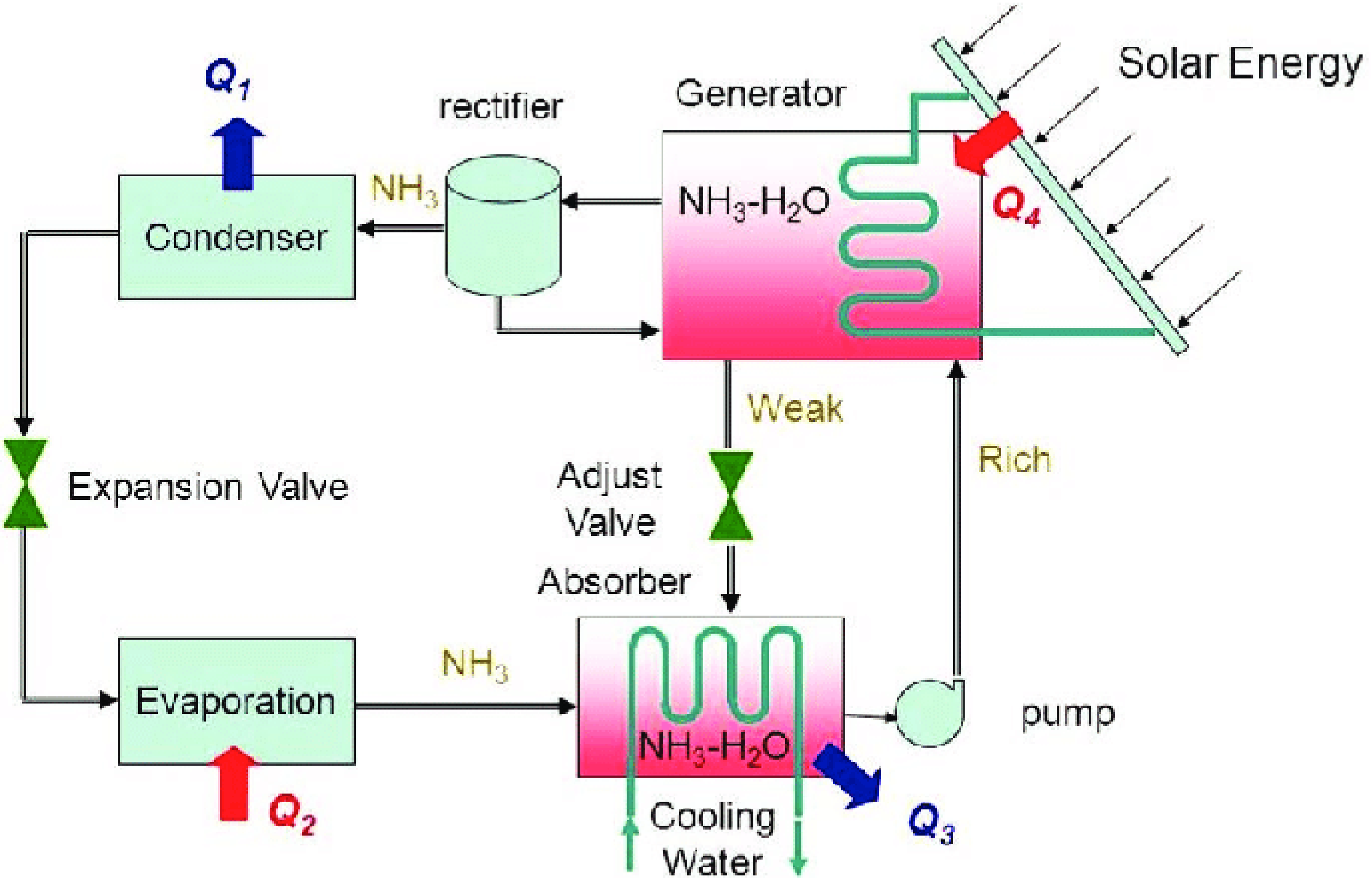
Thermosyphon Hot Water System



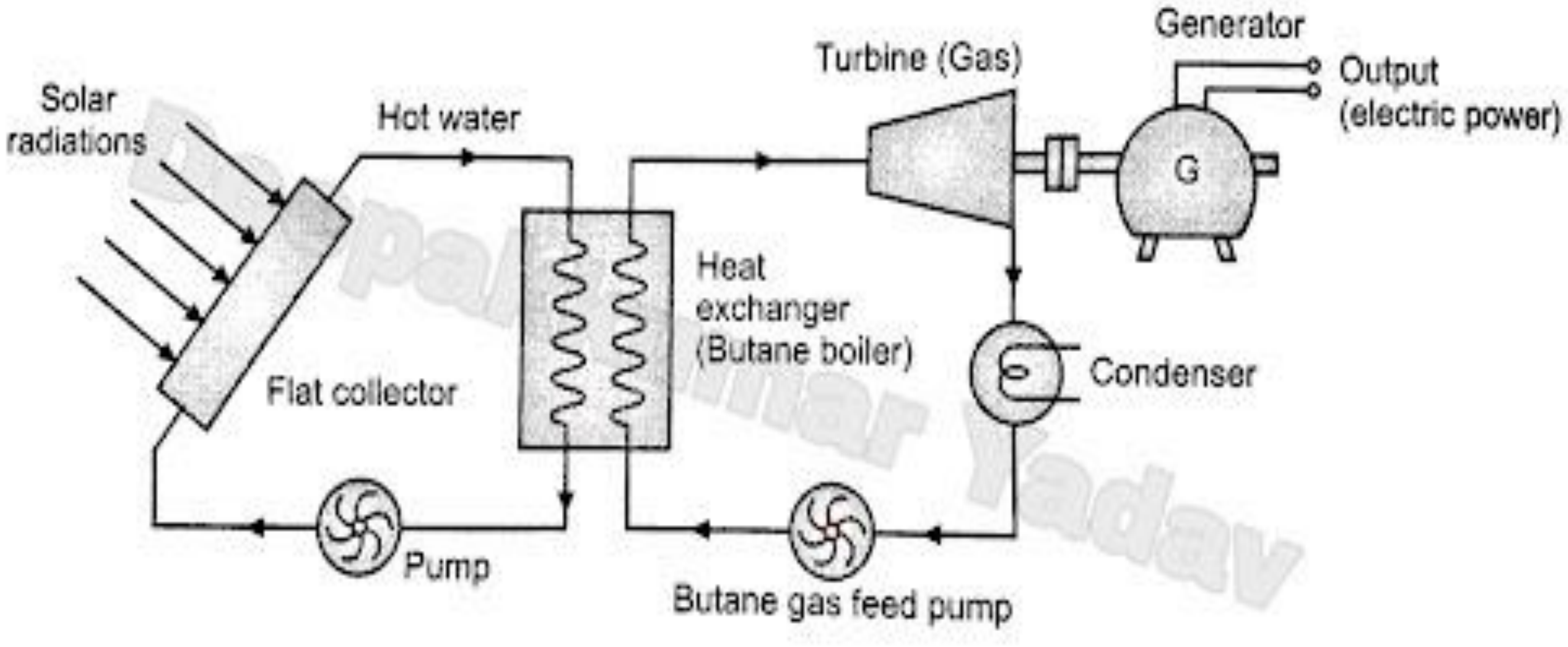
Indirect Solar Thermal System



Vapour absorption refrigeration system



Low Temperature Solar Power Plant

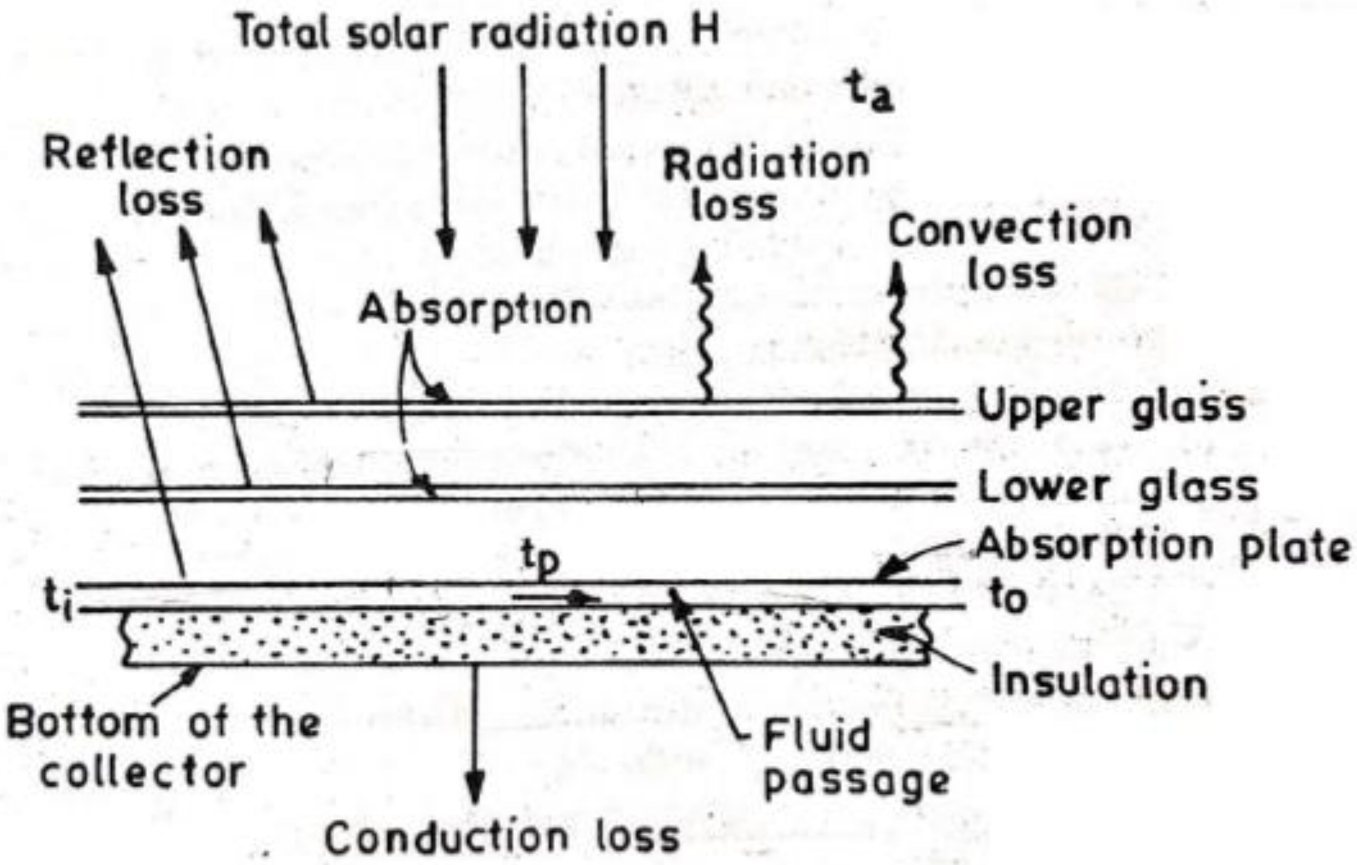


Performance of Flat plate solar collector

Factors affecting the collector performance

- Absorber plate
- Fluid passage (tubes)
- Glass cover
- Insulated container
- Radiation
  - direct
  - diffuse

Heat transfer in flat plate collector



Summary of losses

- Reflection from top cover
  - Top surface
  - Bottom surface
- Absorption by top cover

Incident radiation (15%)

- Emission from the absorber (5%)
- Top loss (Conduction +Convection + Radiation)
- Side loss (Conduction + Convection)
- Bottom loss (Conductive)

After conversion
25%
+13%
+2%
= 40%

Overall efficiency: ~ 40%

Energy balance Equation

$$\begin{pmatrix} Useful\ heat \\ delivered\ by\ the \\ solar\ collector \end{pmatrix} = \begin{pmatrix} Solar\ energy \\ absorbed\ in\ the \\ metal\ surface \end{pmatrix} - \begin{pmatrix} heat\ losses\ from\ the \\ surface\ to\ the \\ surroundings \end{pmatrix}$$

$$Q_u = A_c\, HR\, (\tau\alpha)_e - A_c\, U_L(t_p - t_a)$$

$$Q_u = A_c \left[HR\, (\tau\alpha)_e - U_L(t_p - t_a)\right]$$

Energy balance Equation (contd..)

$$Q_u = A_c\left[HR\,(\tau\alpha)_e - U_L(t_p - t_a)\right]$$

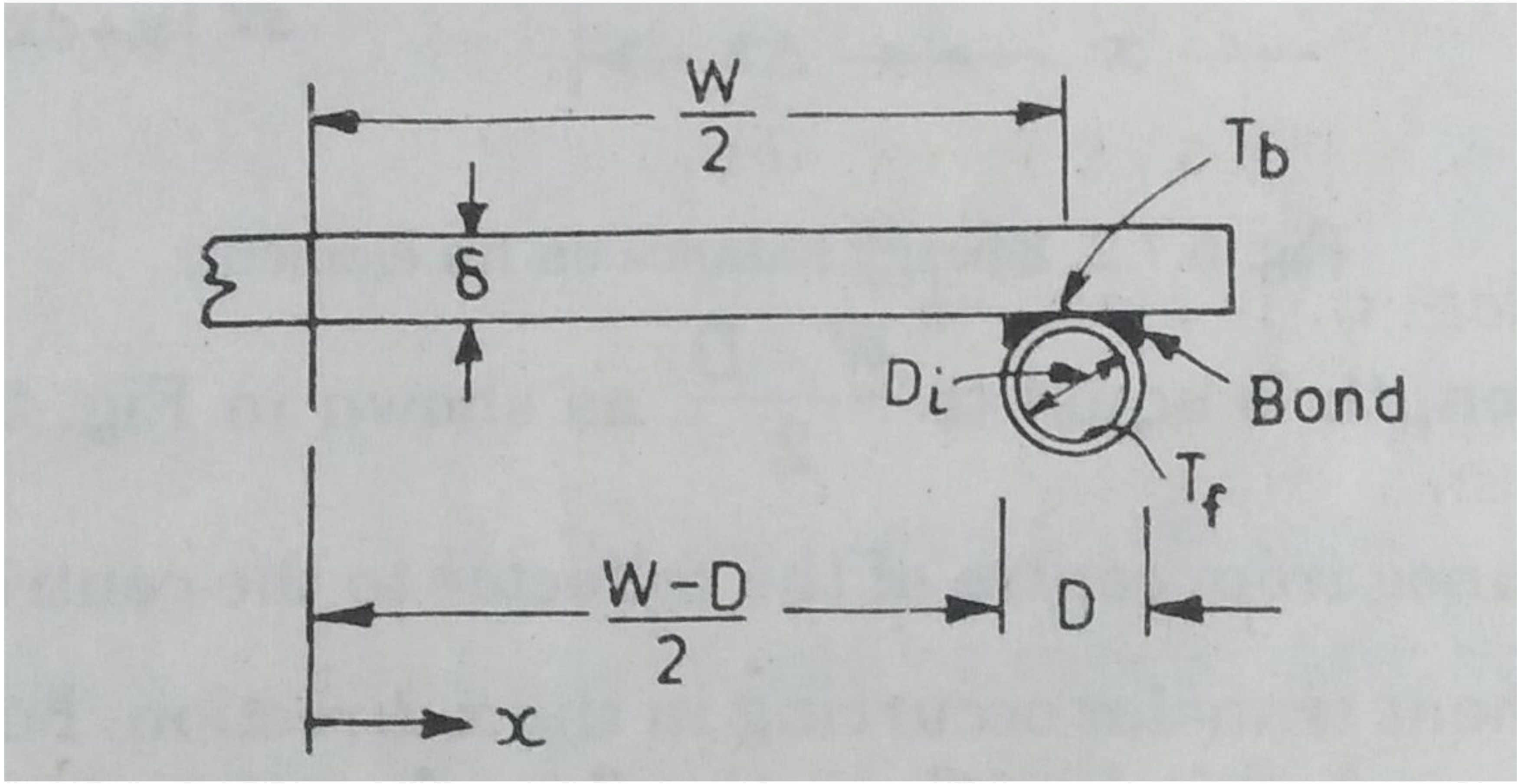
- $Q_u = Useful\ energy\ deliverd\ by\ the\ collector\ , W$
- $A_c\ = collector\ area, m^2$
- $H = Rate\ of\ incident\ beam\ or\ diffuse\ radiation\ per\ unit\ area\ of\ upper\ surface, W/m^2$
- $R = Factor\ to\ convert\ beam\ or\ diffuse\ radiation\ to\ that\ plane\ of\ the\ collector$
- $U_L = Over\ all\ heat\ transfer\ coefficient, W/m^2K$
- $t_p = temperature\ of\ the\ upper\ suface\ of\ the\ plate, C$
- $t_a = Atmospheric\ temperature, C$
- $(\tau\alpha)_e = Effective\ transmittance\ absorptance\ product$
- $(\tau\alpha)_e = \frac{\tau.\alpha}{1-(1-\alpha)\,\rho}$

Energy balance Equation (contd..)

$$R = \frac{\cos\ (\phi - S)\ \ cos\ \delta\ cos\ \omega + \sin(\phi - S)\sin\delta}{\cos\ \phi\ \ cos\ \delta\ cos\ \omega + \sin\phi\sin\delta}$$

- $\phi = Latitude$
- $S = collector\ tilt\ angle$
- $\delta = declination\ angle$
- $\omega = hour\ angle$

Collector tube design



$Heat\ removal\ factor$

$$F_R = \frac{Actual\ useful\ energy\ collected}{\begin{array}{c} Useful\ energy\ collected\ if\ the\ entire\ collector\ absrober \\ surface\ were\ at\ the\ temp.of\ the\ fluid\ entering\ the\ collector \end{array}}$$

$$Q_u = F_R\, A_c \left[HR\ (\tau\alpha)_e - U_L(T_f - T_a)\right]$$

$Heat\ removal\ factor\ (F_R)$

$$F_R = \frac{\dot{m}\, C_p}{U_L\, A_C}\left\{1 - e^{(-U_L\, A_C\, F\prime / \dot{m}\, C_p)}\right\}$$

$\dot{m} - mass\ flow\ rate\ of\ fluid,$ kg/s
$C_p - specific\ heat\ of\ fluid, J/kg\ K$
F' – collector efficiency factor

Collector efficiency factor

$$F' = \frac{1/U_L}{W\left[\frac{1}{U_L(D+(W-D)F)} + \frac{1}{C_b} + \frac{1}{\pi D h_f}\right]}$$

- $D = Diameter\ of\ tube, m$
- $W\ = centre\ distance\ between\ the\ tubes, m$
- $F = Fin\ efficiency$
- $h_f = Convective\ heat\ transfer\ coefficient\ between\ tube\ and\ fluid, W/m^2K$
- $C_b = Bond\ resistance$

Fin efficiency

$$F = \frac{\tanh m\left(\frac{W-D}{2}\right)}{m\left(\frac{W-D}{2}\right)}$$

$$m = \sqrt{\frac{U_L}{K\ \delta_T}}$$

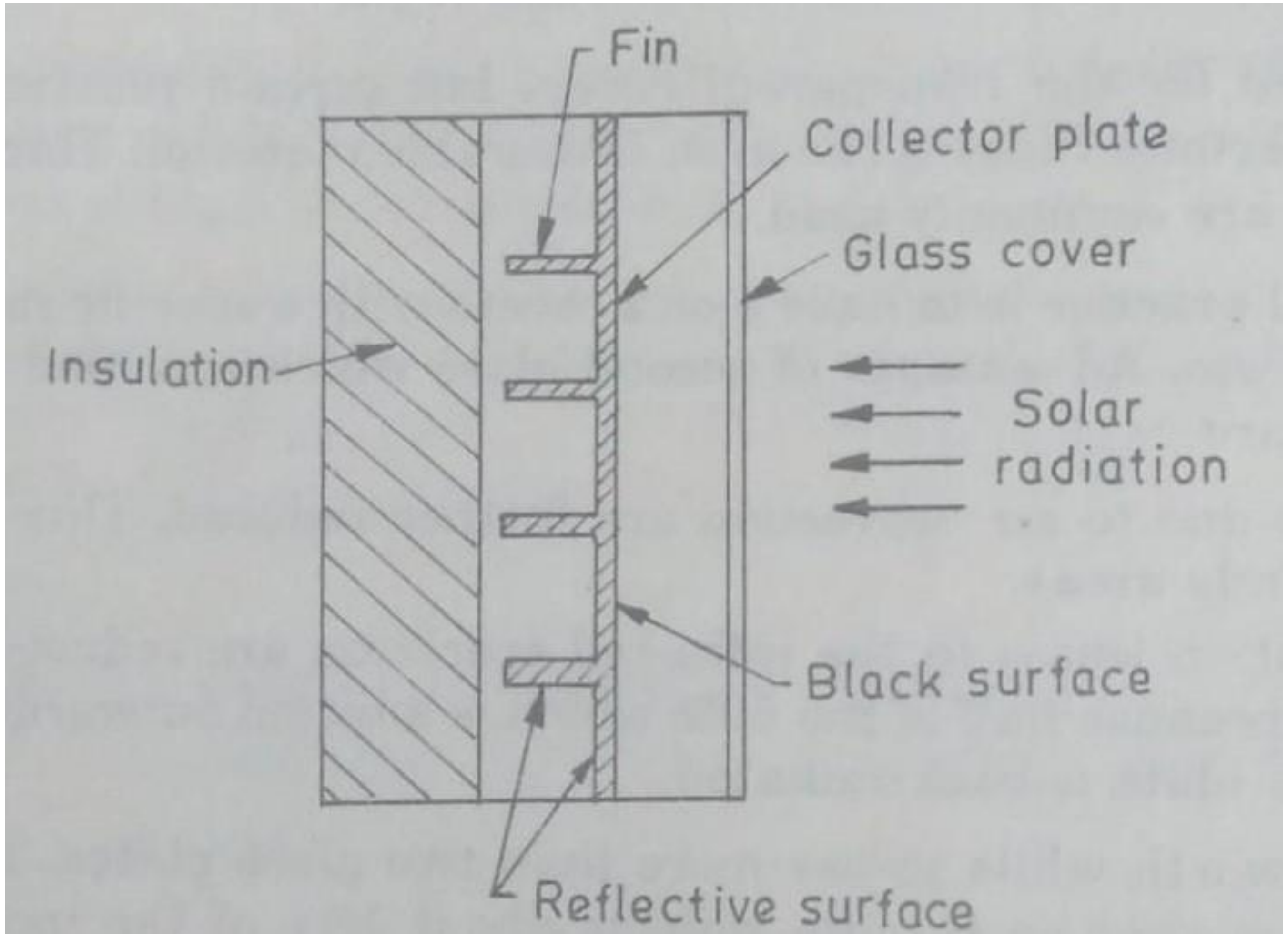
- $K = thermal\ conductivity\ of\ the\ plate, W/m\ K$
- $\delta_t = Fin\ thickness, m$

$Collector\ efficiency$

$$\eta = \frac{Useful\ heat\ energy\ gained}{Incident\ solar\ energy}$$

$$\eta = \frac{Q_u}{A_C HR}$$

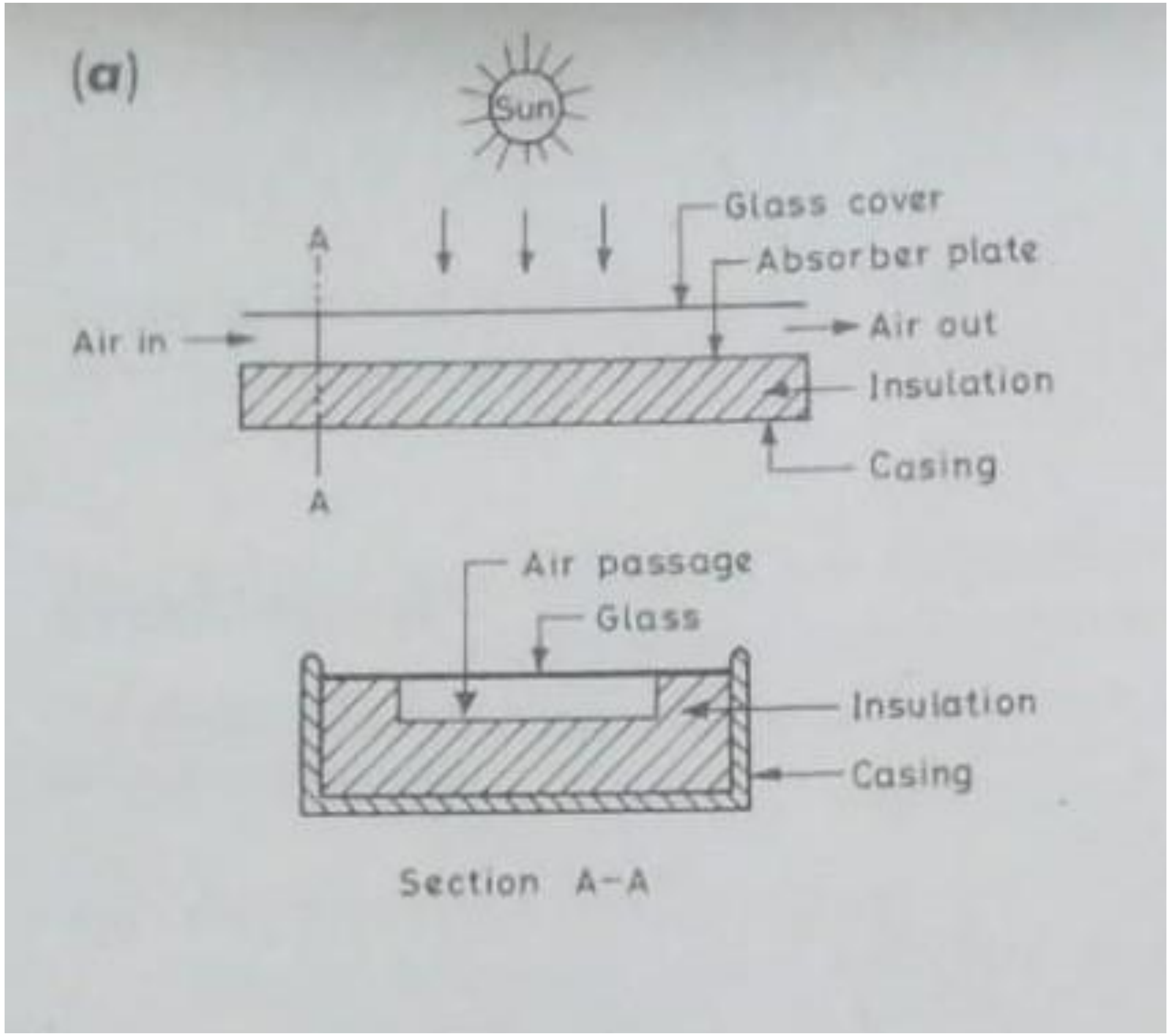
Air Flat Plate collector



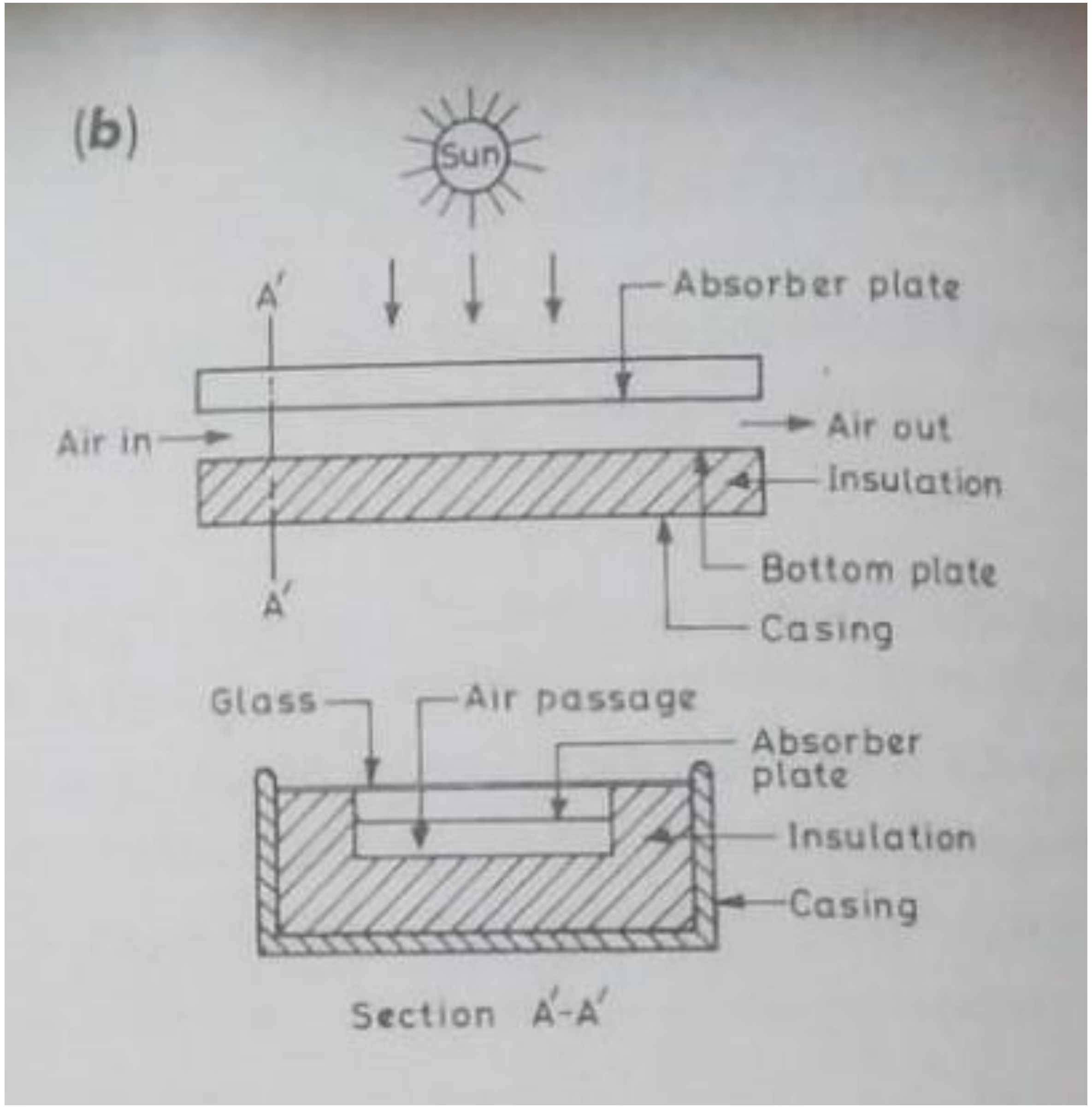
Types of flat plate air collector

- Non porous type collector
- Porous type collector

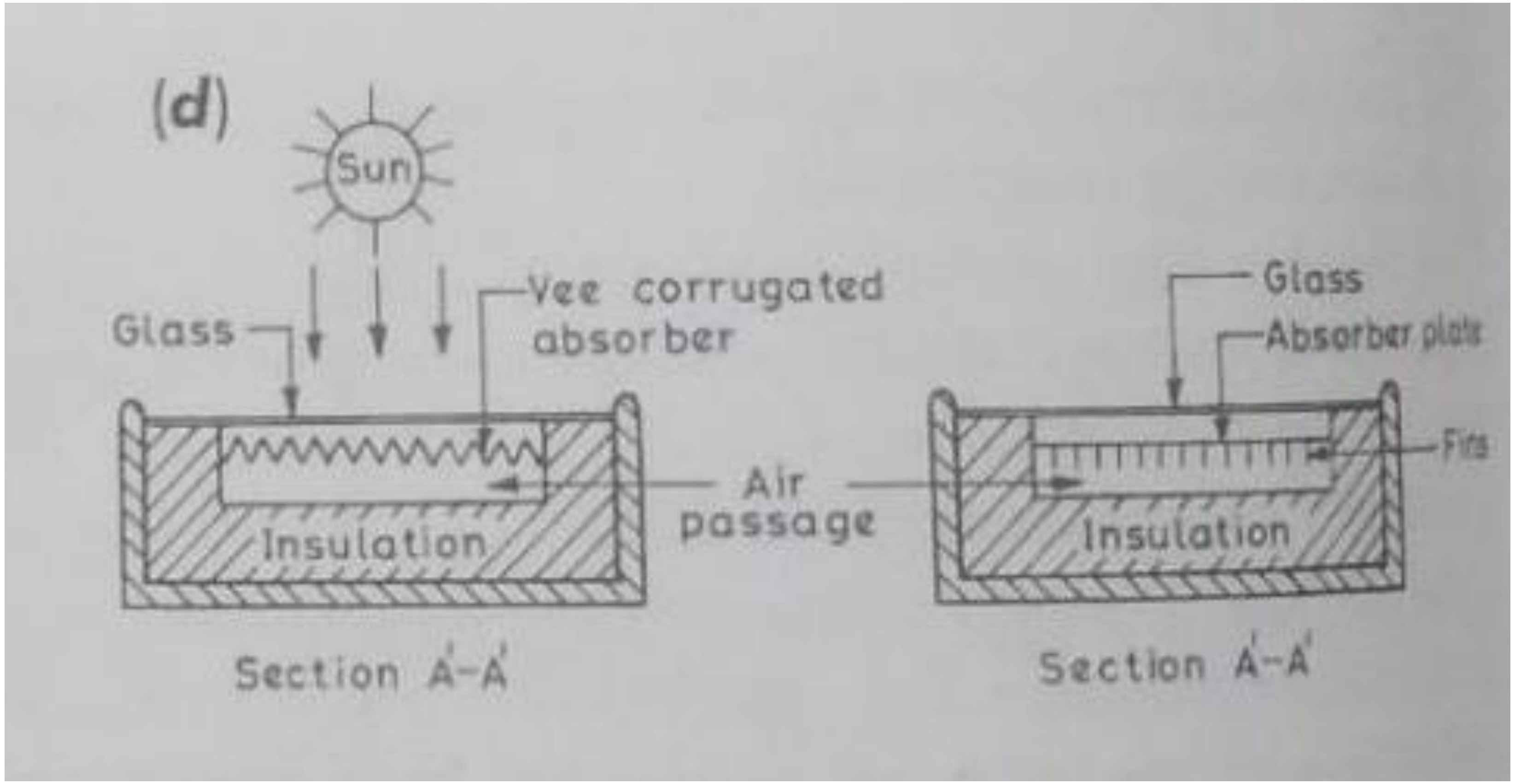
Non porous type collector



Non porous type collector

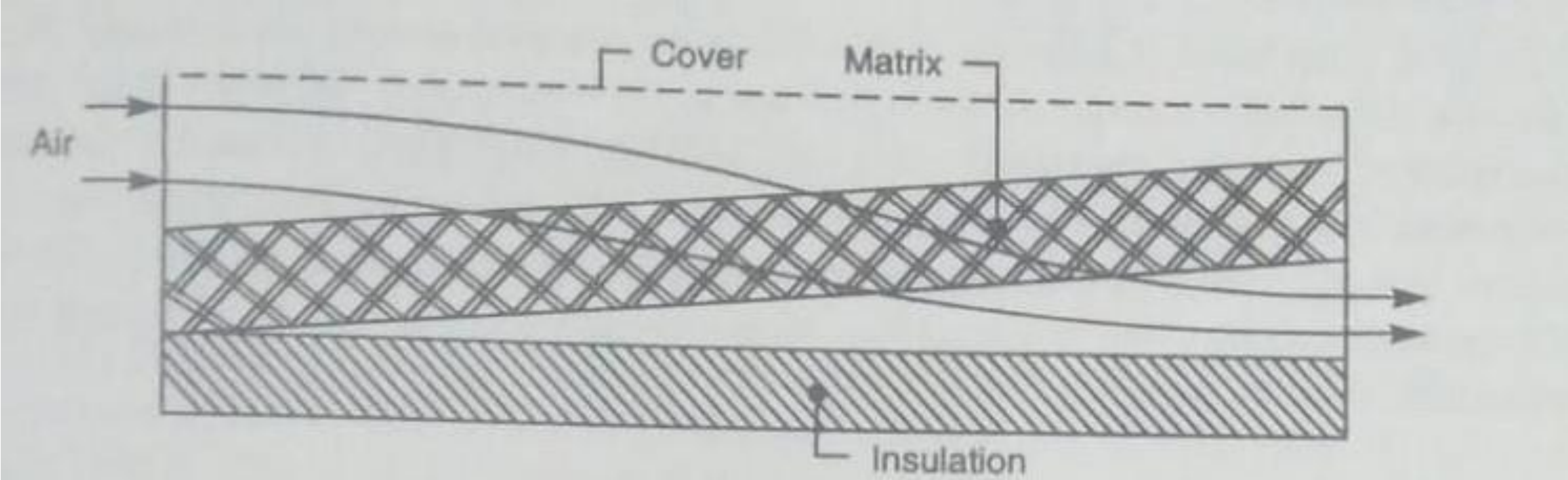


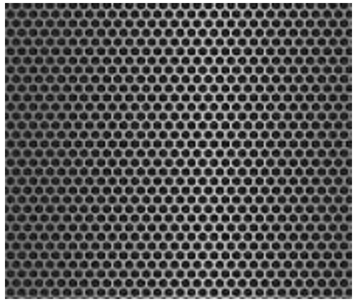
Non porous type collector

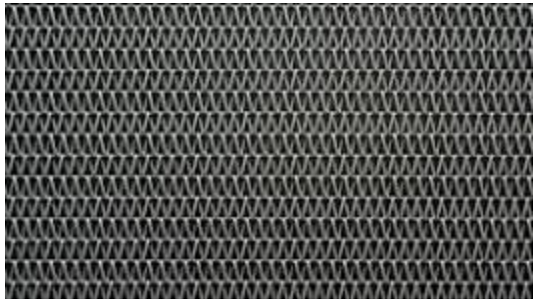


Porous type collector

Matrix air heater

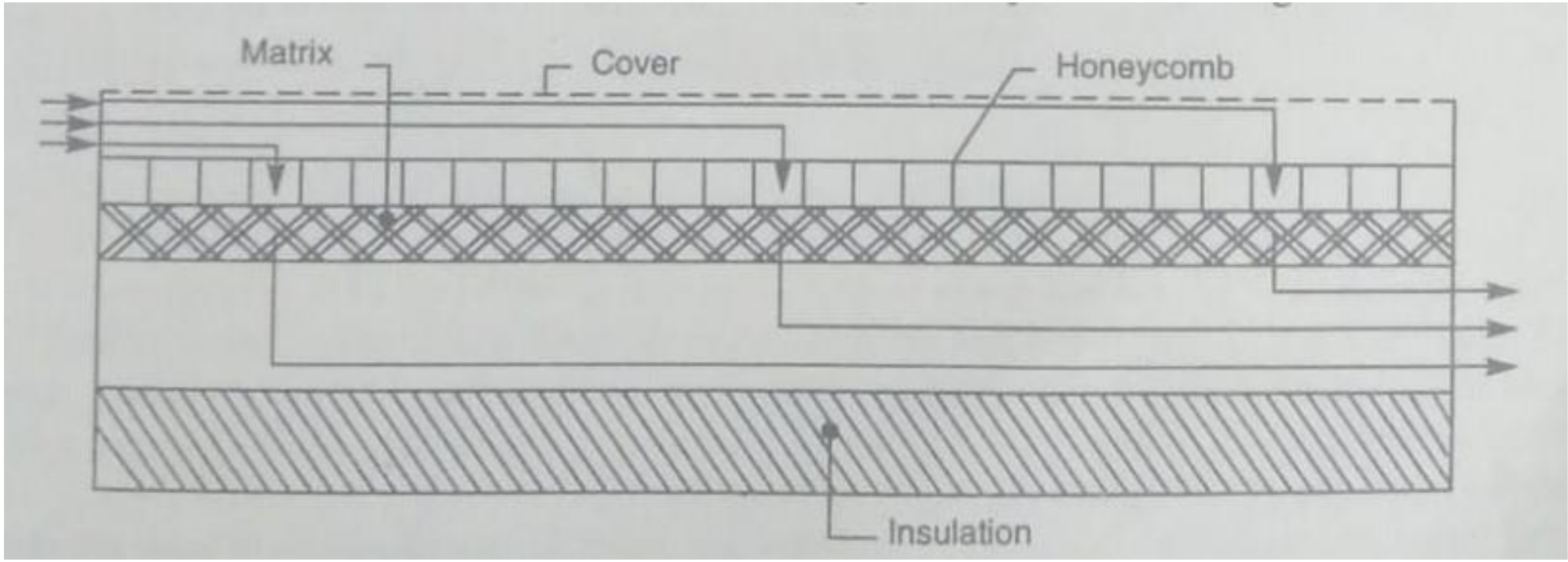






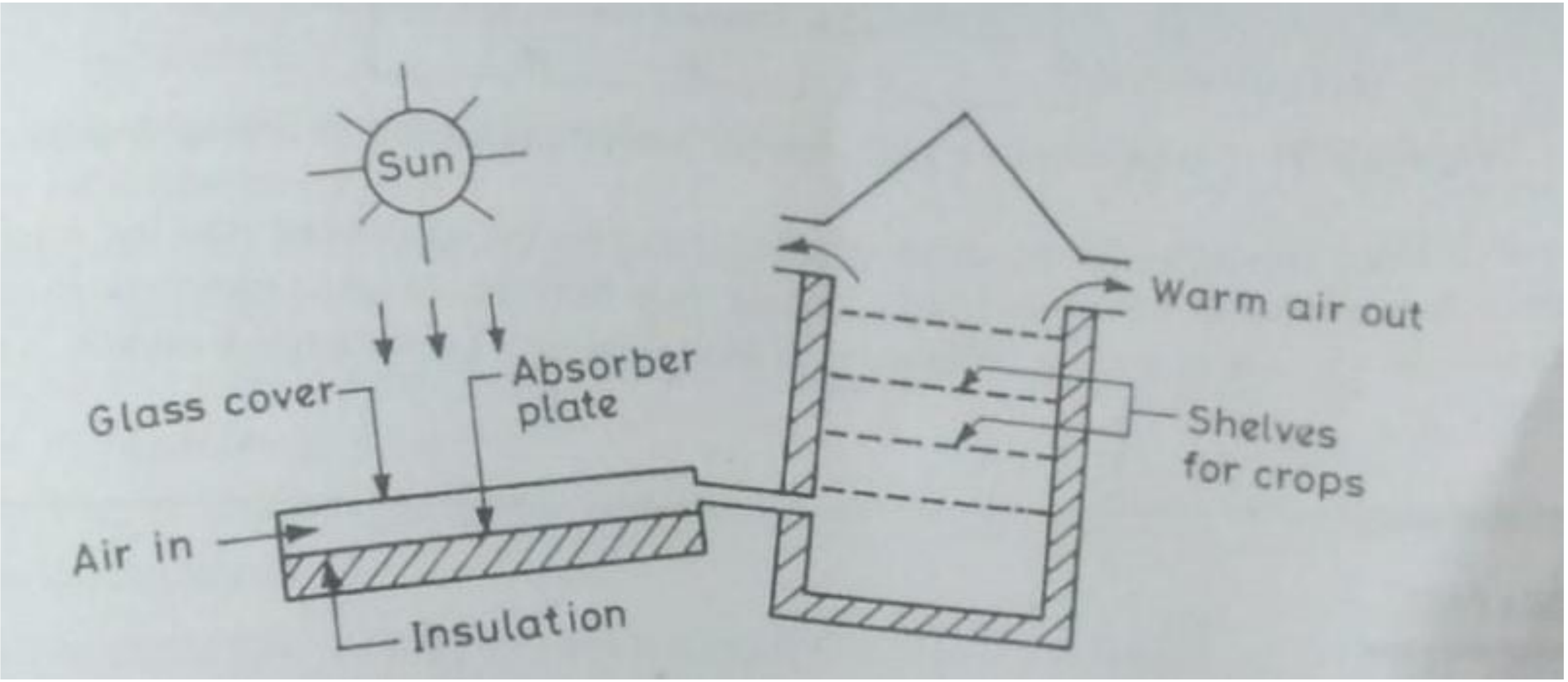
Metal Matrix

Honeycomb porous bed collector

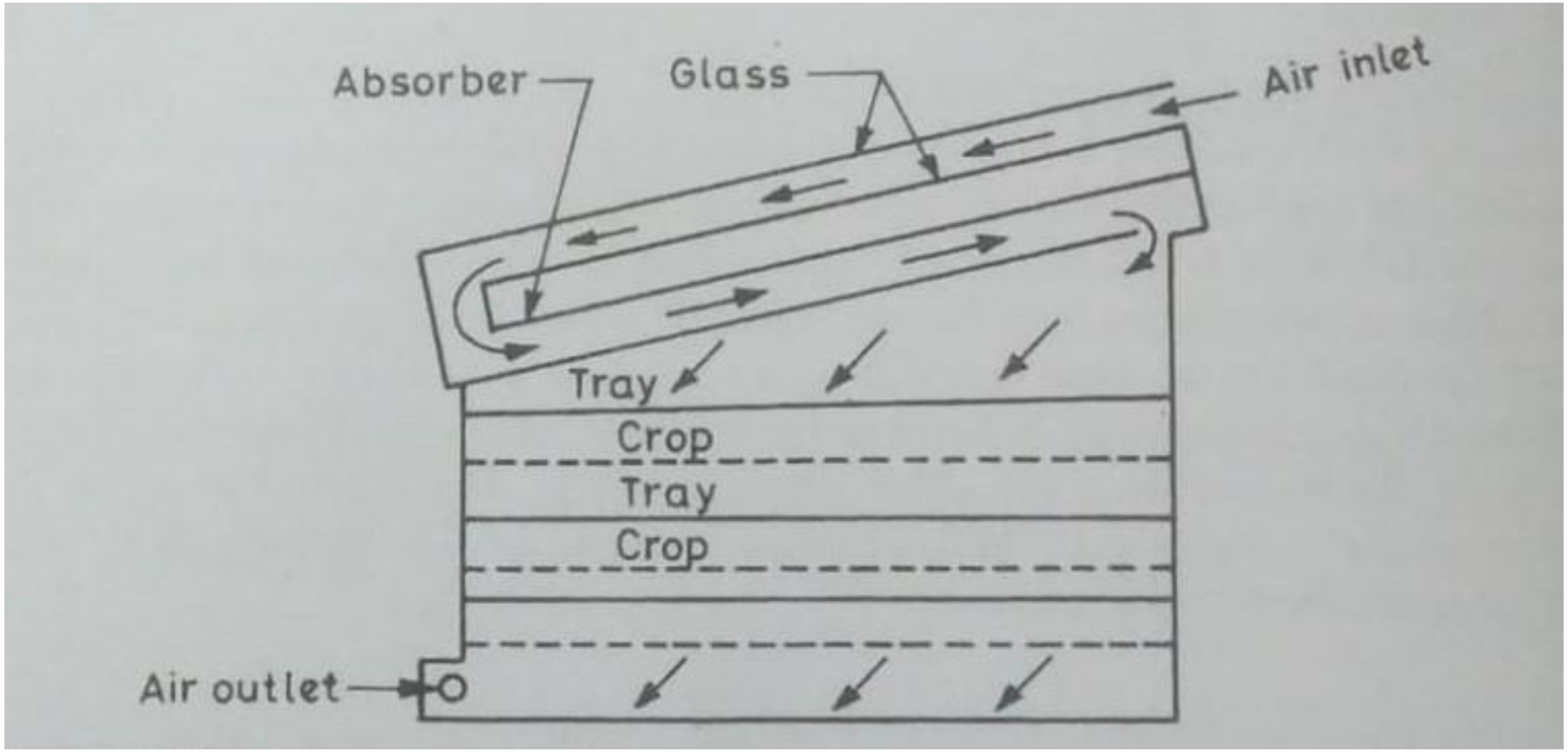


Application of air flat plate collector

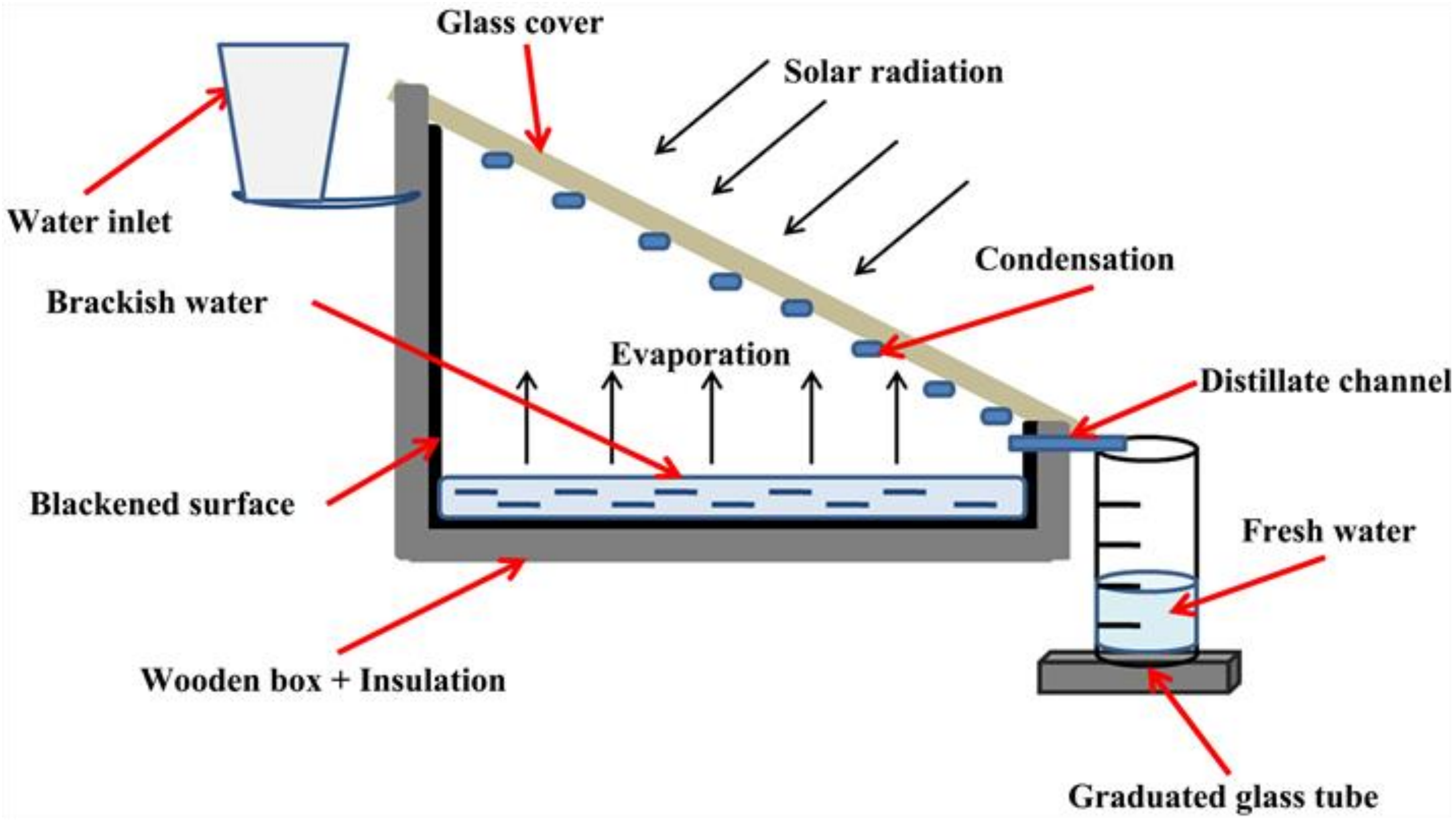
Indirect Crop dryer



Two pass air heater with drying unit



Solar still

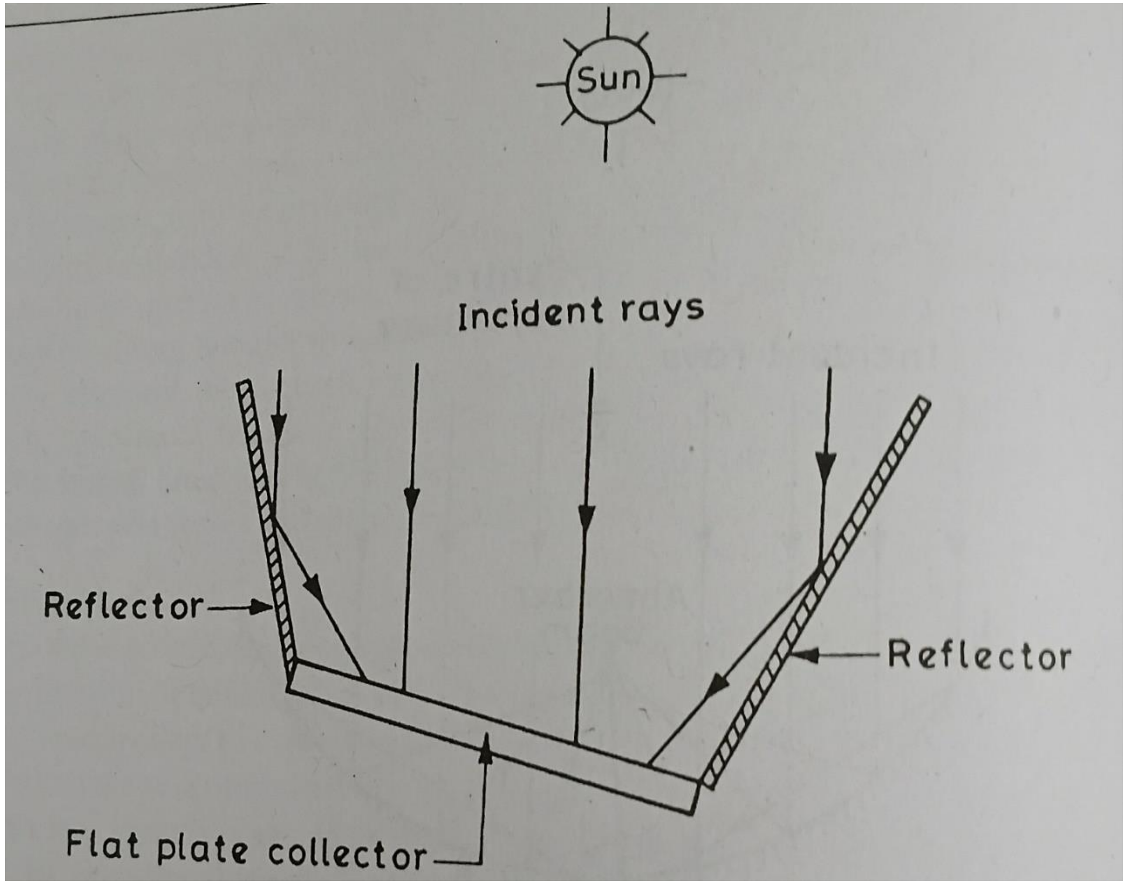


Glass cover
Solar radiation
Water inlet
Condensation
Brackish water
Evaporation
Distillate channel
Blackened surface
Fresh water
Wooden box + Insulation
Graduated glass tube

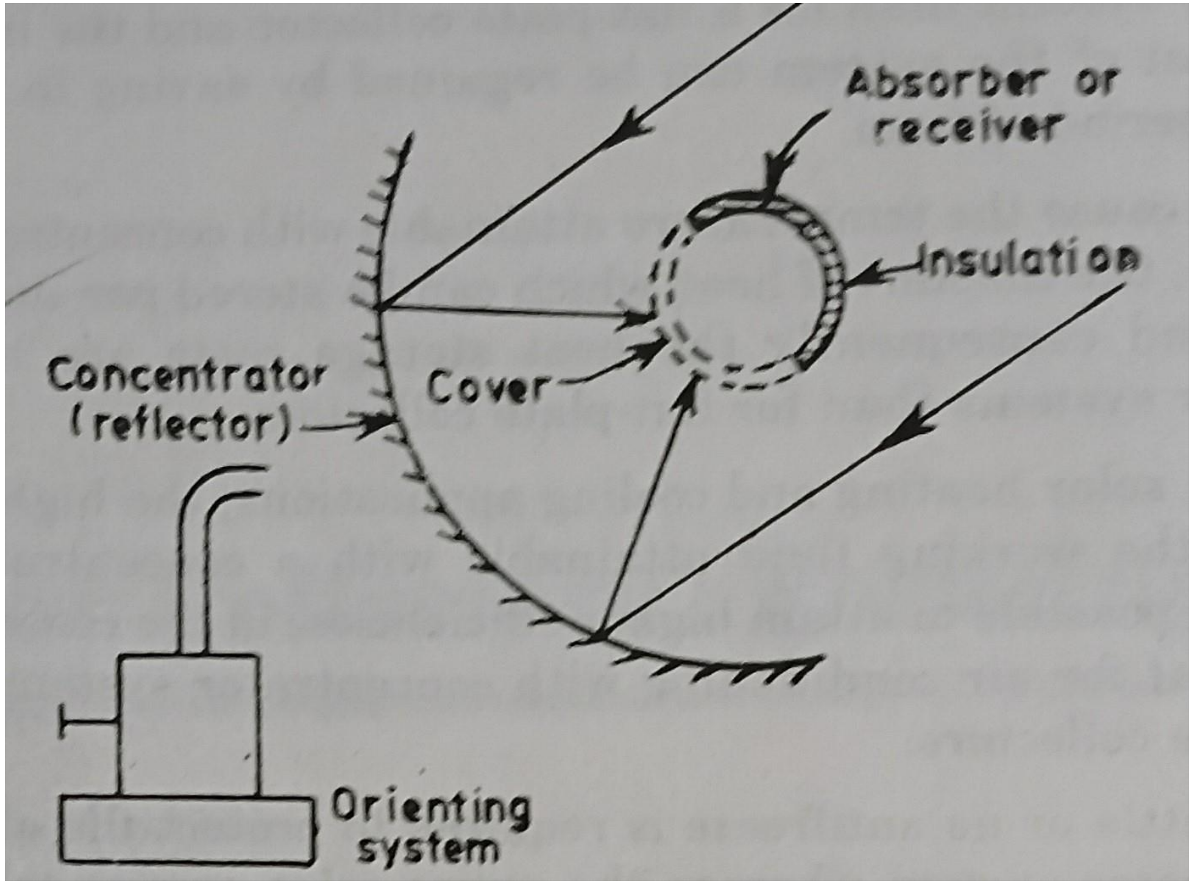
Module III
Concentrating Collectors

Types of collectors

- Low temperature cycle using Flat plate collectors (50 C – 90 C)
- Concentrator collector for medium temperature (150 – 400 C)
- Power tower concept for high temperature   (600 C – 900 C)



Flat plate collector with Reflectors

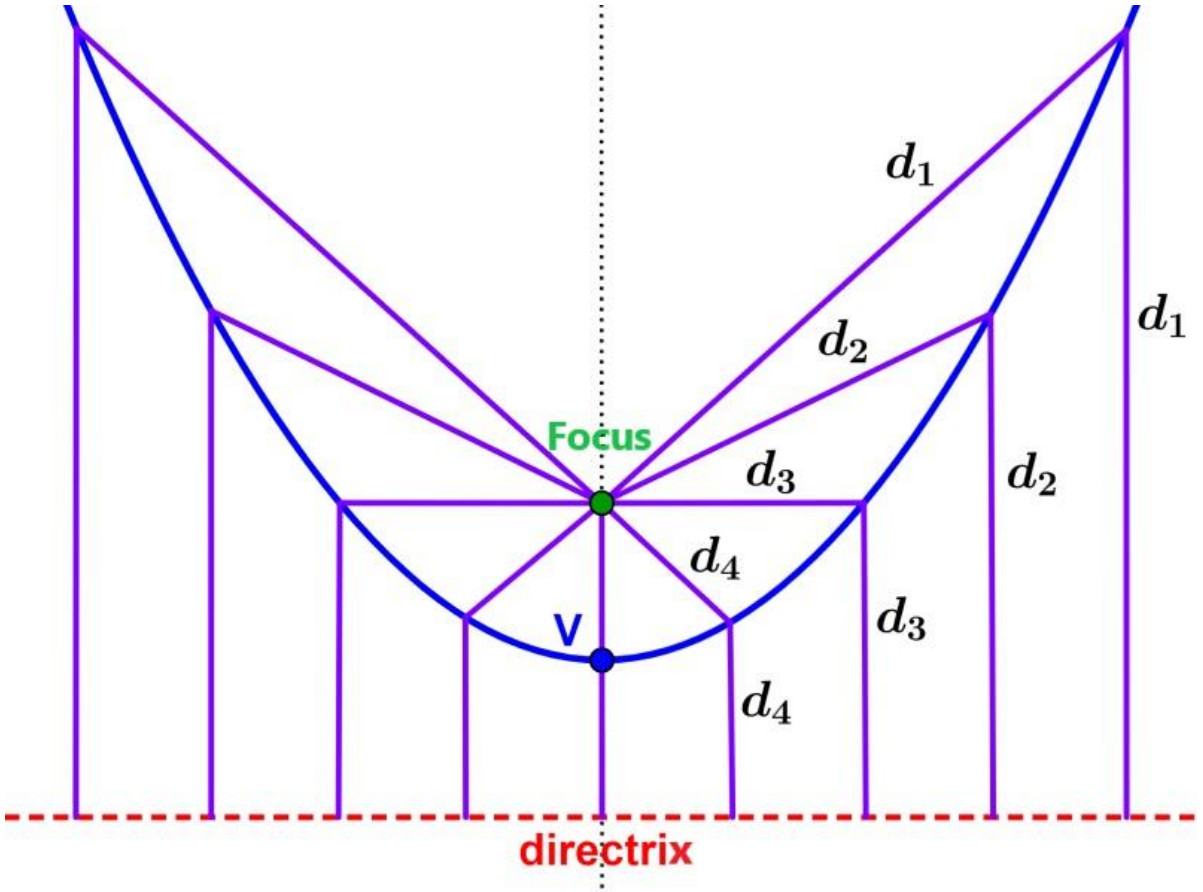


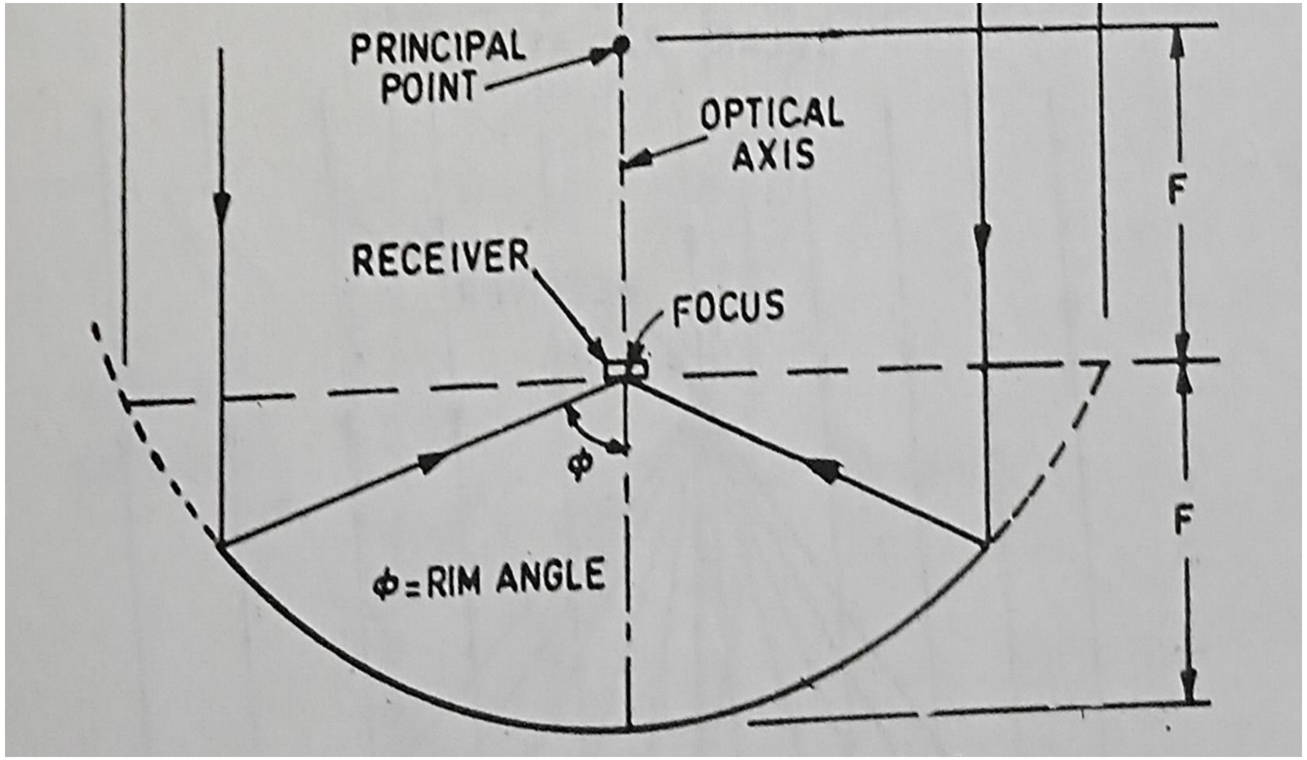
Concentrating collector

Advantages of concentrating type collector

- Smaller absorber area with higher concentration
- Less material requirement and easier fabrication
- Reduced heat loss
- Ideal for power generation
- Heat stored per unit volume is higher

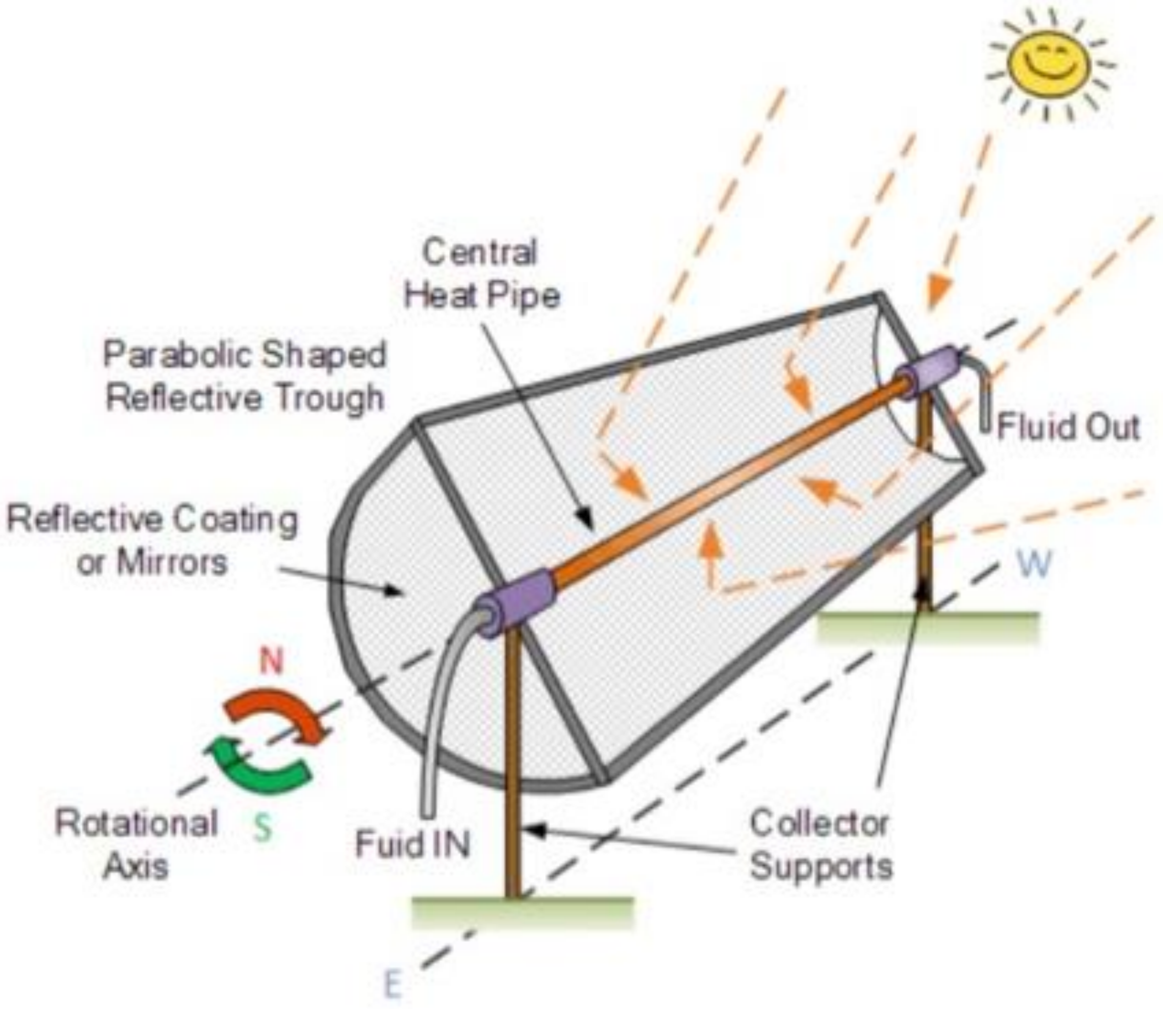
Geometry of parabola



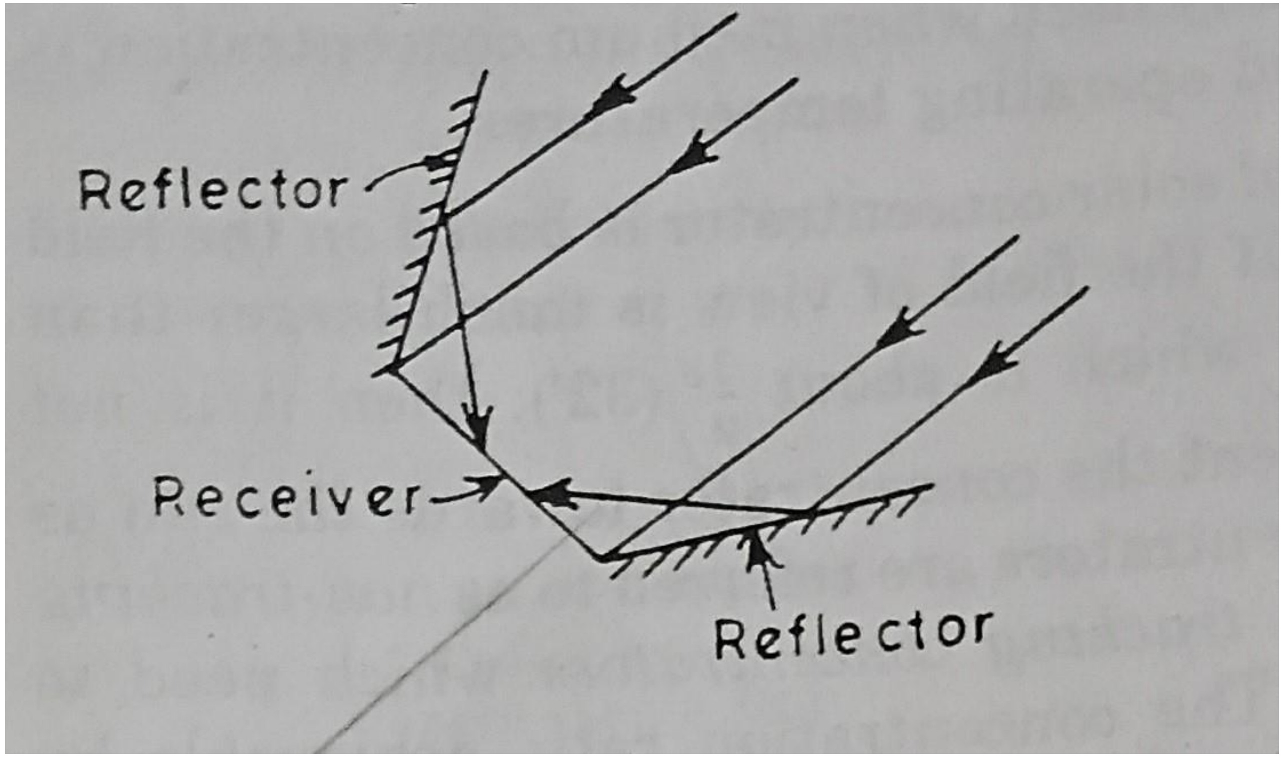


$$Concentration\ ratio\ \mathrm{CR} = \frac{Area\ of\ the\ aperture}{Area\ of\ the\ receiver}$$

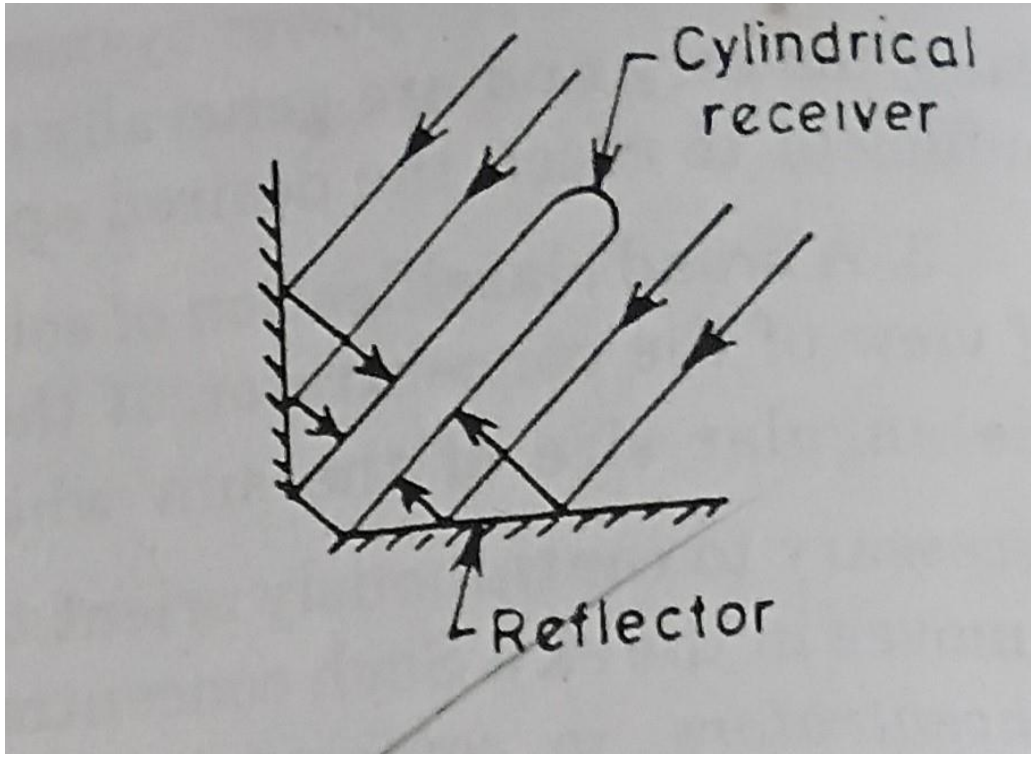
Concentrating collector



Focusing configurations

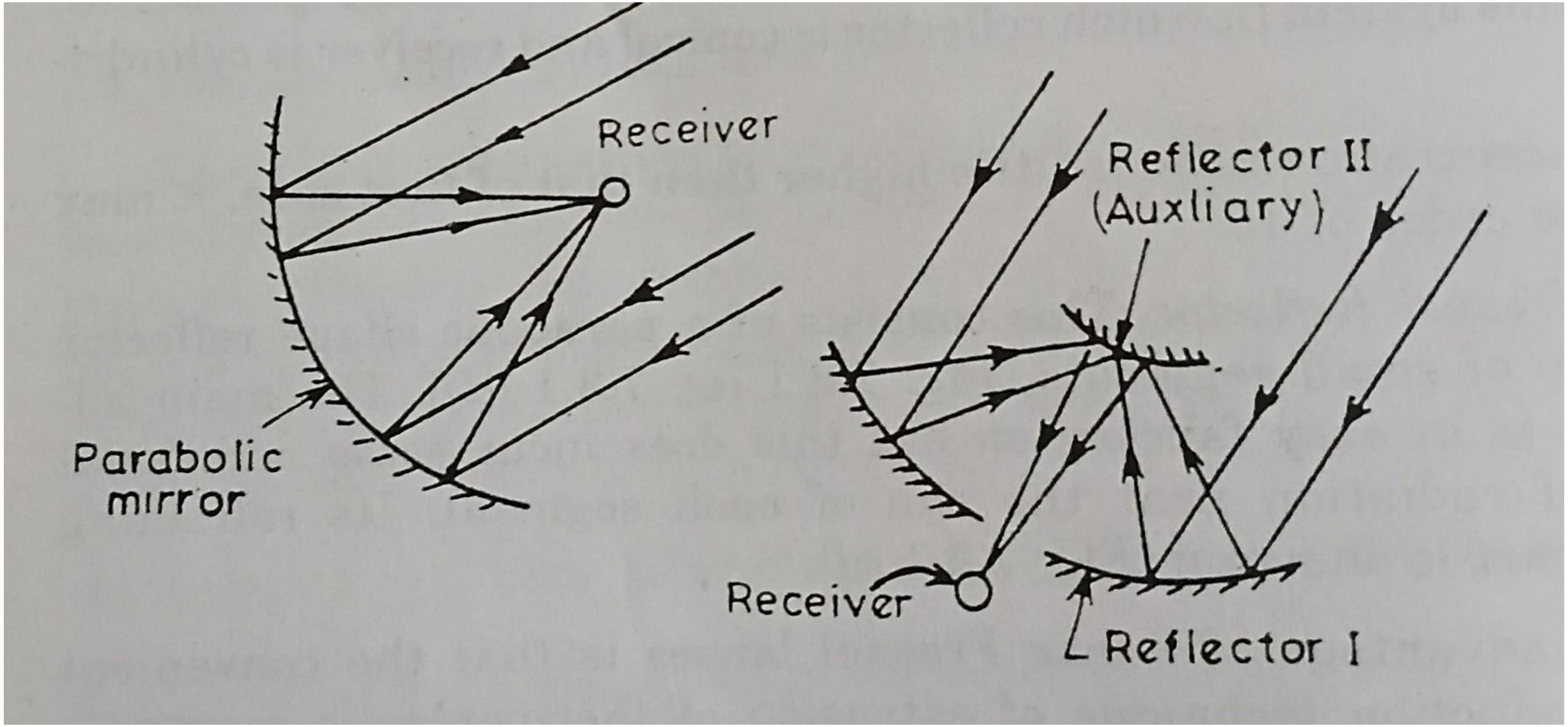


Plane reflector



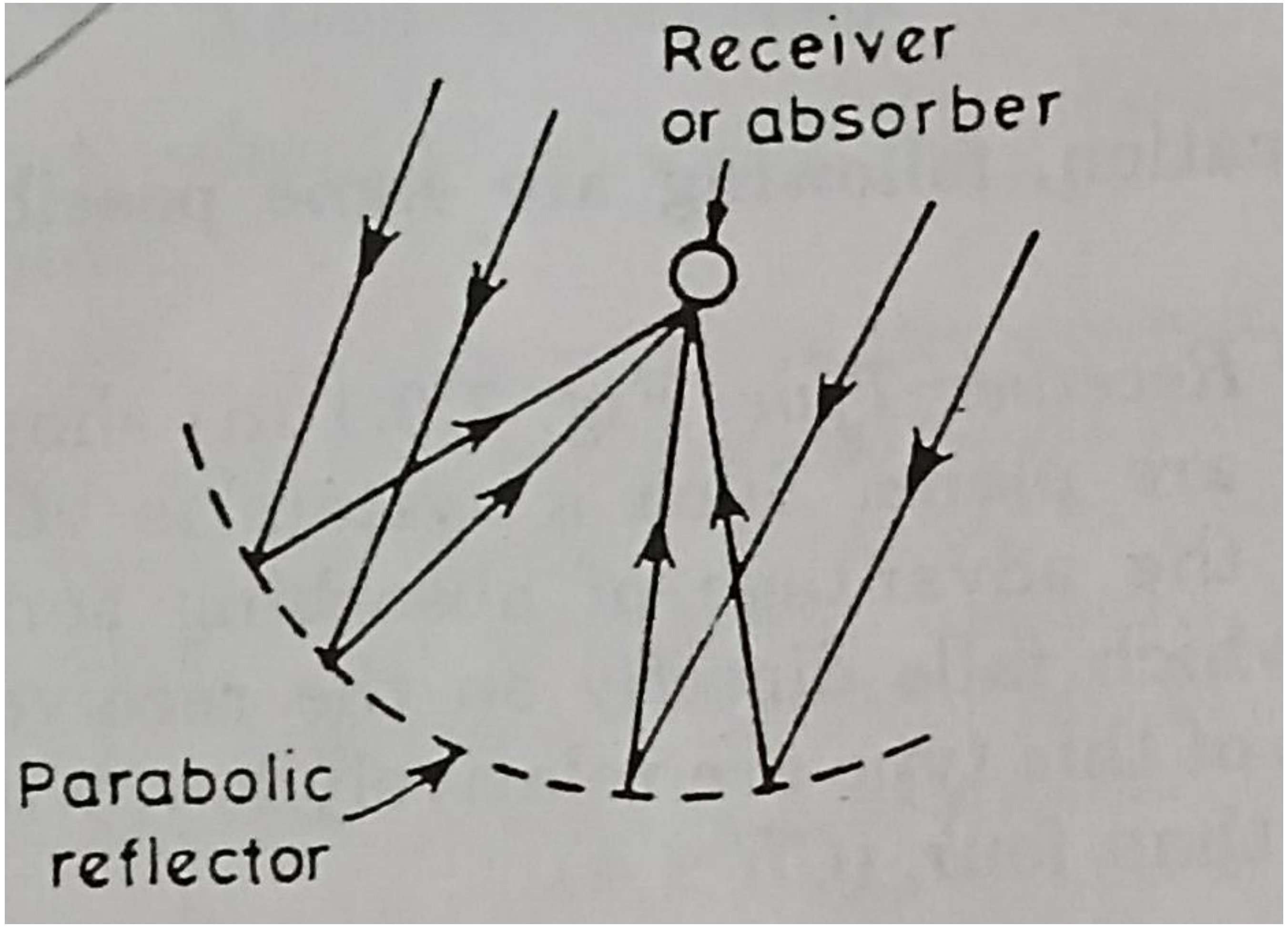
Conical reflector

Focusing configurations



Parabolic system

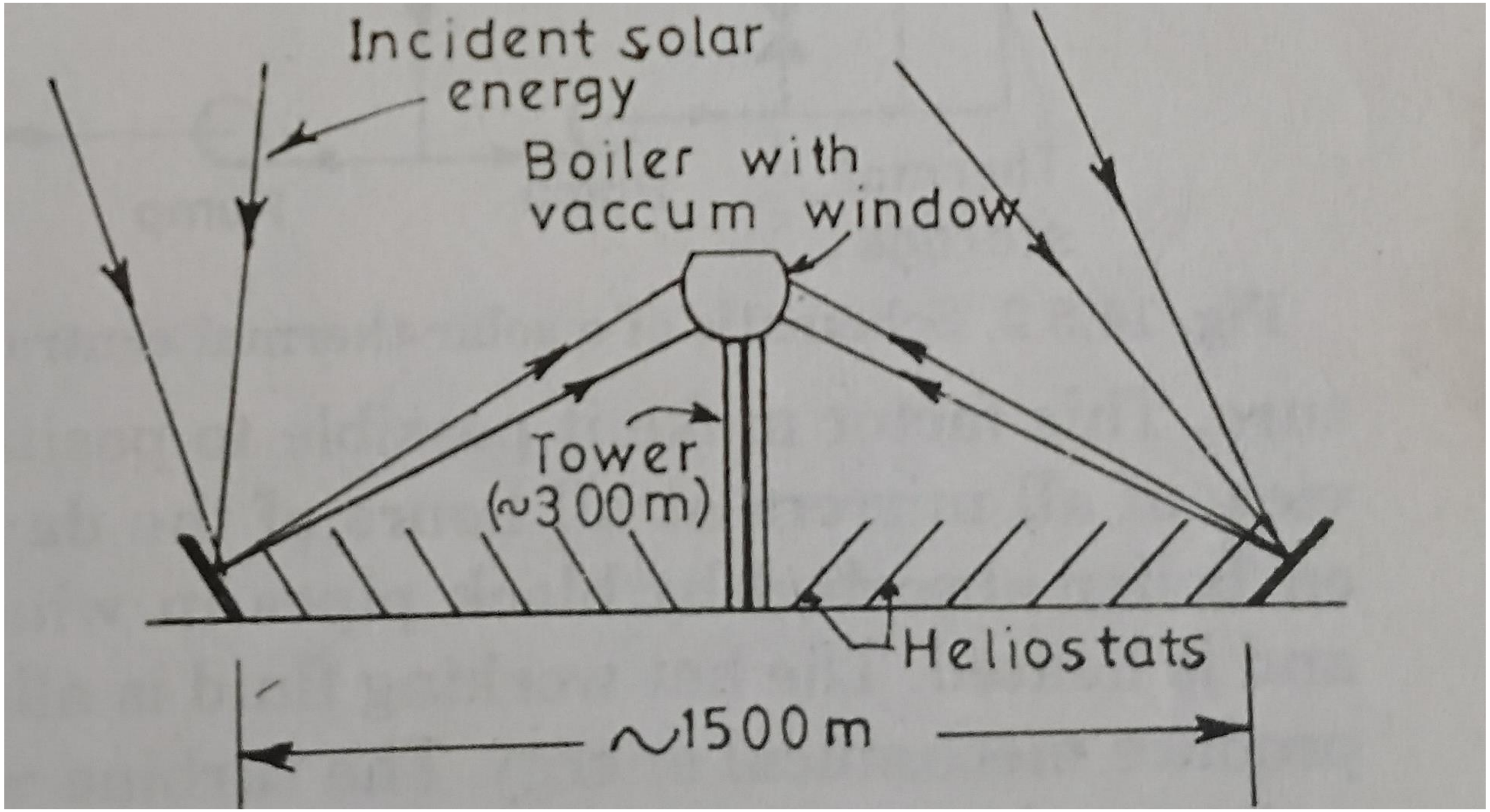
Focusing configurations



Fresnel reflector

Concentrating type collector

Tower collector



Tower solar power Plant

Tower solar power Plant

Solar Thermal Energy storage

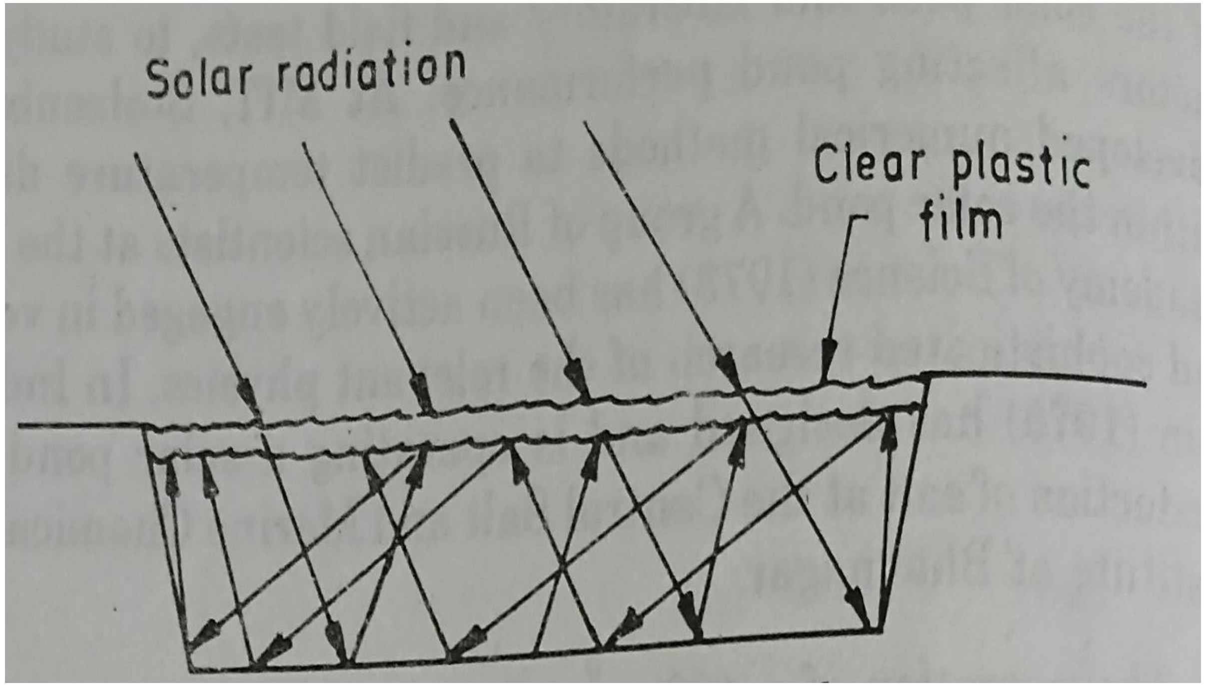
- Solar Pond
- Sensible heat storage
- Latent heat storage
- Fuel cells
- Thermochemical storage

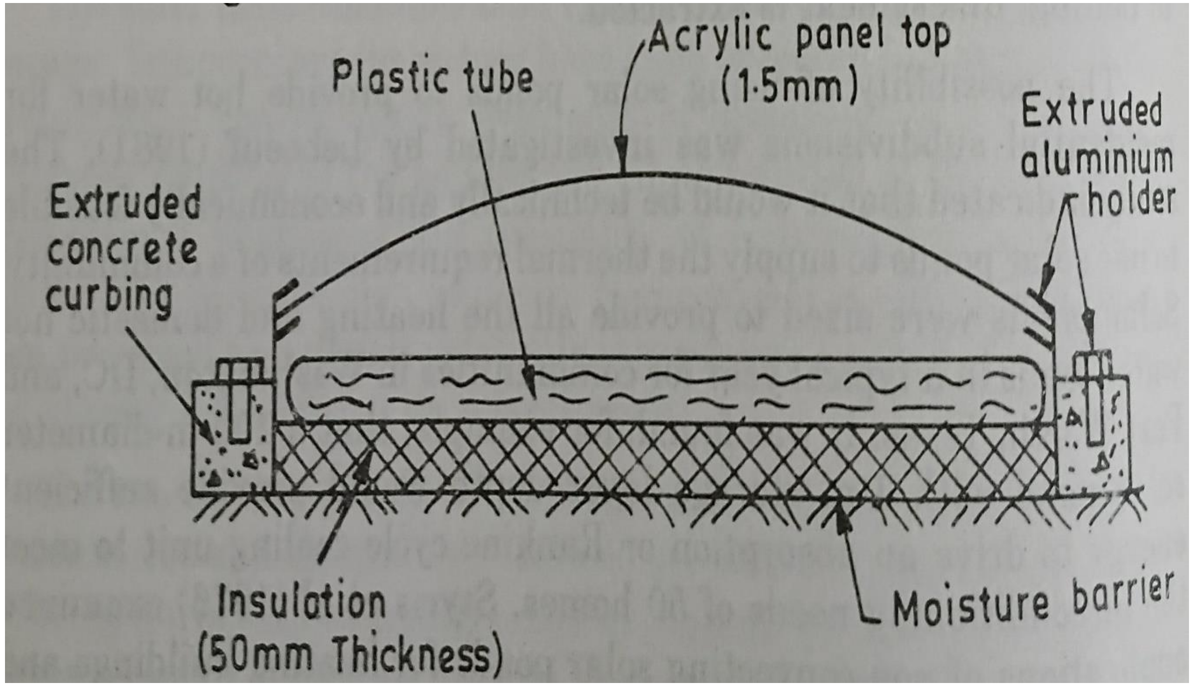
Solar Thermal Energy storage

Solar Pond

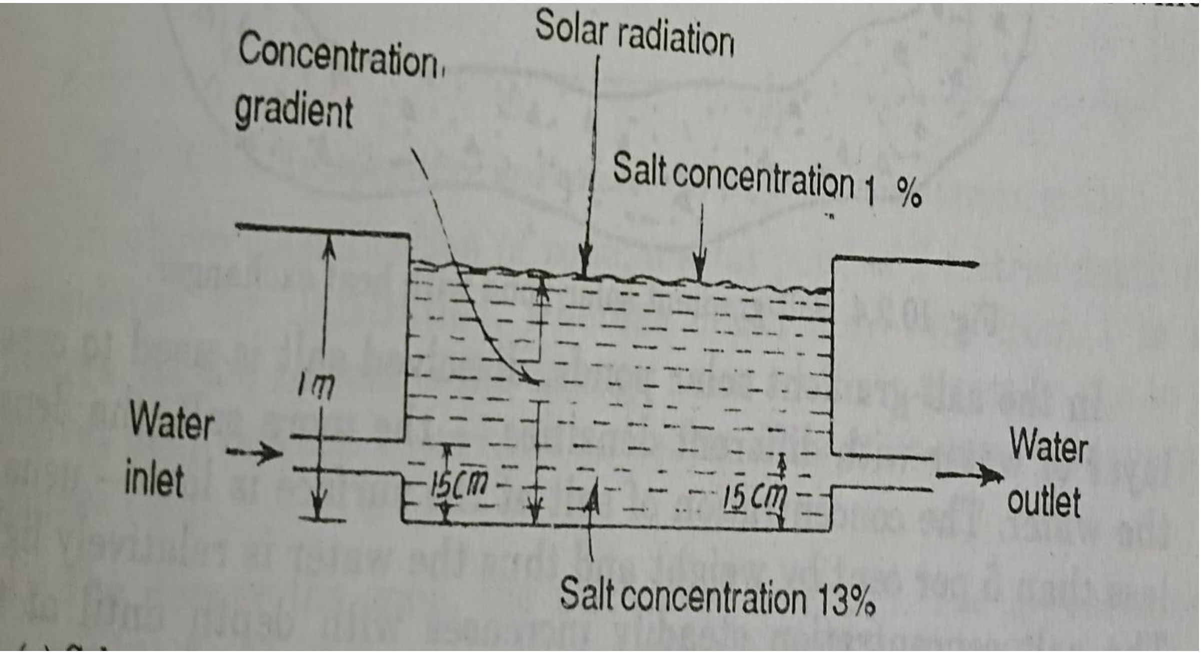
- Convective solar pond
- Non convective solar pond

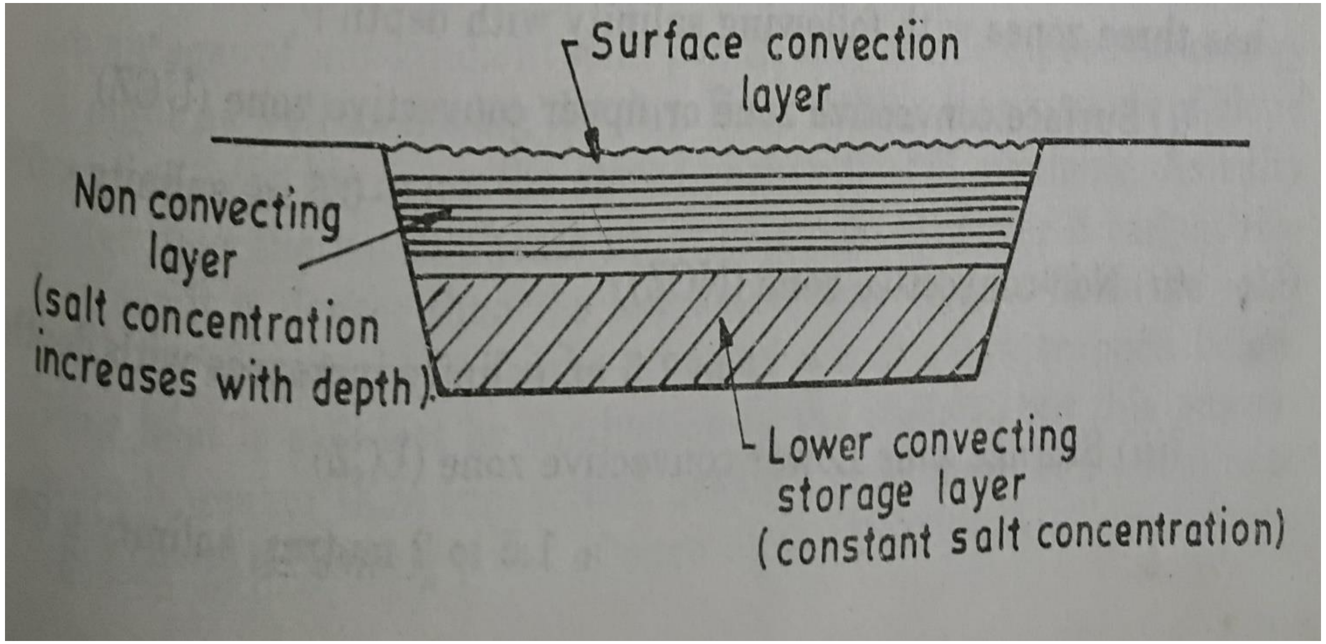
Convective Solar Pond



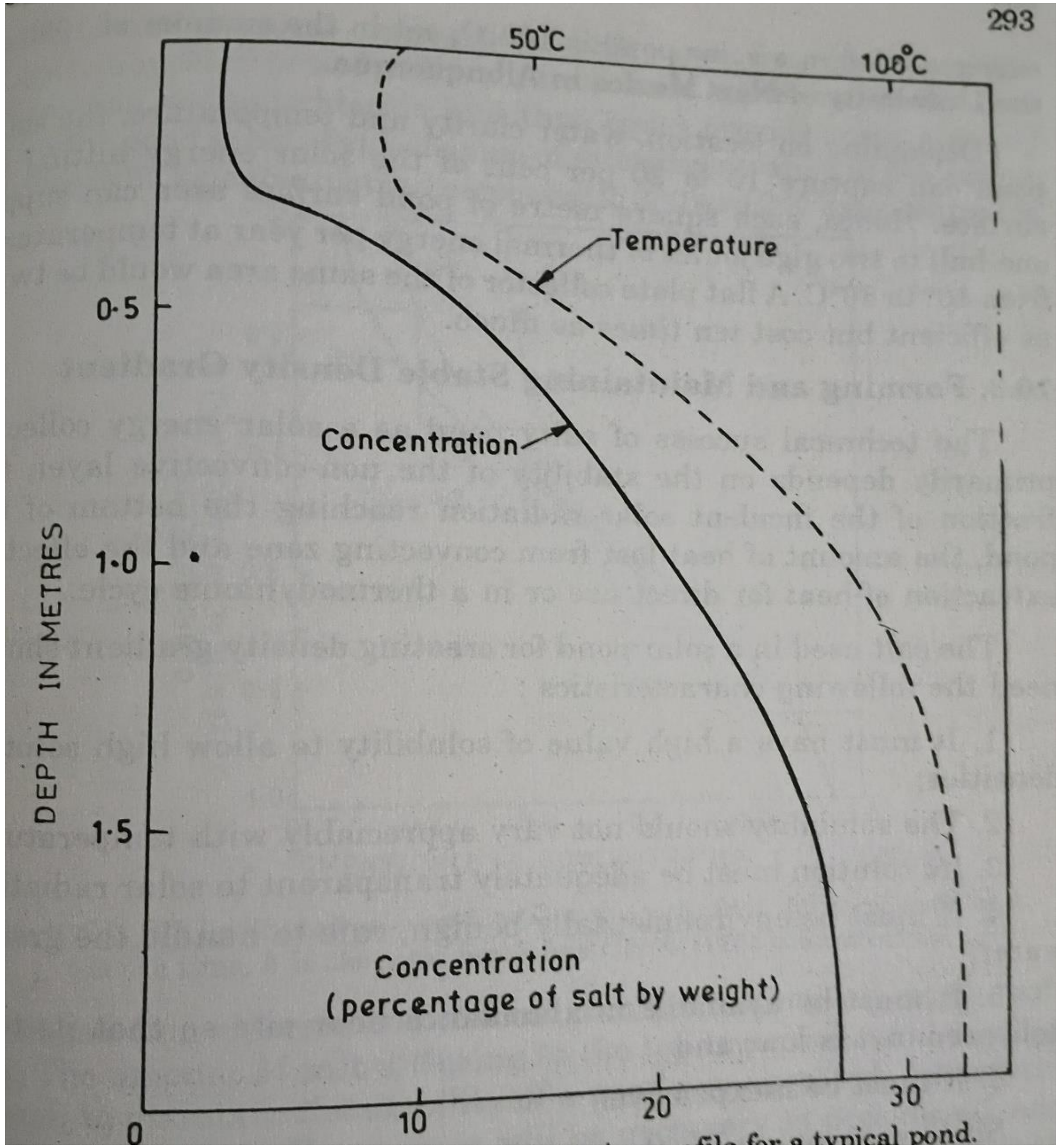


Non convective solar pond

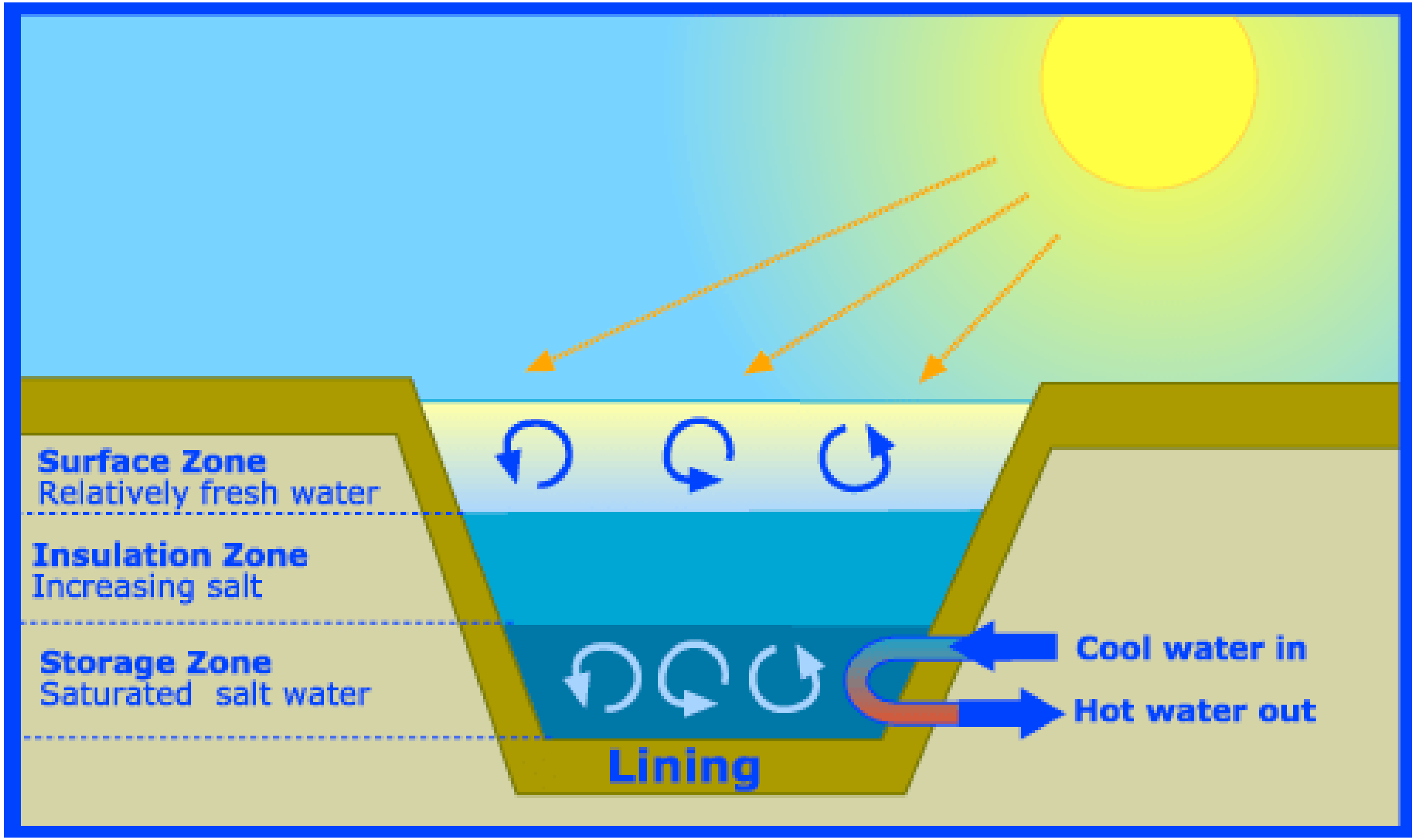




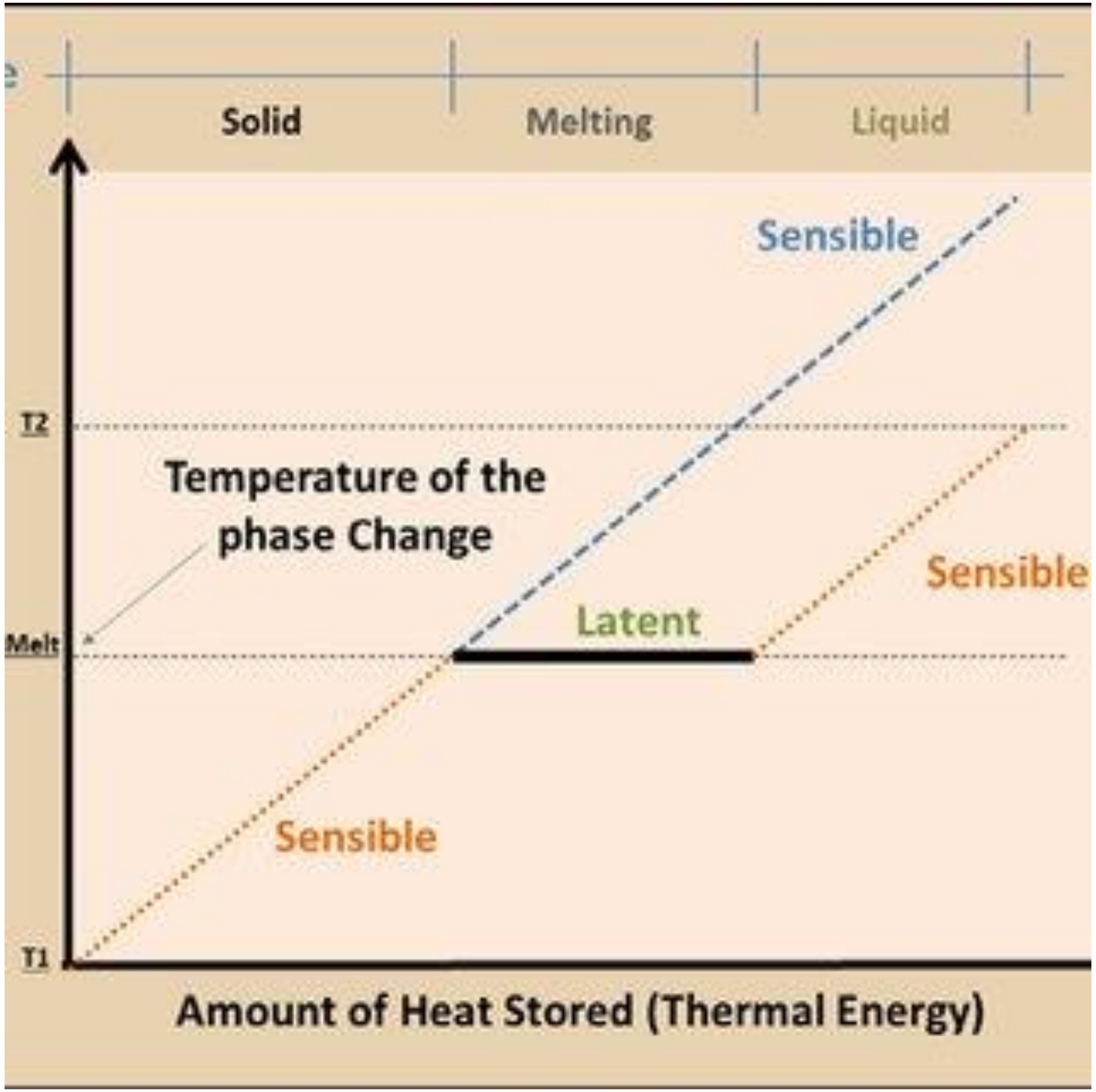
Temperature concentration profile for non convective solar pond



Solar pond


Surface Zone
Relatively fresh water
Insulation Zone
Increasing salt
Storage Zone
Saturated salt water
Lining
Cool water in
Hot water out

Sensible and Latent heat storage



Sensible heat storage

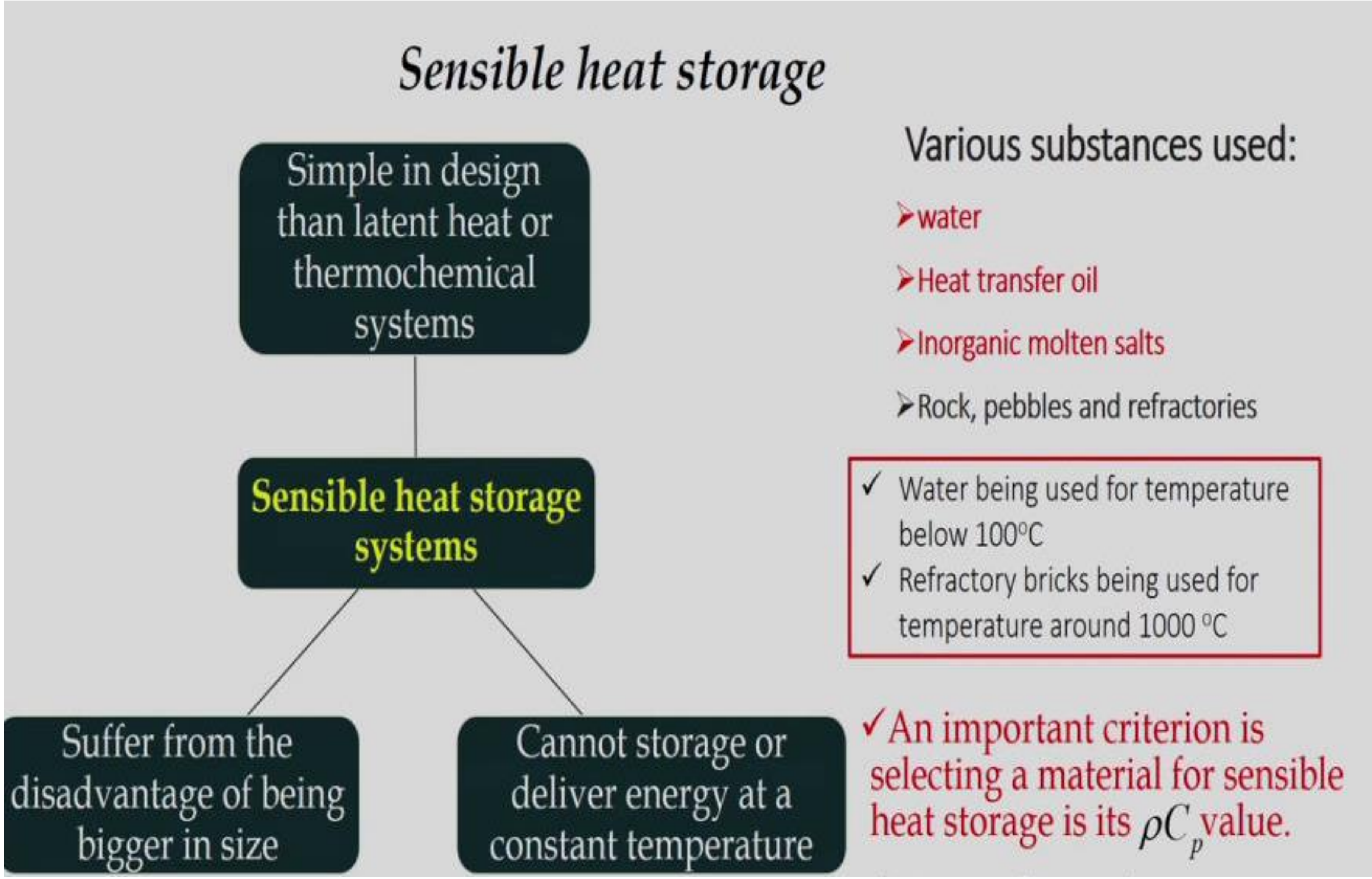
$$E = m\int_{T_1}^{T_2} C_p\, dt$$

Latent heat storage

$$E = mL$$

$$E = m\int_{T_1}^{T'} C_p\, dt + mL + m\int_{T'}^{T_2} C_p\, dt$$

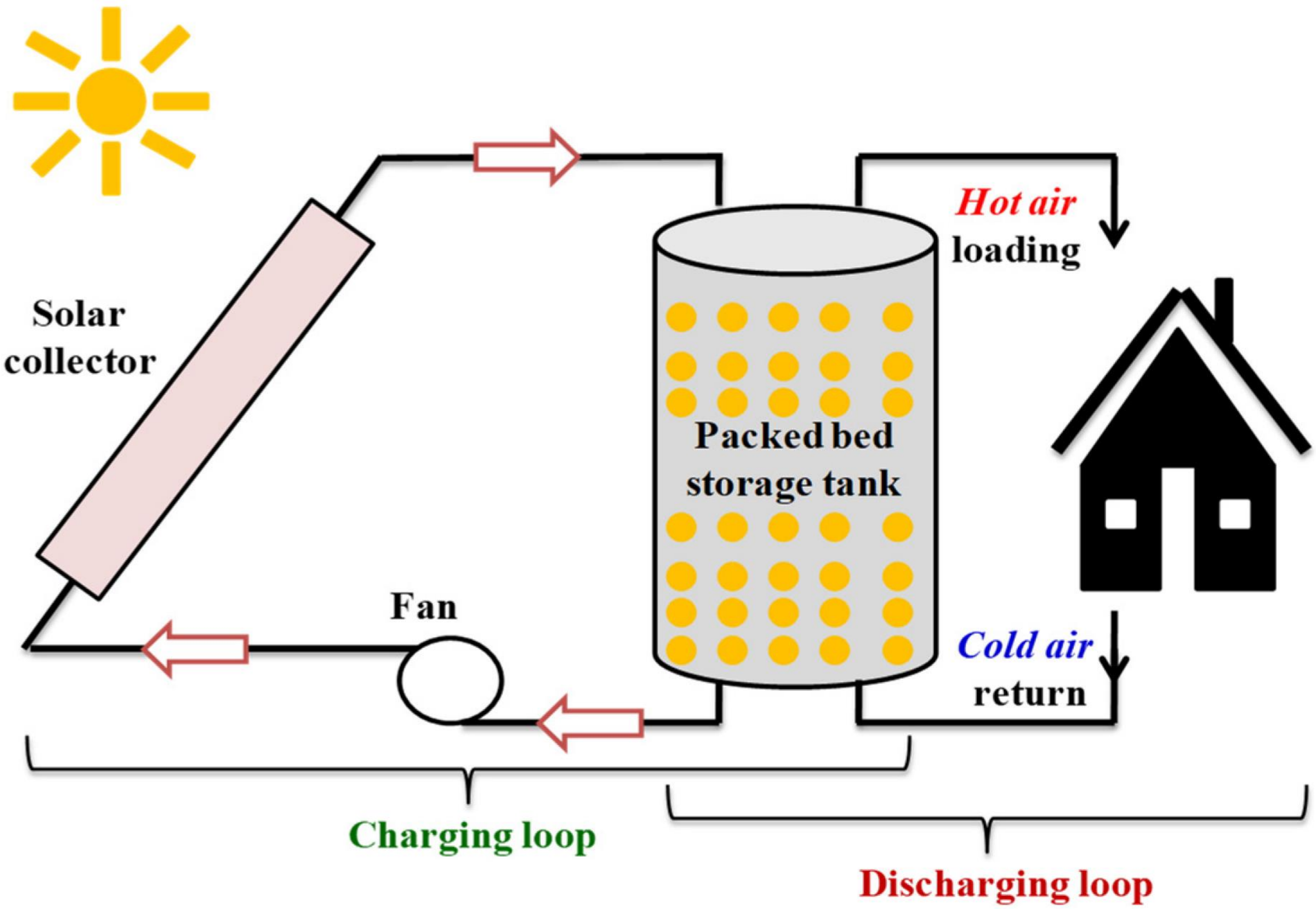
Sensible heat storage



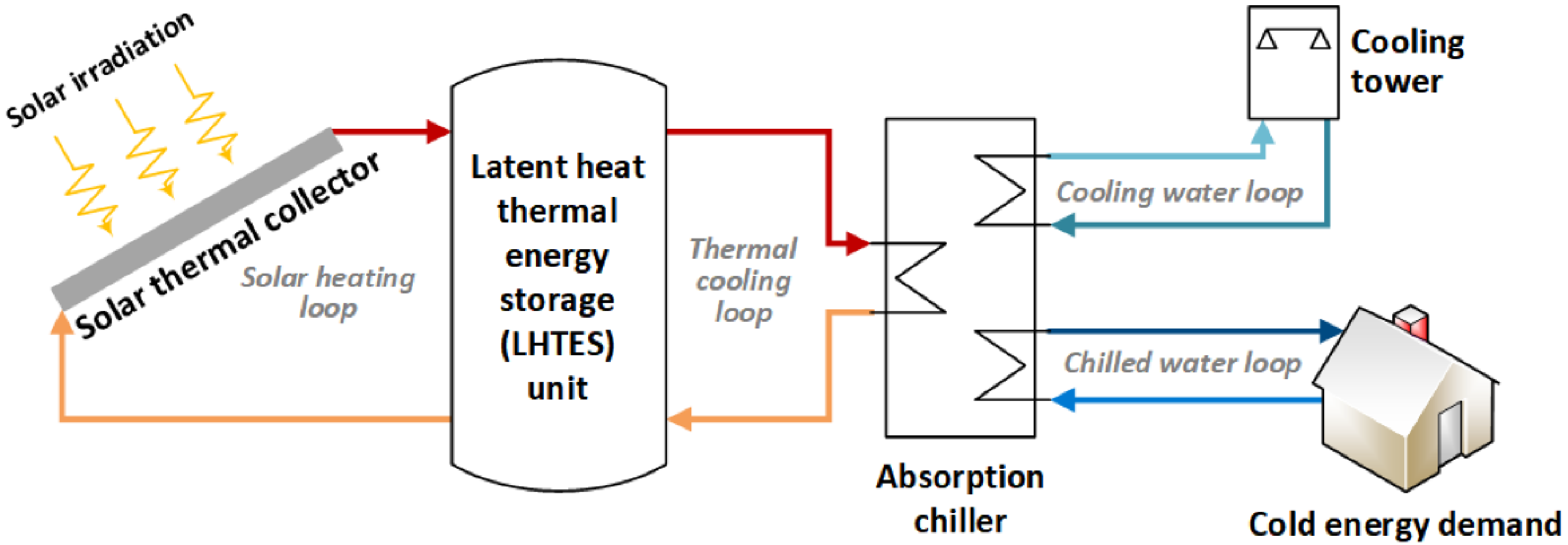
Sensible heat storage materials

Materials	Specific heat kJ/ kg. K	Density kg/ m^3	Volumetric specific heat kJ/ m^3. K
Adobe	1.0	1700	1700
Aluminum	0.896	2700	2420
Brick	0.84	1920	1600
Concrete	0.92	2240	2100
Fiberglass Batt insulation	0.71-0.96	5-30	4-30
Polyurethane Board insulation	1.6	24	38
Rock pebbles	**0.88**	**1600**	**1410**
Steel	0.48	7850	3800
Stone(granite)	0.88	2720	2400
Water	**4.18**	**1000**	**4180**
Wood	2.5	510	1300

Sensible heat storage



Latent heat thermal storage system



Properties of PCM

	Compound	Melting temperature (°C)	Heat of fusion (KJ/ kg)	Thermal conductivity (W/ m . K)	Density (kg/ m3)
Inorganic	$MgCl_2.6H_2O$	117	168.6	0.057(liquid, 120 °C) 0.694 (solid, 90°C)	1450 (liquid, 120 °C) 1569 (solid, 20°C)
	$Mg(NO_3)_2.6H_2O$	89	162.8	0.490(liquid, 95 °C) 0.611(solid, 37°C)	1550 (liquid, 94 °C) 1636 (solid, 25°C)
	$Ba(OH_2).8H_2O$	48	265.7	0.653(liquid, 85.7 °C) 1.225(solid, 23°C)	1937(liquid, 84 °C) 2070(solid, 24°C)
	$CaCl_2.6H_2O$	29	190.8	0.540(liquid, 38.7 °C) 1.088(solid, 23°C)	1562(liquid, 32 °C) 1802(solid, 24°C)
Organic (paraffin)	Paraffin wax	64	173.6	0.167 (liquid, 63.5 °C) 0.346(solid, 33.6°C)	790(liquid, 65 °C) 916(solid, 24°C)
	Polyglycol E600	22	127.2	0.189(liquid, 38.6°C)	1126 (liquid, 25 °C) 1232(solid, 4°C)

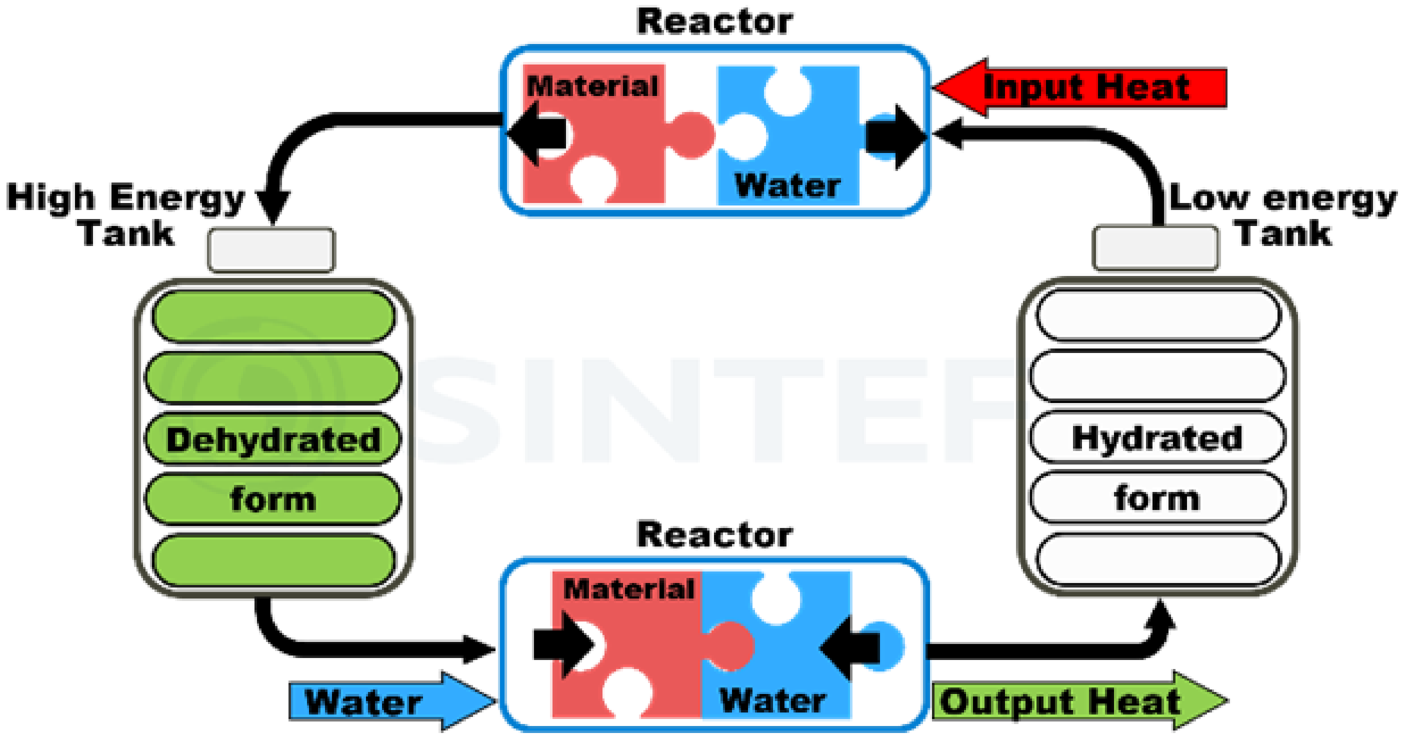
Organic PCM → chemically stable, safe, low thermal conductivity, good for building cooling/heating.

Inorganic PCMs → higher latent heat, better conductivity, cheaper, problems with super cooling

Paraffin and Salt hydrates

Property	Paraffins	Salt Hydrates ($CaCl_2·6H_2O$, $Na_2SO_4·10H_2O$)
Melting Point (°C)	Moderate range (18–70 °C)	Wide range (25–120 °C)
Latent Heat of Fusion (kJ/kg)	Moderate (150–200 kJ/kg)	High (200–350 kJ/kg)
Thermal Conductivity	Very low (~0.2 W/m·K) → needs enhancement (graphite, fins, metal foams)	Higher (~0.5–1 W/m·K), better heat transfer
Vapour Pressure	Very low (safe, minimal losses)	Relatively higher
Volume Change on Phase Change	Small (~10%)	Small to moderate (~10–15%),
Supercooling / Superheating	Negligible (phase change occurs reliably)	significant supercooling
Stability (cycling performance)	Very stable chemically, long cycle life	Can face phase separation, incongruent melting (salt & water separate after many cycles)
Applications	Building cooling/heating, textiles, electronics cooling	Solar thermal storage, industrial heat storage, seasonal storage

Thermochemical storage system



Charging

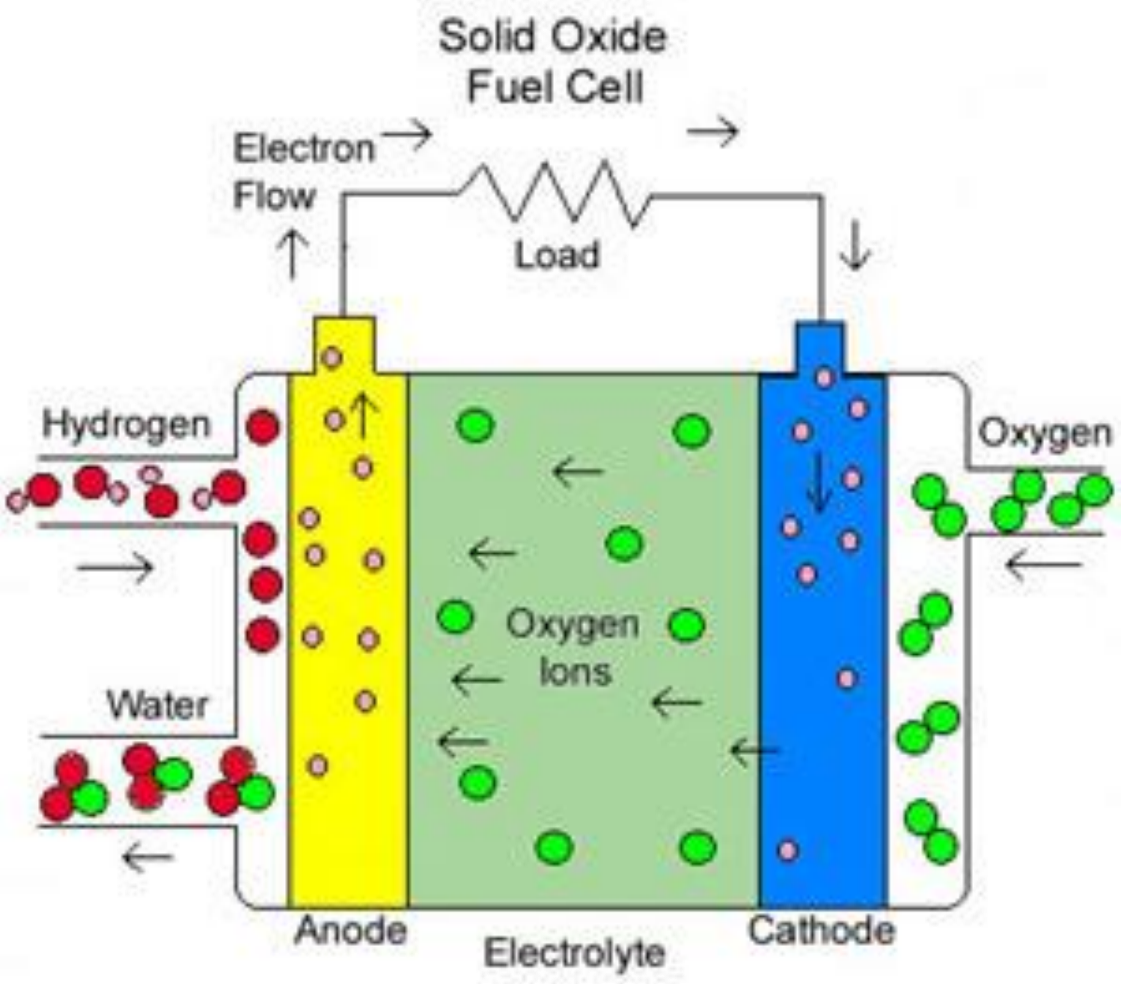
$$\mathrm{Ca}(OH)_2 \overset{\Delta H}{\Rightarrow} CaO + H_2O\ (Steam)$$

Discharging

$$\mathrm{CaO} + H_2O \rightarrow \mathrm{Ca(OH)_2} + \Delta H$$

- **Input Heat (Charging)** → Hydrated material → **Dehydrated + water**
- **Storage (High-Energy Tank)** → Stable dehydrated material holds chemical energy.
- **Adding Water (Discharging)** → Releases stored energy as useful heat.
- **Low-Energy Tank** → Hydrated form is ready for next cycle.

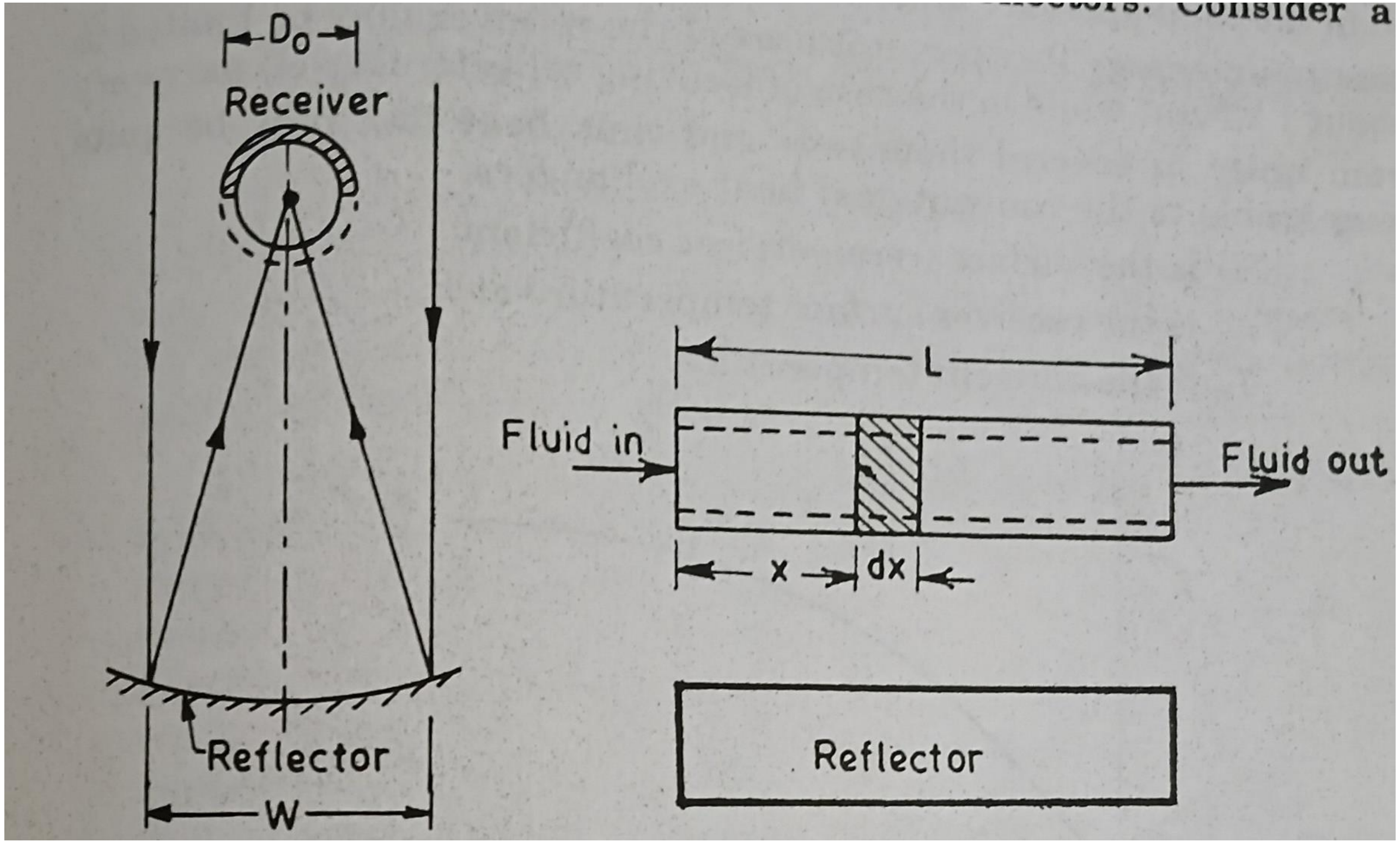
Fuel cell



Solid Oxide
Fuel Cell
Electron
Flow
Load
Hydrogen
Oxygen
Water
Oxygen
Ions
Anode
Electrolyte
Cathode

Performance of concentrating collector

Concentrating Collector tube design



Energy balance Equation

$$Q_u = F_R\ \left[A_a HR\,\rho\,\gamma\,(\tau\alpha)_e - A_r\,U_L(T_{fi} - T_a)\right]$$

- $Q_u = Useful\ energy\ deliverd\ by\ the\ collector\ , W$
- $A_a\ = Aperture\ area, m^2$
- $A_r\ = Receiver\ area, m^2$
- $H = Rate\ of\ incident\ beam\ per\ unit\ area\ of\ upper\ surface, W/m^2$
- $R = Factor\ to\ convert\ beam\ or\ diffuse\ radiation\ to\ that\ plane\ of\ the\ collector$
- $T_{fi} = Inlet\ temperature\ of\ fluid, C$
- $T_a = Atmospheric\ temperature, C$
- γ = Intercept factor
- $(\tau\alpha)_e = Effective\ transmittance\ absorptance\ product$
- $(\tau\alpha)_e = \frac{\tau.\alpha}{1-(1-\alpha)\,\rho}$

Collector efficiency Factor

$$F' = \frac{U_0}{U_L}$$

- $U_0 = Over\ all\ heat\ transfer\ coefficient\ between\ receiver\ fluid\ and\ surroundings, W/m^2K$
- $U_L = Over\ all\ heat\ transfer\ coefficient\ between\ absorber\ surface\ and\ surroundings, W/m^2K$

Heat Removal Factor

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

Useful heat Energy

$$Q_u = \dot{m}\, C_p(T_{fo} - T_{fi})$$

Collector efficiency

$$\eta = \frac{heat\ energy\ gained}{Incident\ solar\ energy}$$

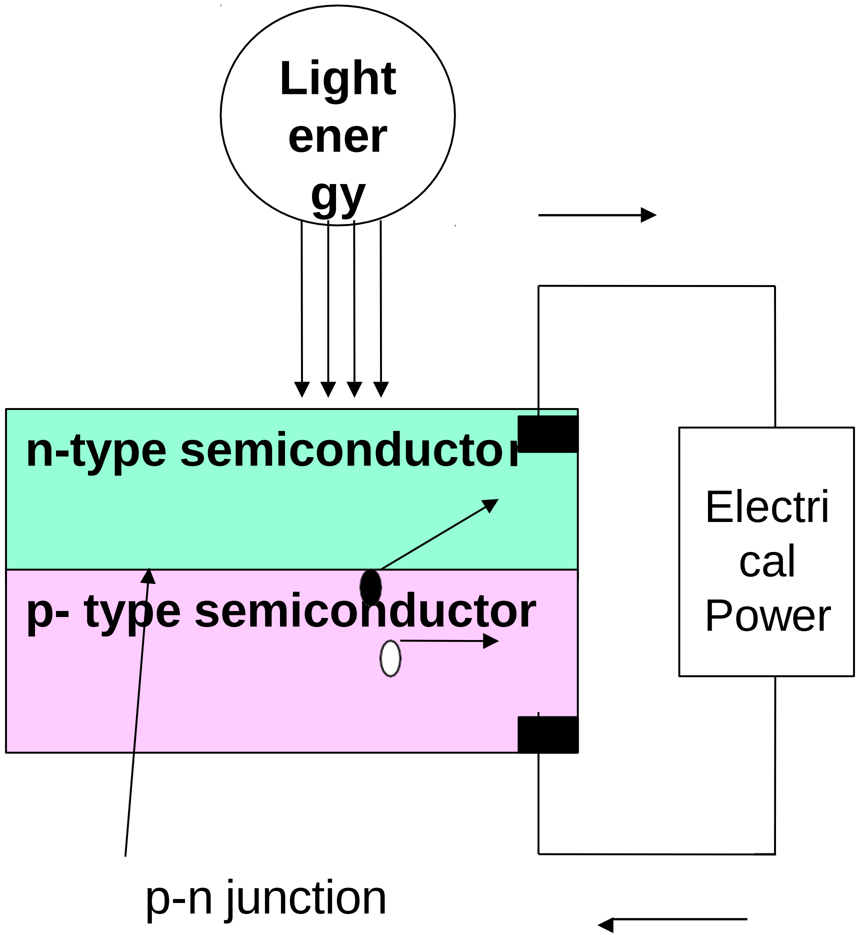
$$\eta = \frac{Q_u}{A_a HR}$$

Module - IV

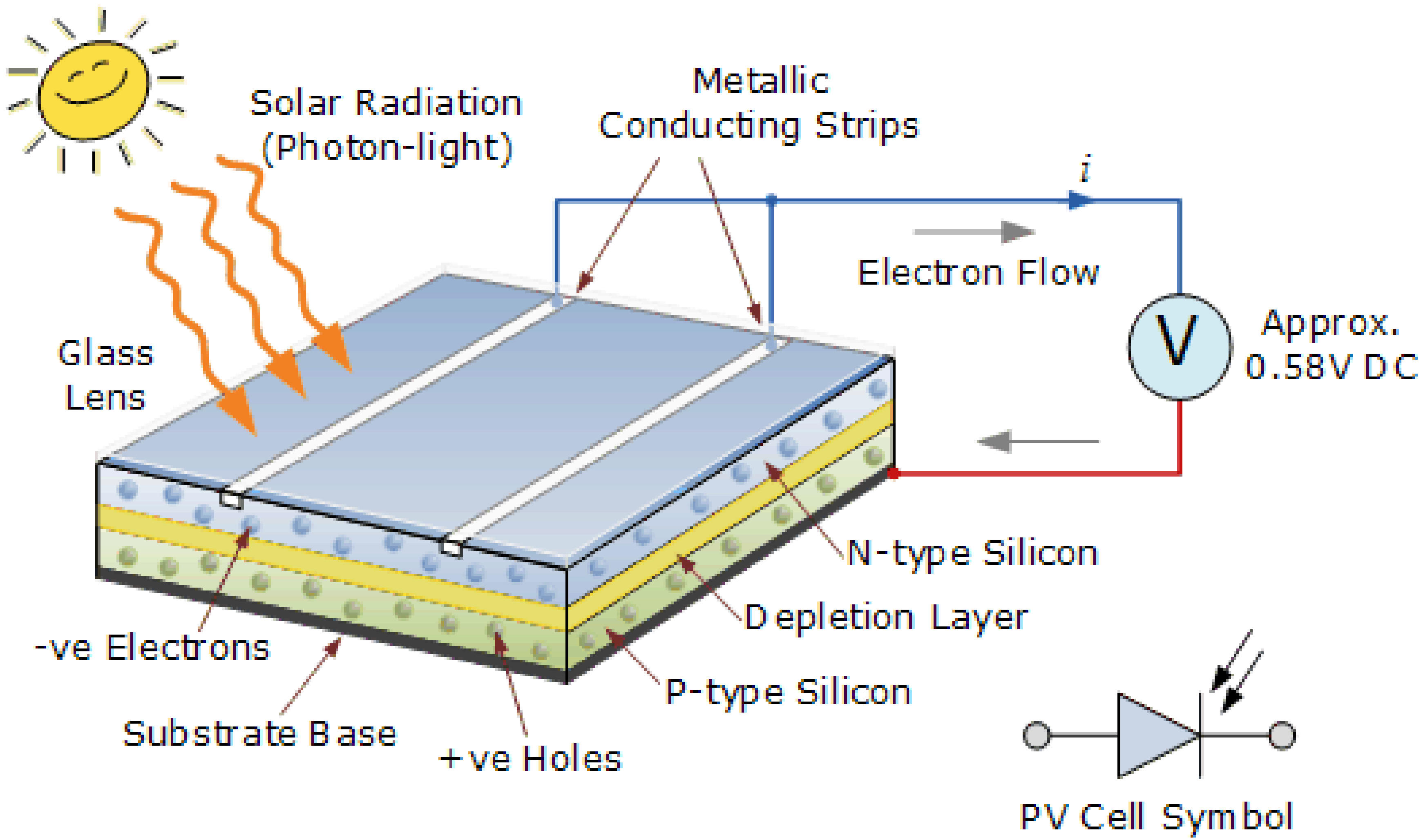
Solar cells

Photovoltaic effect

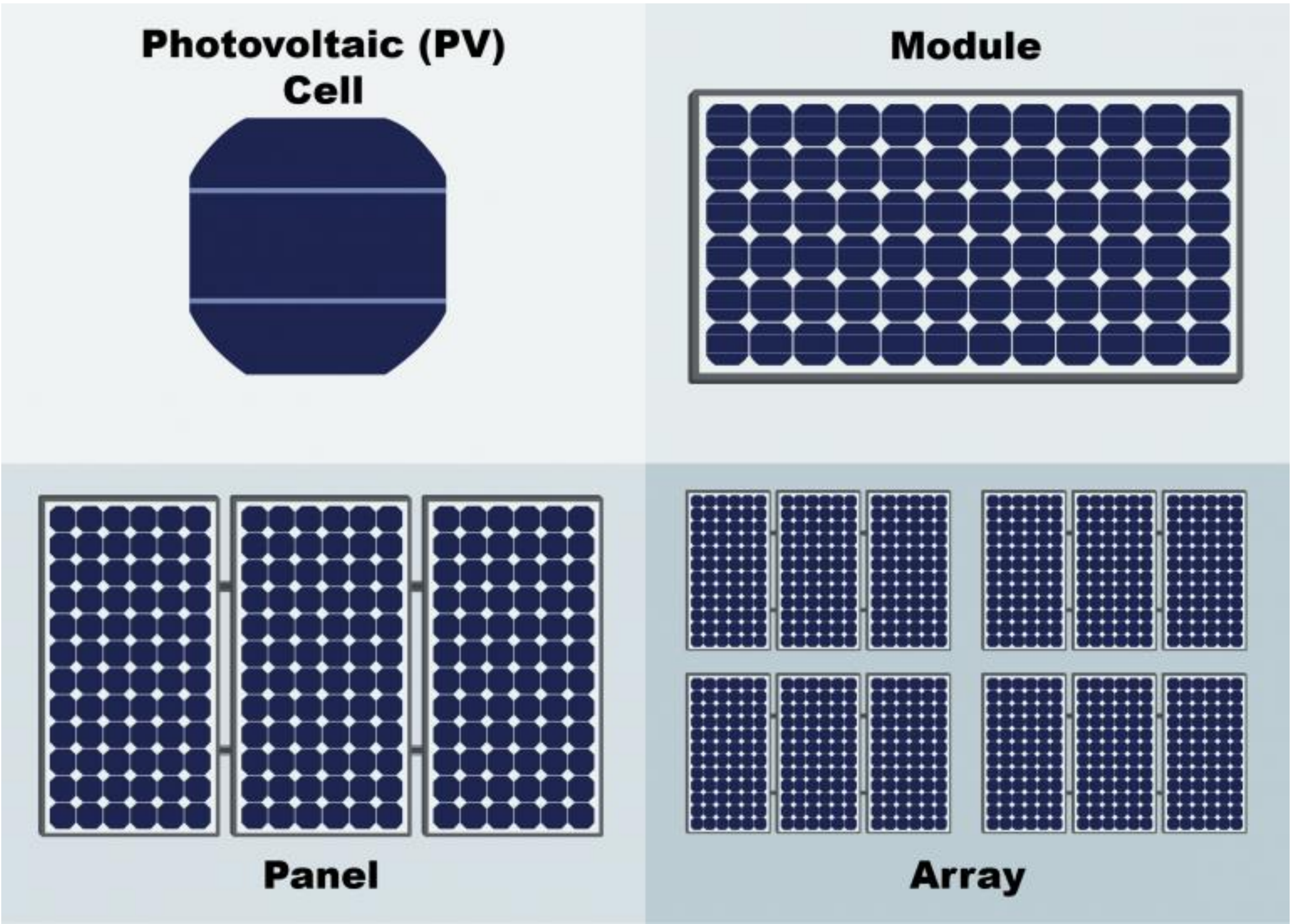
The generation of voltage across the PN junction in a semiconductor due to the absorption of light radiation is called photovoltaic effect. The Devices based on this effect is called photovoltaic device.



Construction of solar cell (PV cell)



PV module and Arrays



PV cell Materials

Silicon

- Most widely used material in PV industry (about 90% of solar cells).
- Abundant in Earth surface
- Non-toxic and long-lasting.
- Requires anti-reflective coating due to high reflection losses.
- Relatively expensive to process.
- Needs encapsulation to reduce surface recombination

Monocrystalline Silicon Cell

- Made from a single, continuous crystal structure.
- Highest efficiency among silicon cells (18–24%).
- Requires more energy and cost to manufacture.
- Longer lifespan (>25 years).
- High fill factor (0.8) → better IV characteristics.
- Higher embodied energy and cost, but lowest degradation rate (0.3%/year).

Polycrystalline Silicon Cell

- Made from multiple small silicon crystals melted together.
- Grain boundaries present → higher recombination losses.
- Lower efficiency (15–18%) compared to monocrystalline.
- Relatively Less cost to produce.
- Slightly shorter lifespan than monocrystalline.
- Cheaper due to casting process.
- Slightly higher temperature coefficient (performance drops more in heat).

Cadmium Telluride

- Most successful thin-film solar technology.
- Cheaper to produce than silicon.
- Concerns about cadmium toxicity.
- Efficiency improving (15-20%).
- Cadmium toxicity and limited Tellurium supply.

Perovskite Materials

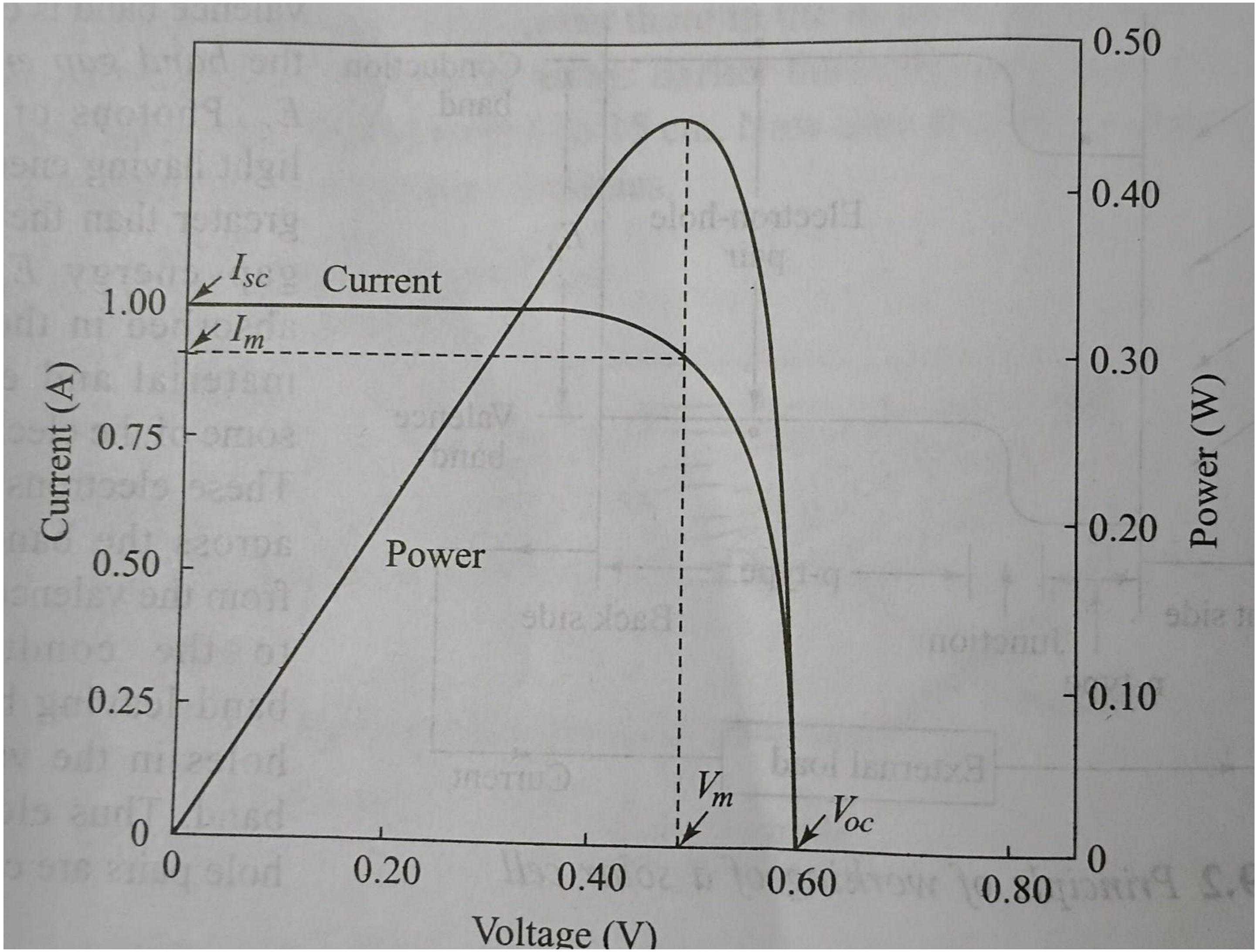
- New generation of PV materials with high efficiency potential (>25%).
- Easy and low-cost to manufacture (solution processable).
- Fabricated by spray coating → low-temperature, low-cost.
- Lightweight and flexible.
- Stability and durability issues (degrades in moisture/heat).
- Can be combined with silicon to form tandem cells.
- Challenges:moisture sensitivity, lead toxicity.

Material comparison

Material	Efficiency Range	Cost	Durability/Stability	Major Limitations
Silicon	15–22%	High	Very stable, long life	Thick, costly process
Monocrystalline Si	18–24%	High	>25 years, very stable	Expensive, energy-intensive
Polycrystalline Si	15–18%	Medium	20–25 years, stable	Grain boundaries, lower efficiency
Cadmium Telluride	15–20%	Low–Medium	Good, but toxic concerns	Cadmium toxicity, Te scarcity
Perovskite	18–25%	Low	Poor (degrades fast)	Instability, Pb toxicity

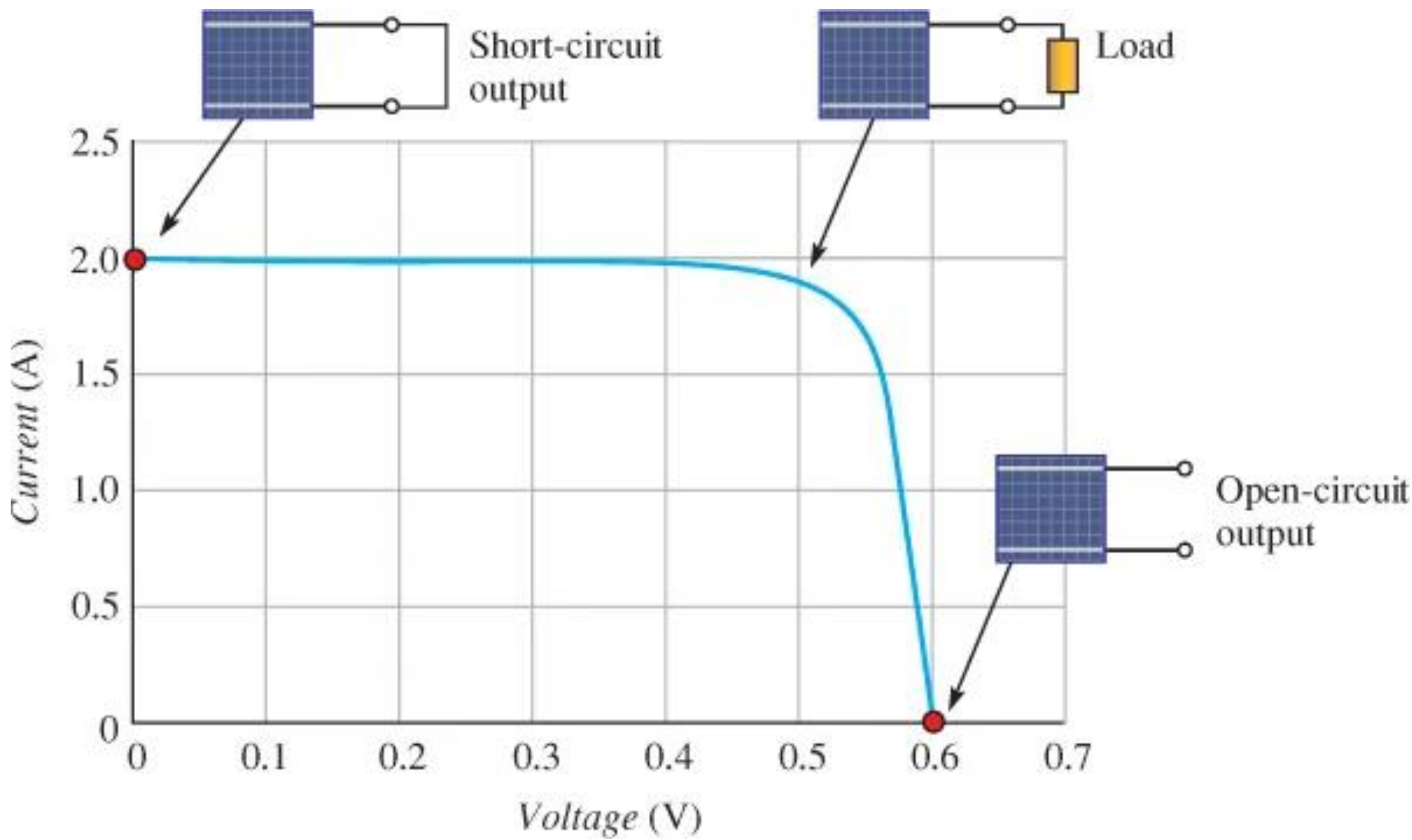
Performance characteristics

Current - voltage (I-V) characteristics

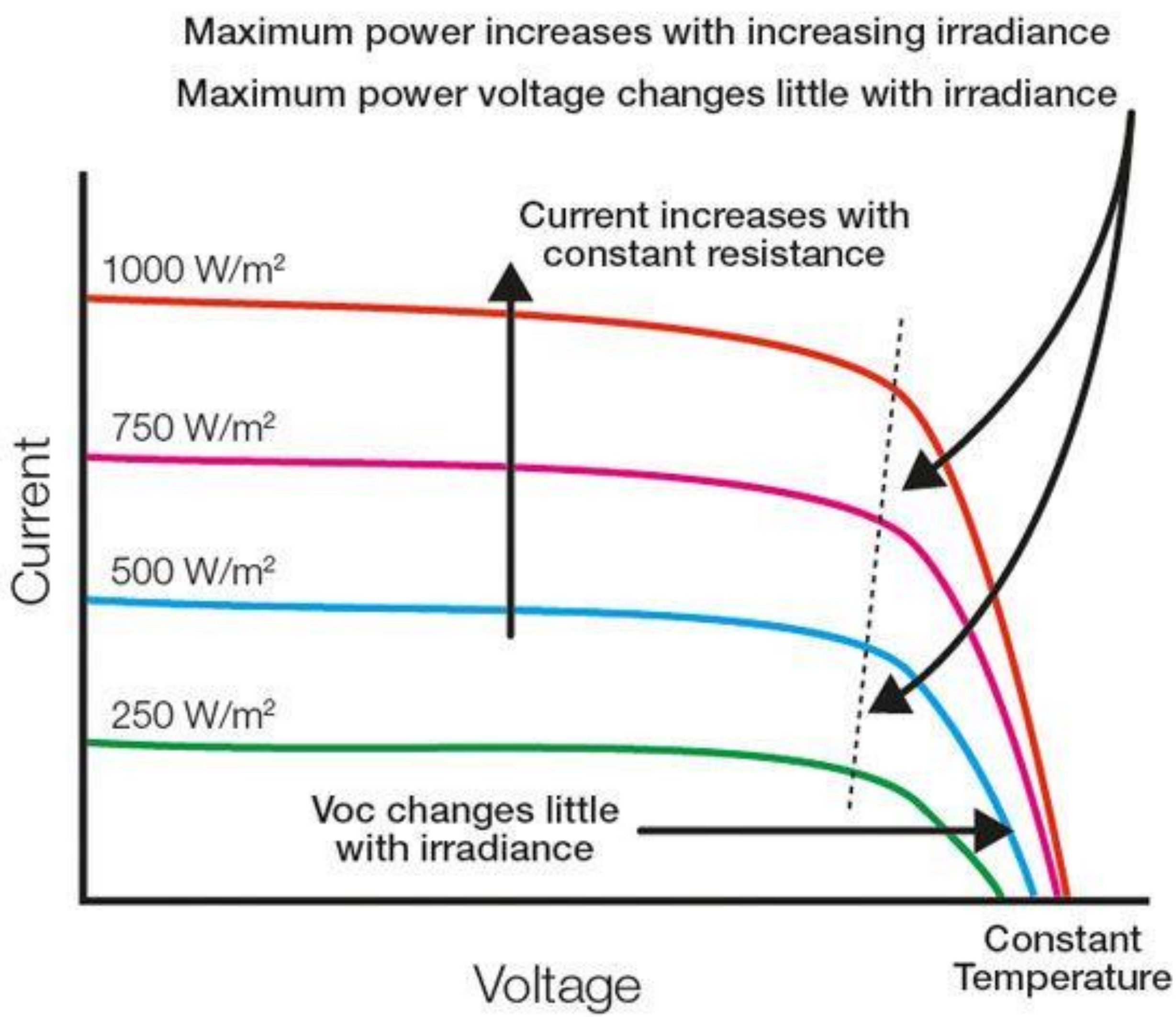


$$Fill\ Factor = \frac{V_m . I_m}{V_{oc} . I_{sc}} \qquad \eta = \frac{V_m . I_m}{Incident\ solar\ radation}$$

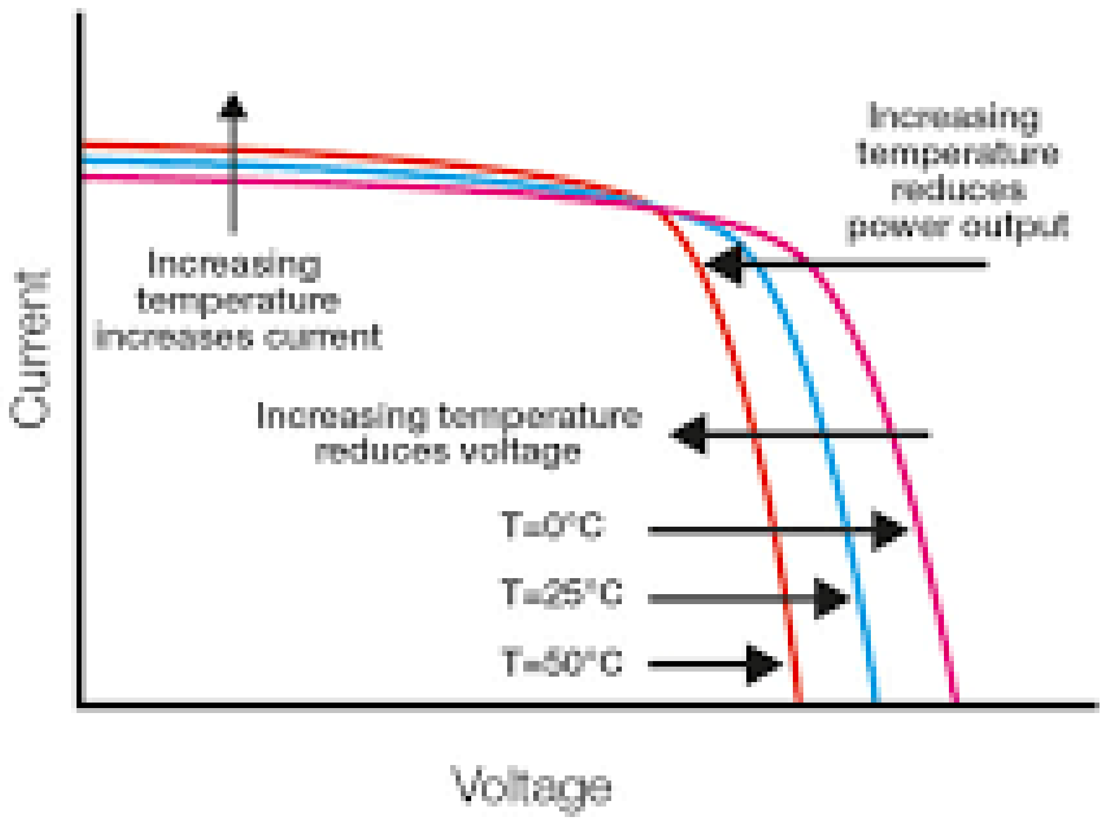
Current voltage characteristics



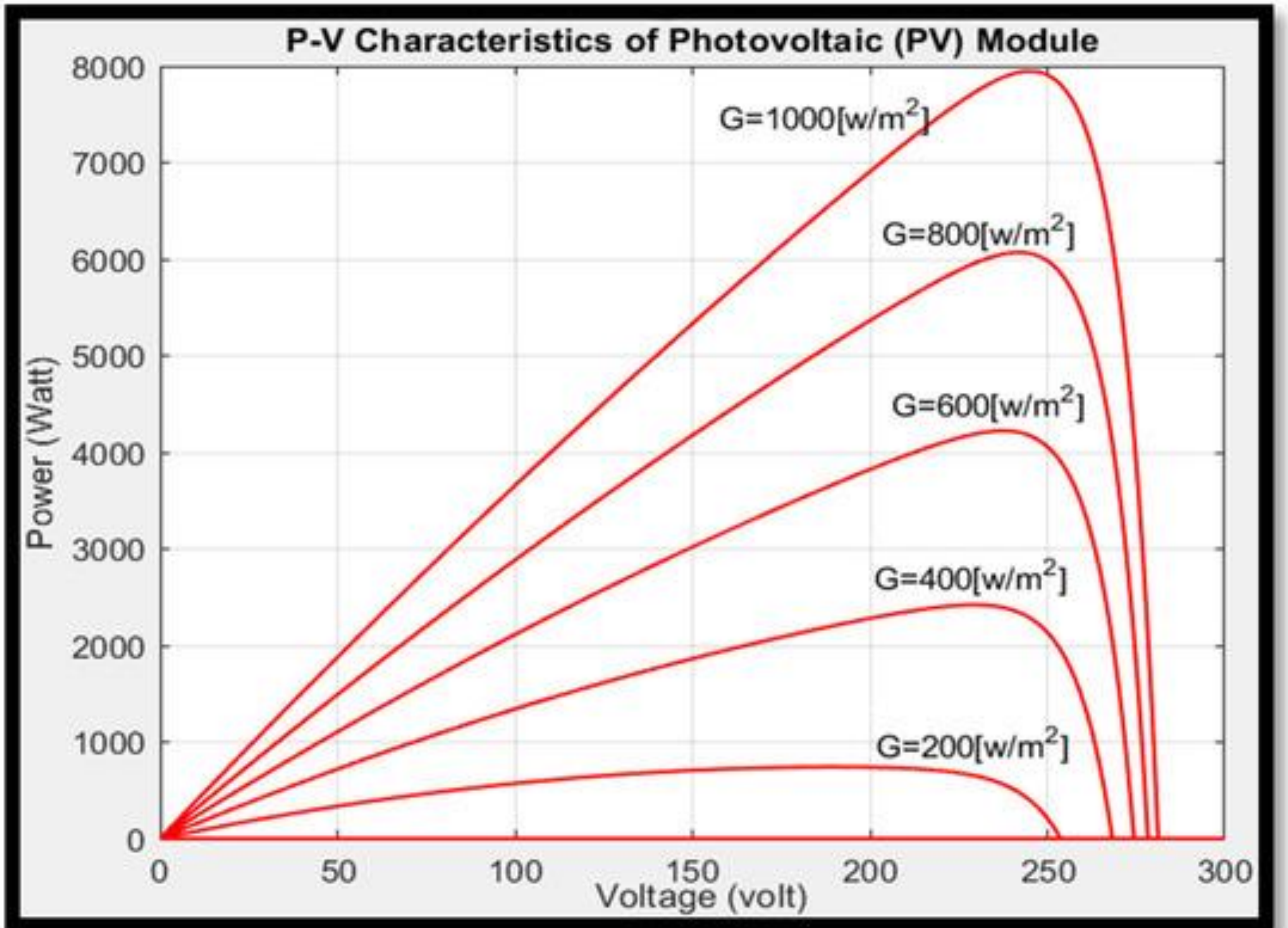
I-V characteristics with varying Irradiance



I-V characteristics with varying Cell temperature



Voltage -Power characteristics



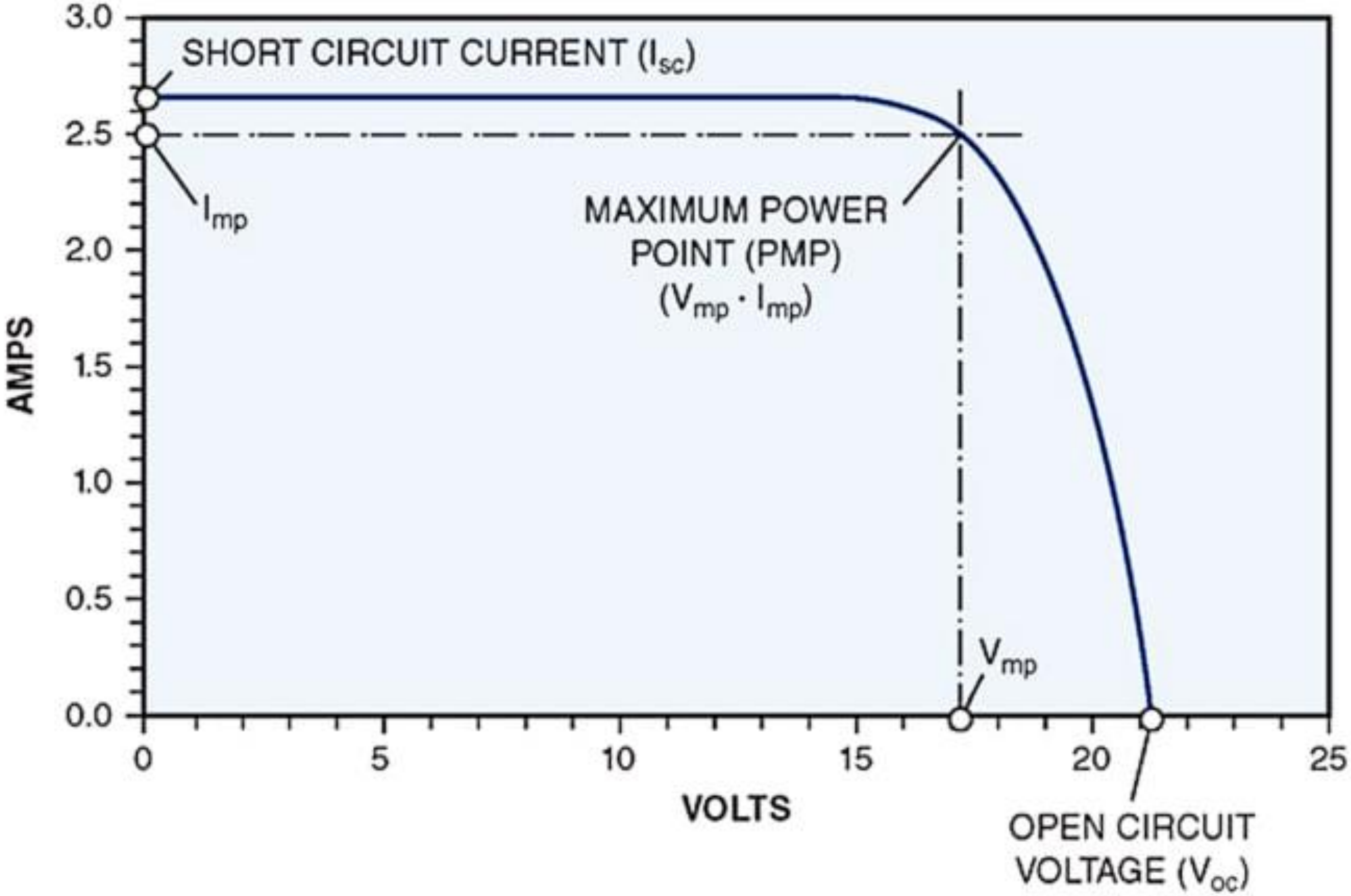
Factors affecting solar cell performance

- **Material Quality**
- **Reflection**
- **Degradation**
- **Temperature**
- **Light Intensity**
- **Shading**
- **Dirt and Dust**
- **Panel Orientation and Tilt**
- **Ventilation**

Solar cell properties

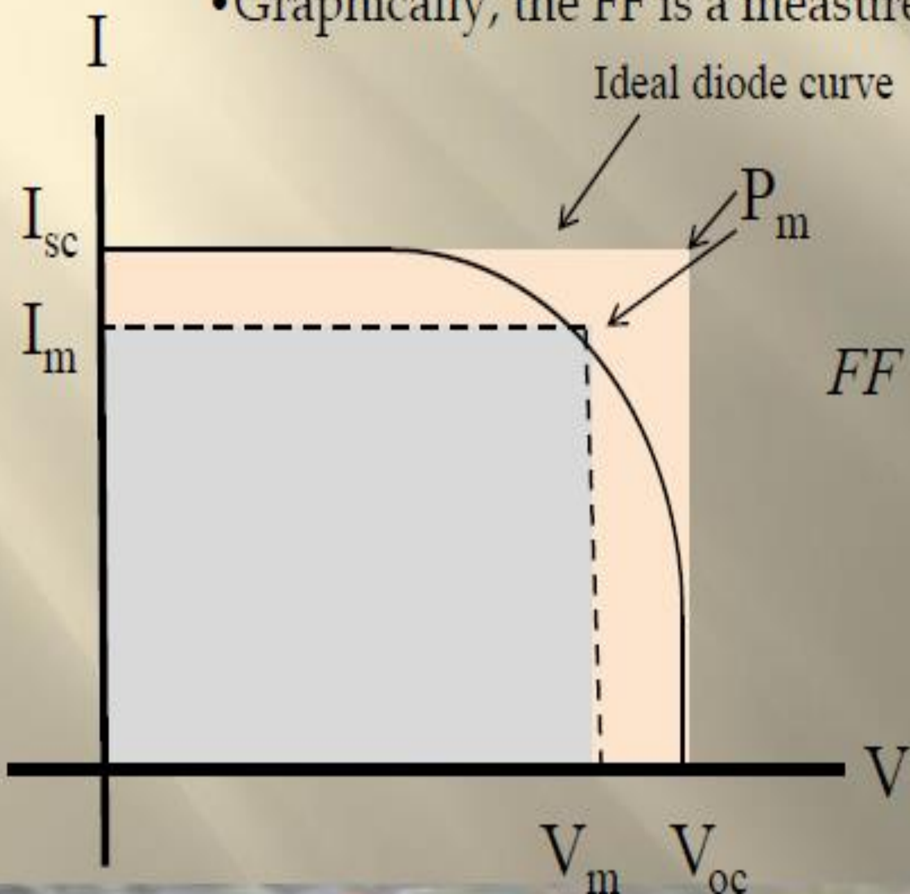
- Open circuit voltage
- Short circuit current
- Maximum power
- Efficiency
- Fill factor

Maximum Power



Fill Factor

- The FF is defined as the ratio of the maximum power from the actual solar cell to the maximum power from a ideal solar cell
- Graphically, the FF is a measure of the "squareness" of the solar cell.



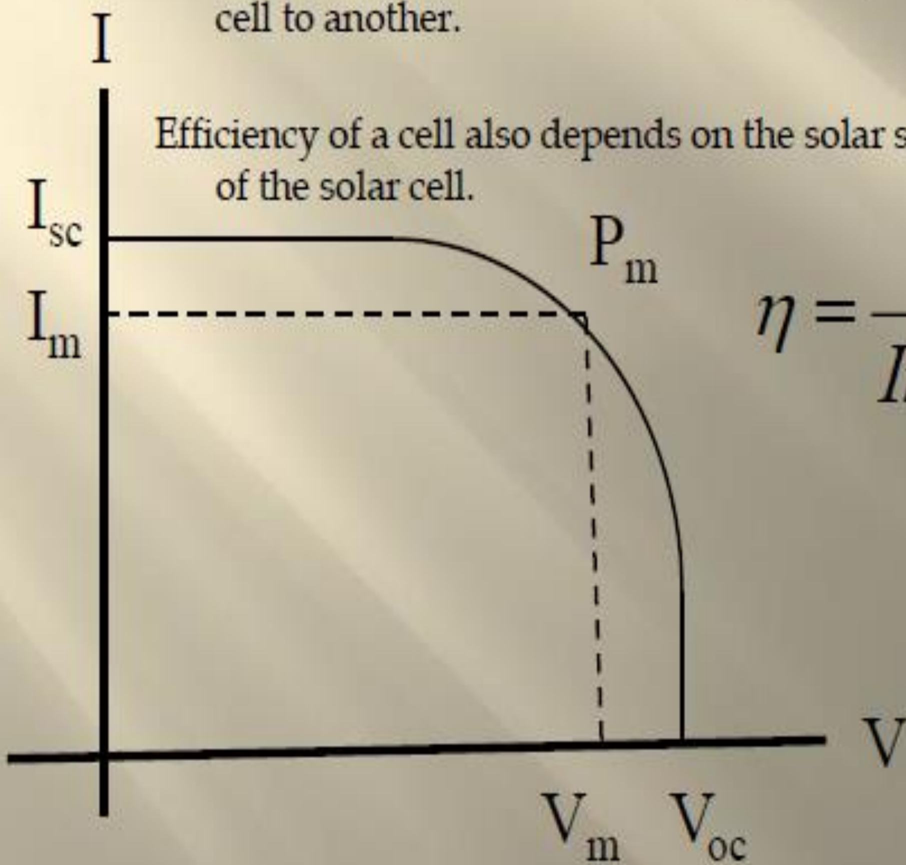
$$FF = \frac{\text{Max power from real cell}}{\text{Max power from ideal cell}} = \frac{V_m I_m}{V_{oc} I_{sc}}$$

Efficiency

Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun.

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another.

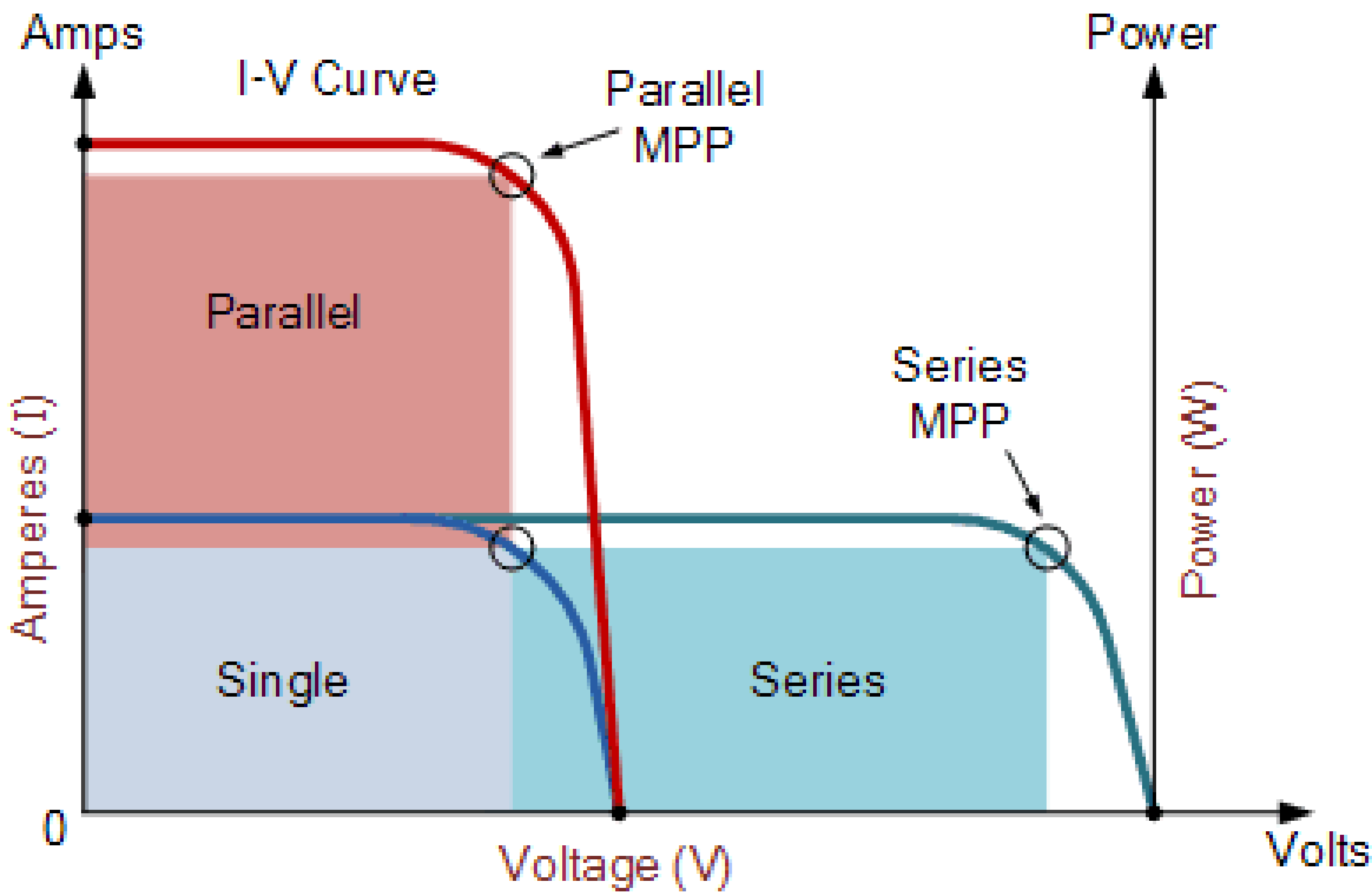
Efficiency of a cell also depends on the solar spectrum, intensity of sunlight and the temperature of the solar cell.



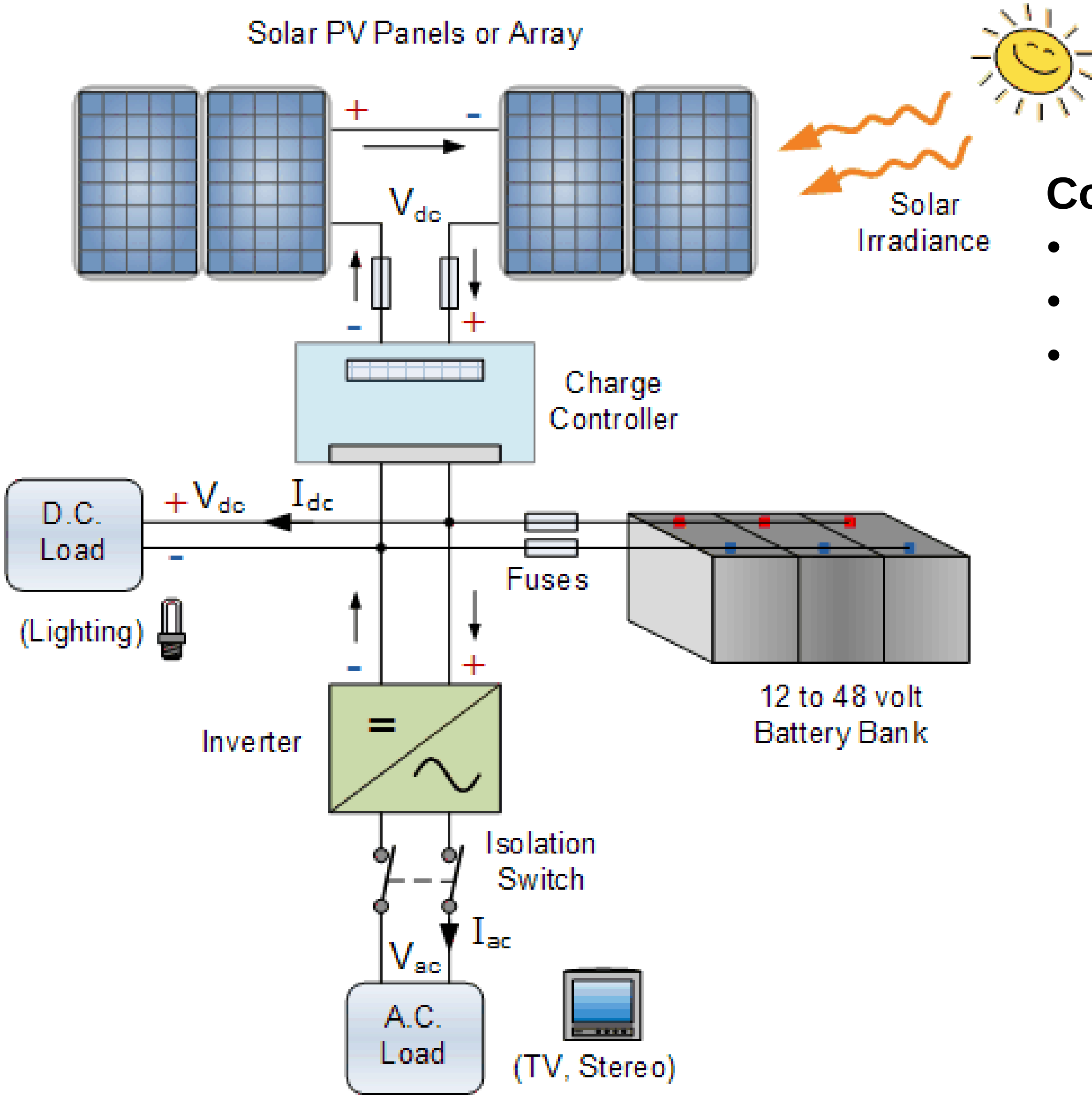
$$\eta = \frac{Max\,Cell\,Power}{Incident\,light\,Intensity} = \frac{V_m I_m}{P_{in}}$$

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

PV cell- Series and Parallel connections



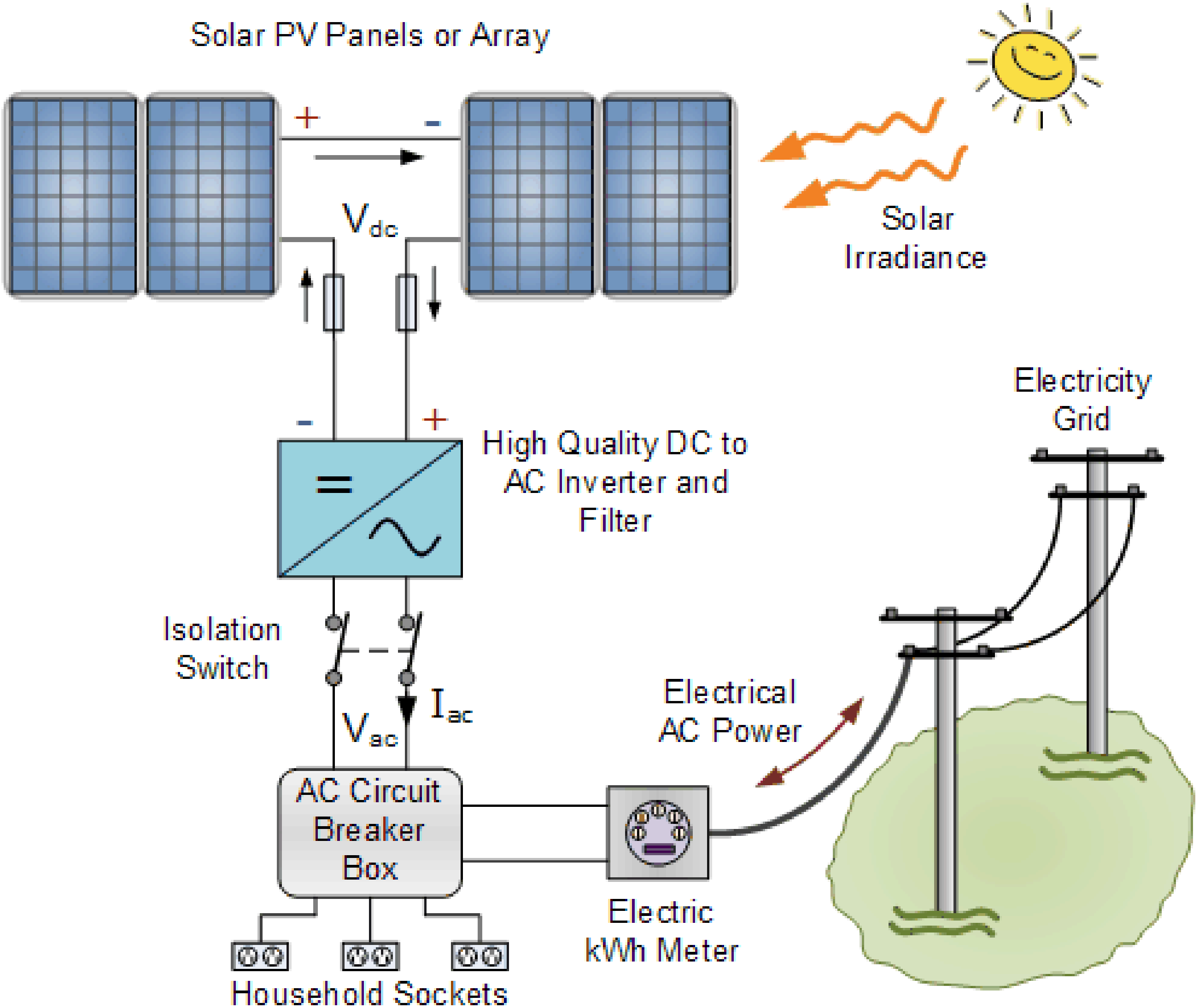
Standalone PV system



Components

- Solar PV modules or arrays
- Charge controller
- Inverter

Grid connected PV system



Factors to be considered for the design of standalone PV system

- load characteristics
- solar resource availability
- system sizing
- system configuration
- system protection

Comparison of solar conversion Technologies

Parameter	Conversion to Electricity (PV)	Conversion to Usable Heat (Solar Thermal)	Conversion to Fuel (Biomass)
Basic Principle	Photovoltaic effect: photons excite electrons, generating electric current	Solar radiation absorbed → converted into heat energy	Photosynthesis: CO_2 + H_2O + sunlight → biomass
Typical Technologies	Silicon solar cells, thin-film PV, perovskite PV	Flat-plate collectors, evacuated tube collectors, concentrating solar collectors	Crops and agricultural residues
Conversion Efficiency	15–25%	30–70%	7–10%

Comparison of solar conversion Technologies

Parameter	Conversion to Electricity (PV)	Conversion to Usable Heat (Solar Thermal)	Conversion to Fuel (Biomass)
Output Form	Electricity (DC, DC converted to AC)	Low/medium/high temperature heat (water/air/steam)	Chemical energy stored in biomass (solid, liquid, or gas fuels)
Time Scale of Conversion	Instantaneous (as long as sunlight is available)	Instantaneous (direct heat gain)	Slow, days to months (biological growth cycles)
Storage Possibilities	Batteries, hydrogen (via electrolysis)	Thermal storage (water tanks, molten salts, PCM)	Biomass storage as feedstock, biofuels (biogas, biodiesel)

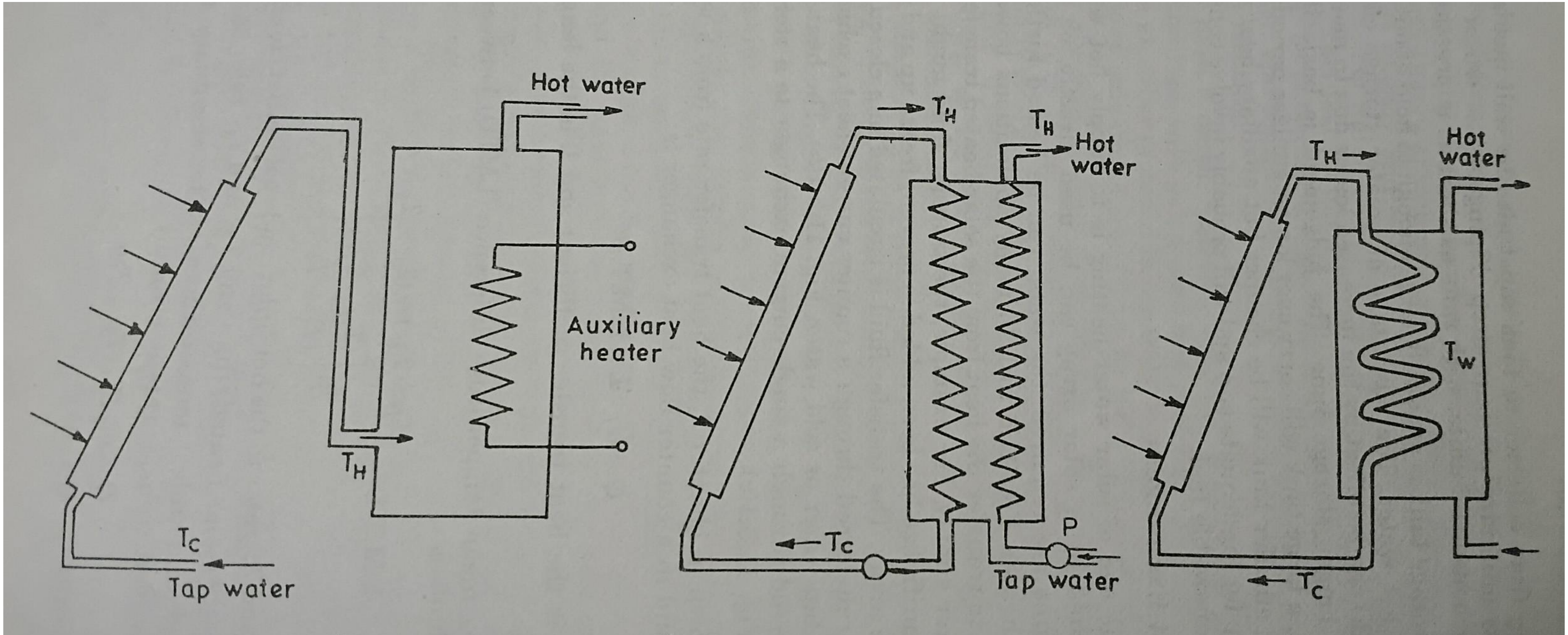
Comparison of solar conversion Technologies

Parameter	Conversion to Electricity (PV)	Conversion to Usable Heat (Solar Thermal)	Conversion to Matter/Fuel (Biomass)
Applications	Rooftop/grid solar power, calculators, satellites	Domestic water heating, space heating, industrial process heat, solar thermal power plants	Cooking fuel, power generation via biomass plants, transportation fuels
Advantages	Clean electricity, modular, scalable, rapidly deployable	Higher direct efficiency, cost-effective for heating, mature technology	Carbon-neutral, rural employment
Limitations	Intermittent, needs storage, high upfront cost	Only provides heat, not electricity directly, requires large area for high temp	Very low solar-to-fuel efficiency, land and water use issues, seasonal dependence

Module V

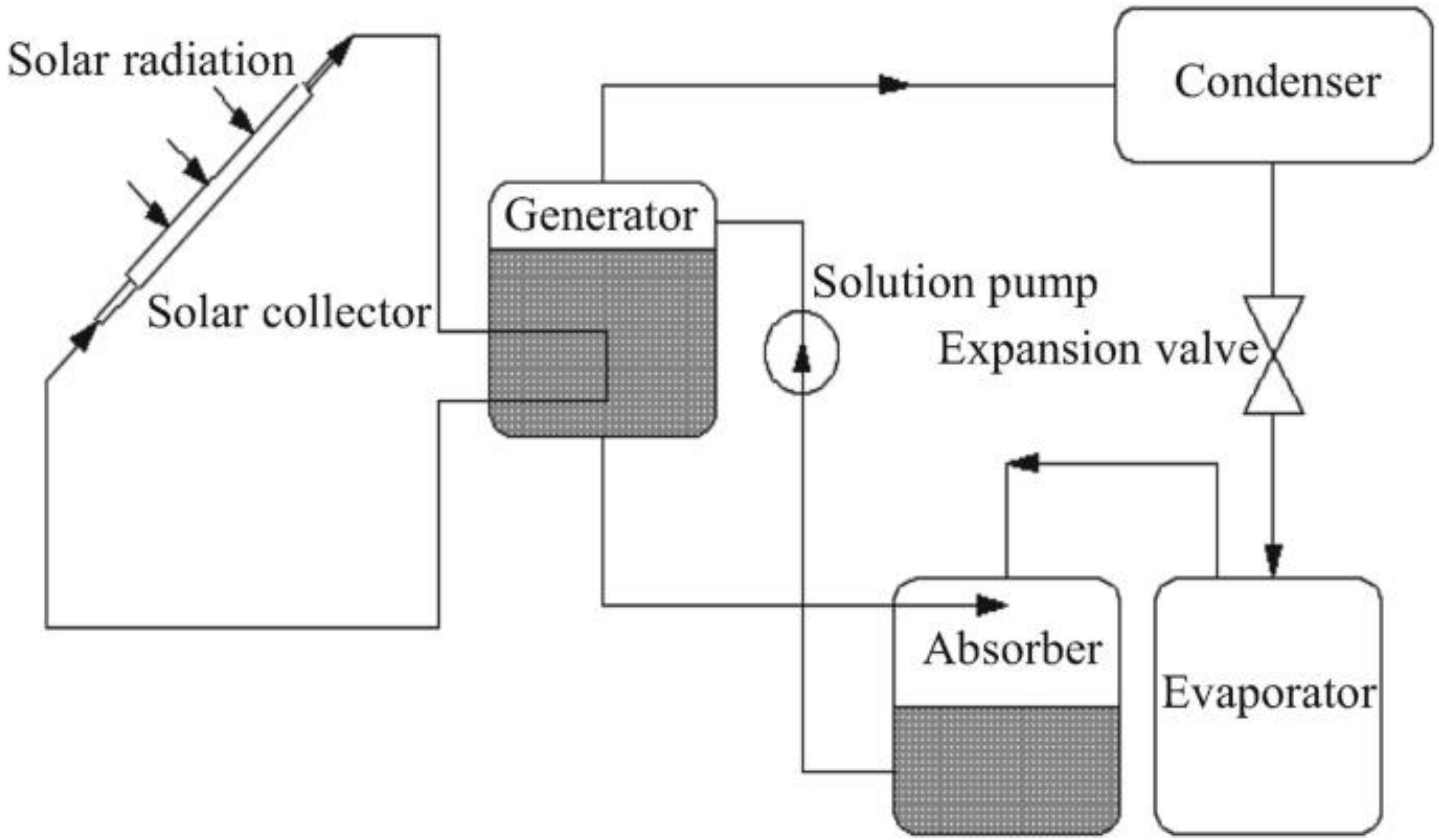
Solar Thermal Applications and Economic Analysis

Solar heating

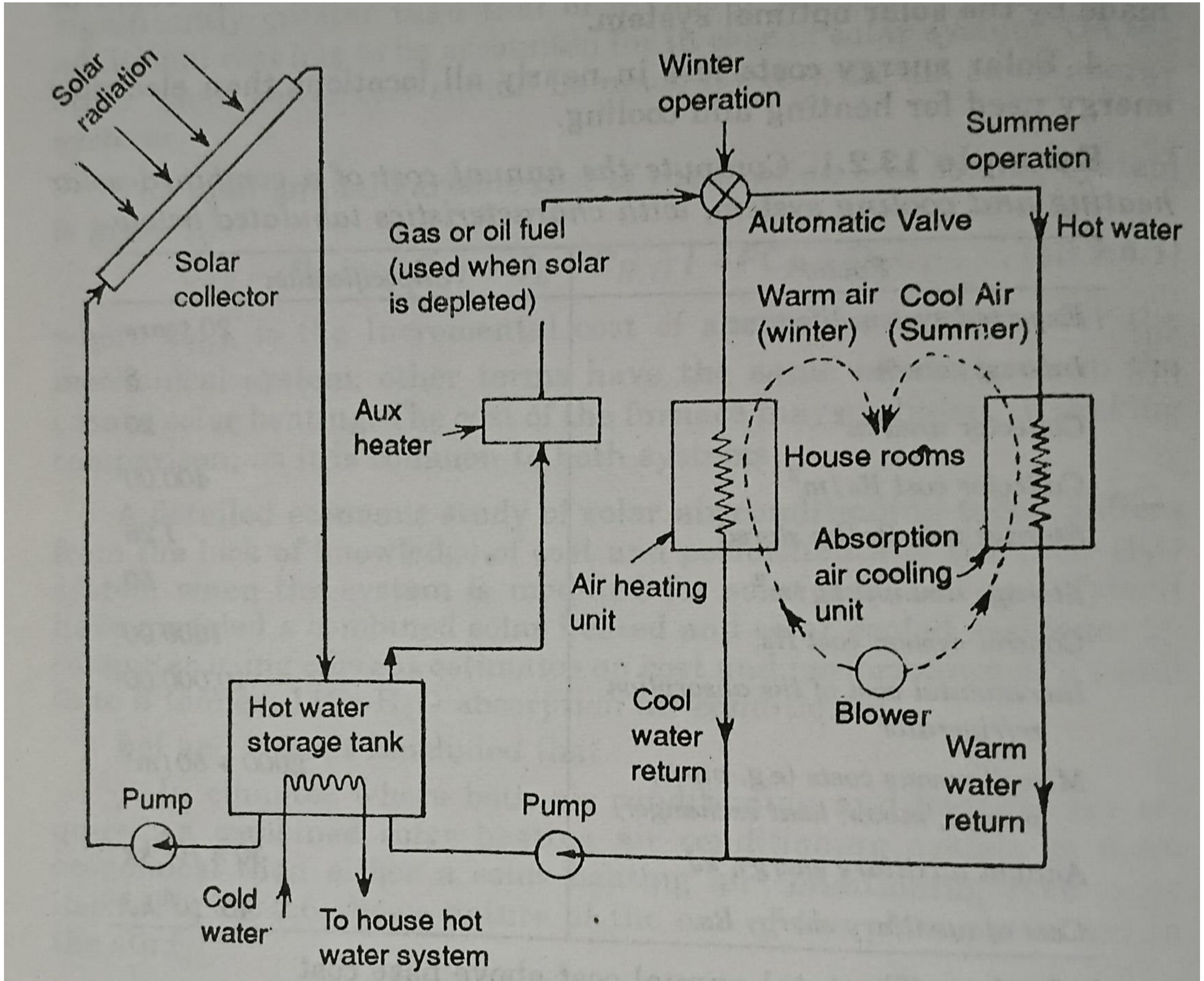


(a) (b) (c)

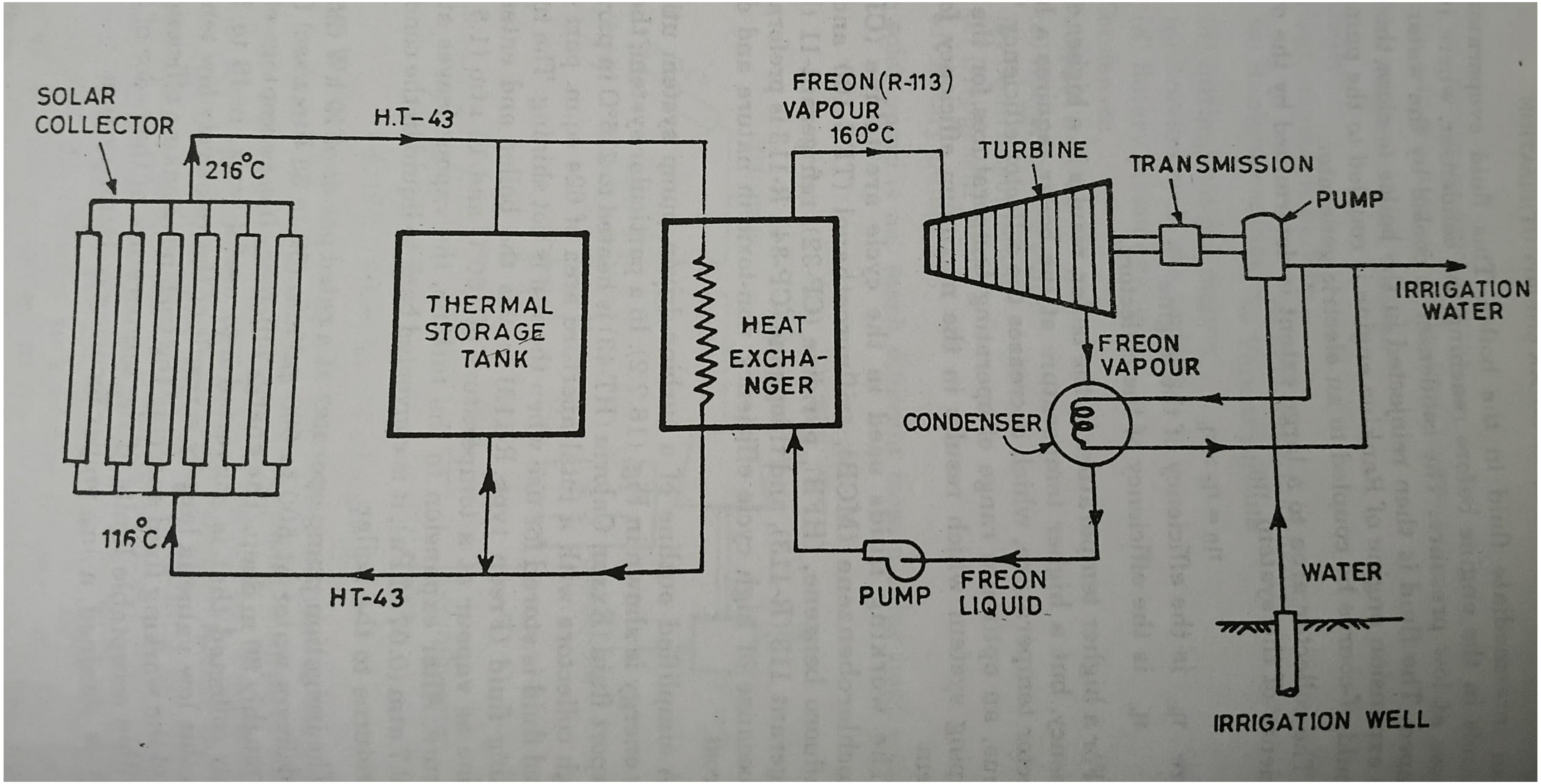
Solar cooling



Combined Solar heating and cooling system

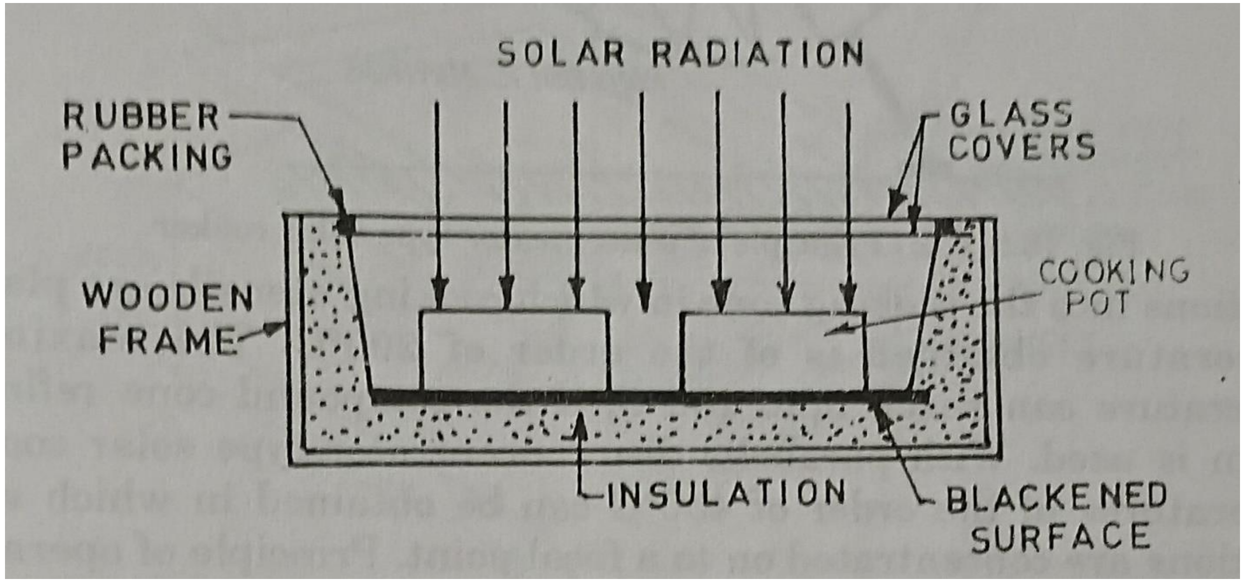


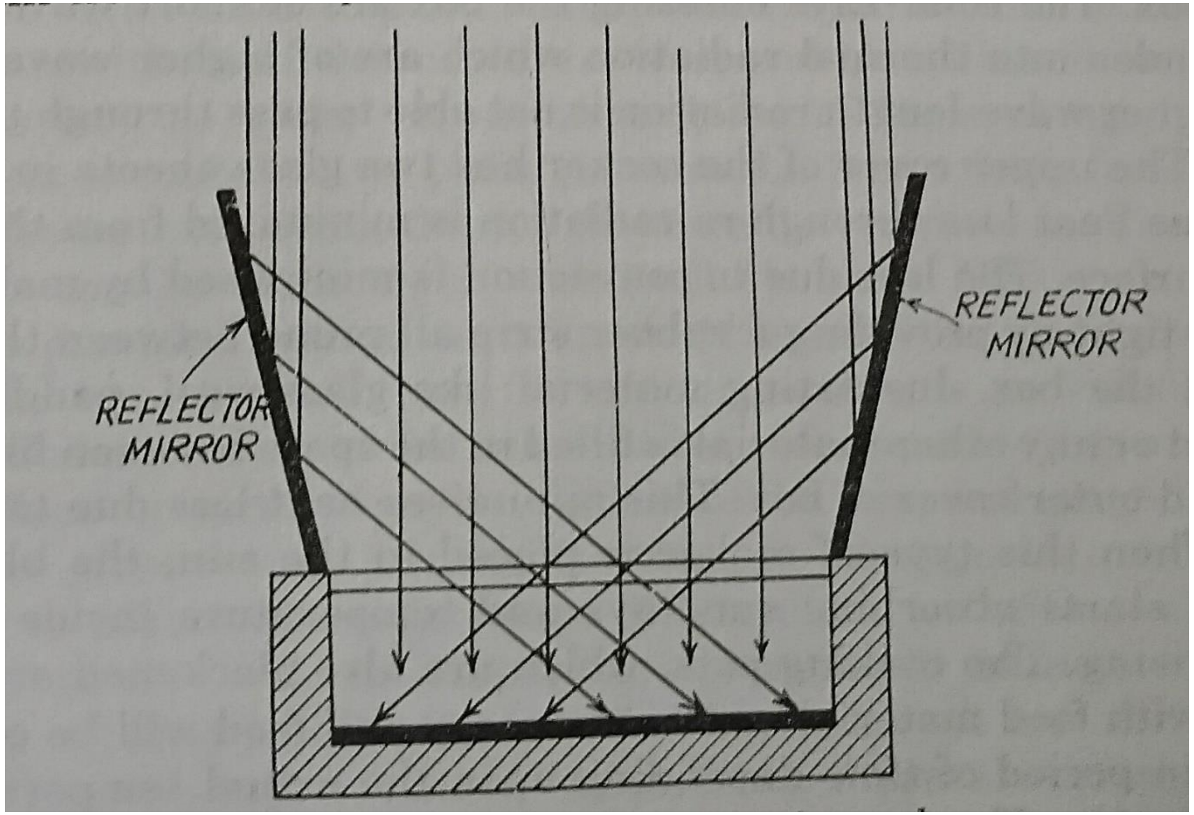
Solar pump



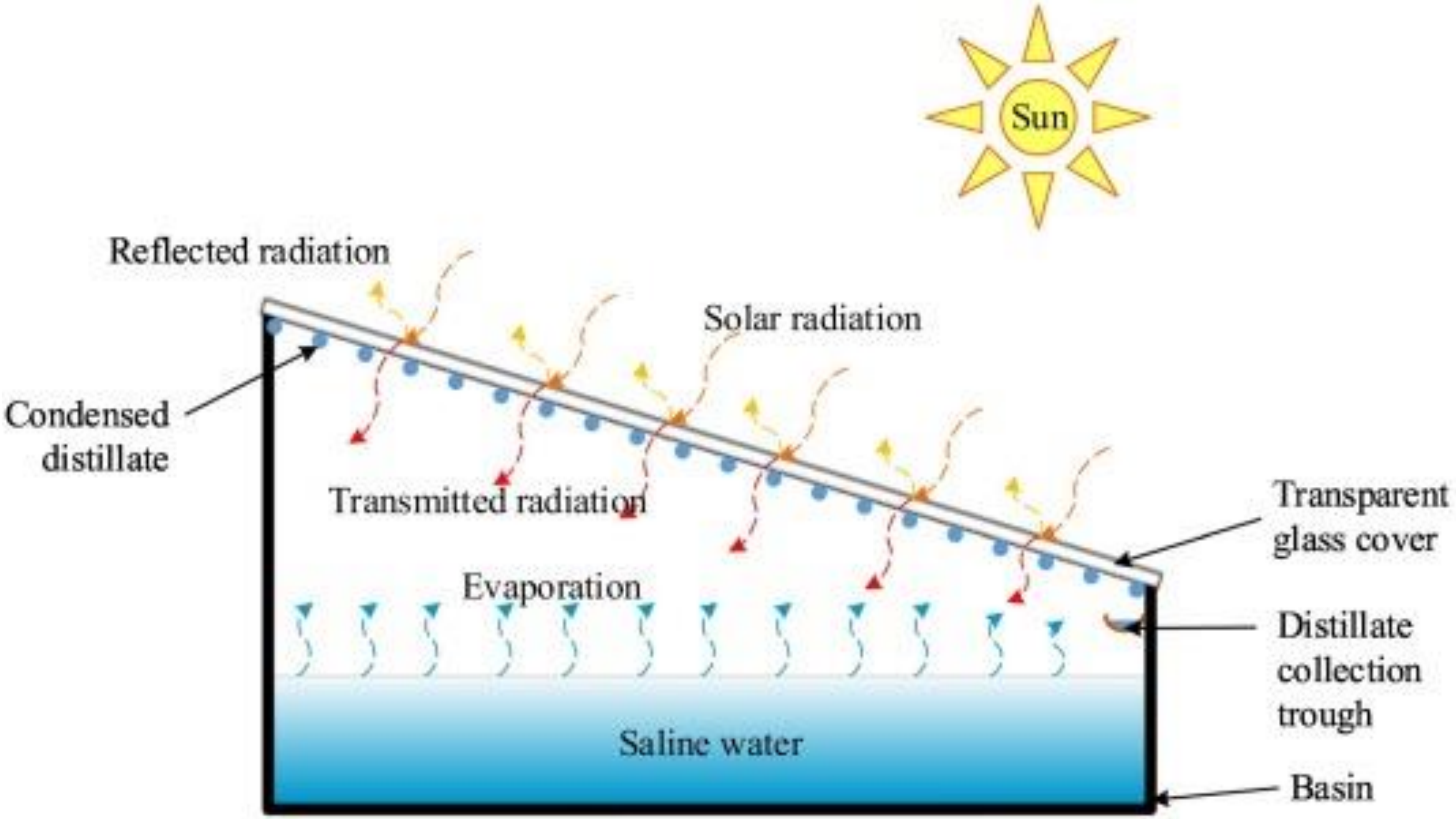
SOLAR COLLECTOR
H.T-43
216°C
116°C
HT-43
THERMAL STORAGE TANK
HEAT EXCHA-NGER
FREON (R-113) VAPOUR 160°C
TURBINE
TRANSMISSION
PUMP
IRRIGATION WATER
FREON VAPOUR
CONDENSER
PUMP
FREON LIQUID
WATER
IRRIGATION WELL

Solar cooking



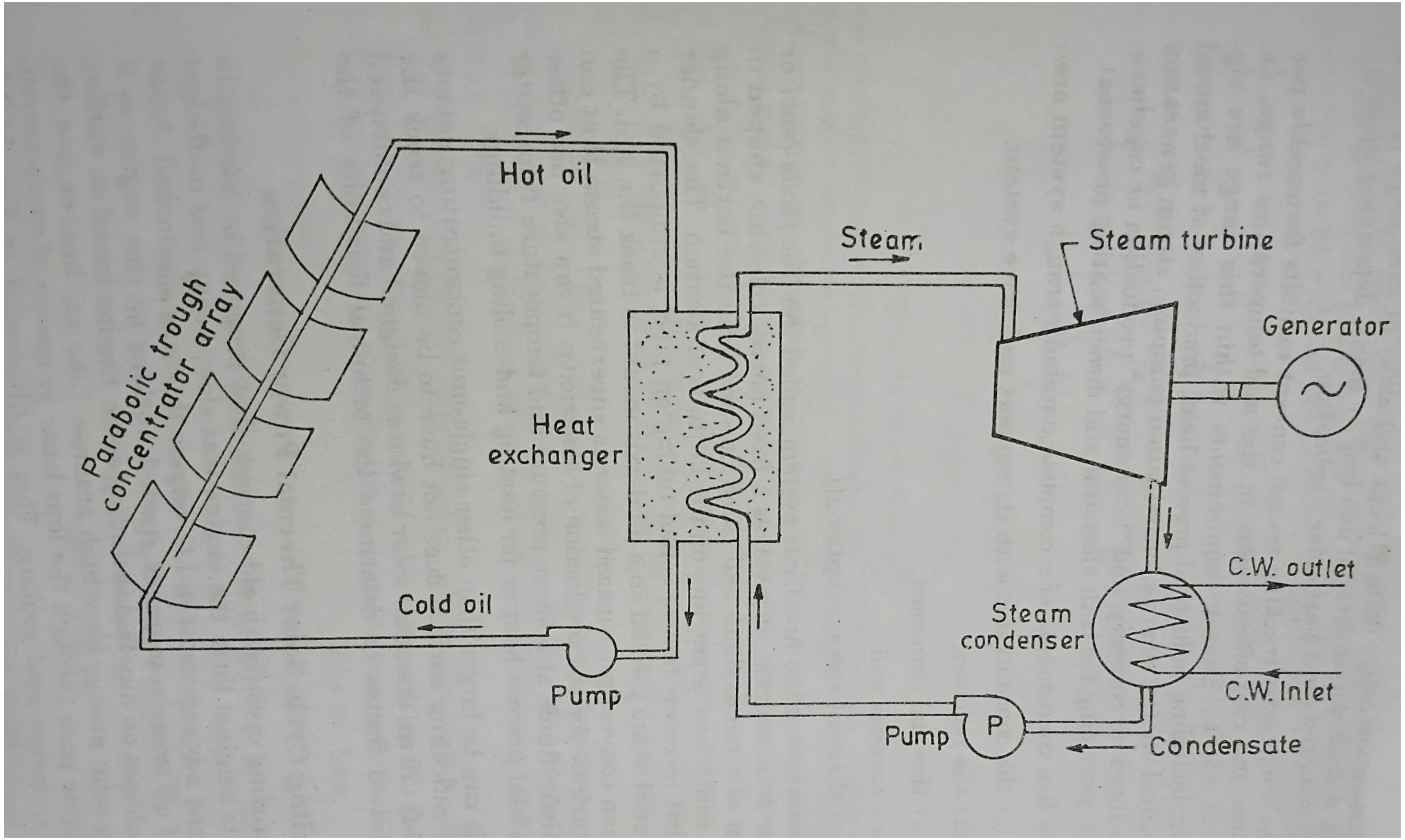


Solar distillation



Solar Thermal Power generation

Cylindrical parabolic collector for power generation



Economic analysis

Annual Cost of solar heating system

$C_{SH} = (C_c A_c + C_S + C_E)I + P\ C_P + C_{MM} + C_{LM}$

- $C_c - \mathit{Cost\ of\ the\ Collector\ per\ unit\ area}$
- $A_c - \mathit{Collector\ area}$
- $C_S - \mathit{Capital\ cost\ of\ Storage\ cost}$
- $C_E - \mathit{Capital\ cost\ of\ the\ equipment, pump, pipings, ducts}$
- $I - \mathit{Fraction\ of\ investment\ to\ be\ charged\ per\ year}$
- $P - \mathit{Power\ requirments\ for\ solar\ energy\ systems}$
- $C_P - \mathit{Unit\ cost\ of\ power}$
- $C_{MM} - \mathit{Cost\ of\ material\ maintenance}$
- $C_{LM} - \mathit{Cost\ of\ labour\ maintenance}$

Annual Cost of auxiliary heating system

$$C_{AH} = C_B I + P' \, C_P + C_{MM}{}' + C_{LM}{}'$$

- $C_B - Cost\ of\ the\ auxilary\ heating\ system$
- $I -\ Fraction\ of\ investment\ to\ be\ charged\ per\ year$
- $P -\ power\ requirment\ for\ auxialiary\ system$
- $C_P -\ Unit\ cost\ of\ power$
- $C_{MM}{}' - Cost\ of\ Material\ maintenance\ for\ auxialiary\ system$
- $C_{LM}{}' -\ Cost\ of\ labour\ maintenance\ for\ auxialiary\ system$

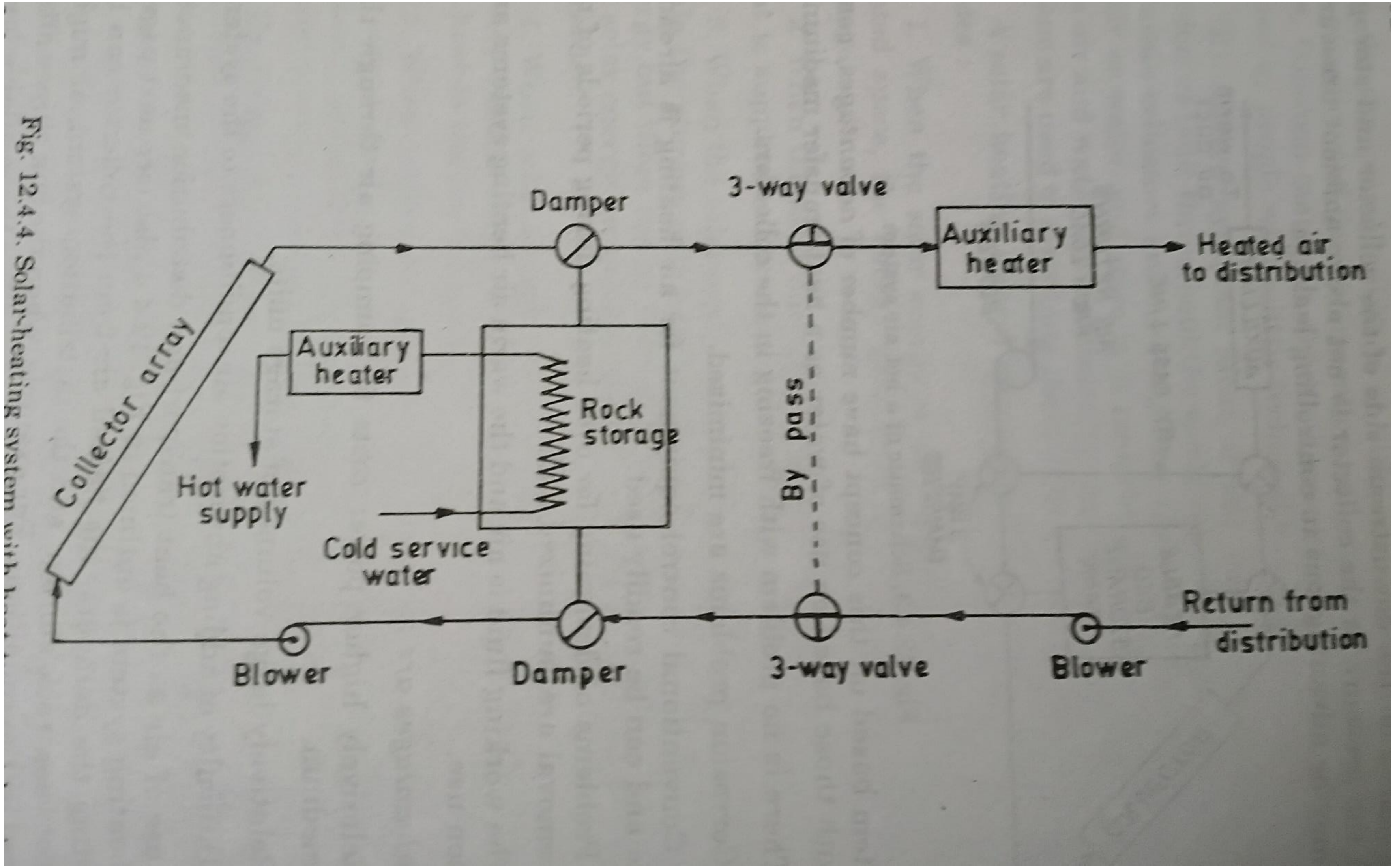
$$\boldsymbol{Total\ annual\ cost = C_{SH} + C_{AH}}$$

$$\boldsymbol{Fraction\ of\ investment\ to\ be\ charged\ per\ year}$$

$$I = \frac{i\,(1+i)^t}{(1+i)^t - 1}$$

- $i -$ Annual rate of interest
- $t -$ Expected life time of the system in years

Solar heating



Solar Thermal central receiver system power plant