Solar Radiation

- The output of sun is 2.8×10^{23}KW.
- The energy reaching the earth is 1.5×10^{18}KWH/year.
- When light travels from outer space to earth, solar energy is lost because of following reasons:
- Scattering: The rays collide with particles present in atmosphere
- Absorption: Because of water vapor there is absorption
- Cloud cover: The light rays are diffused because of clouds.
- Reflection: When the light rays hit the mountains present on the earth surface there is reflection.
- Climate: Latitude of the location, day (time in the year) also affects the amount of solar energy received by the place.

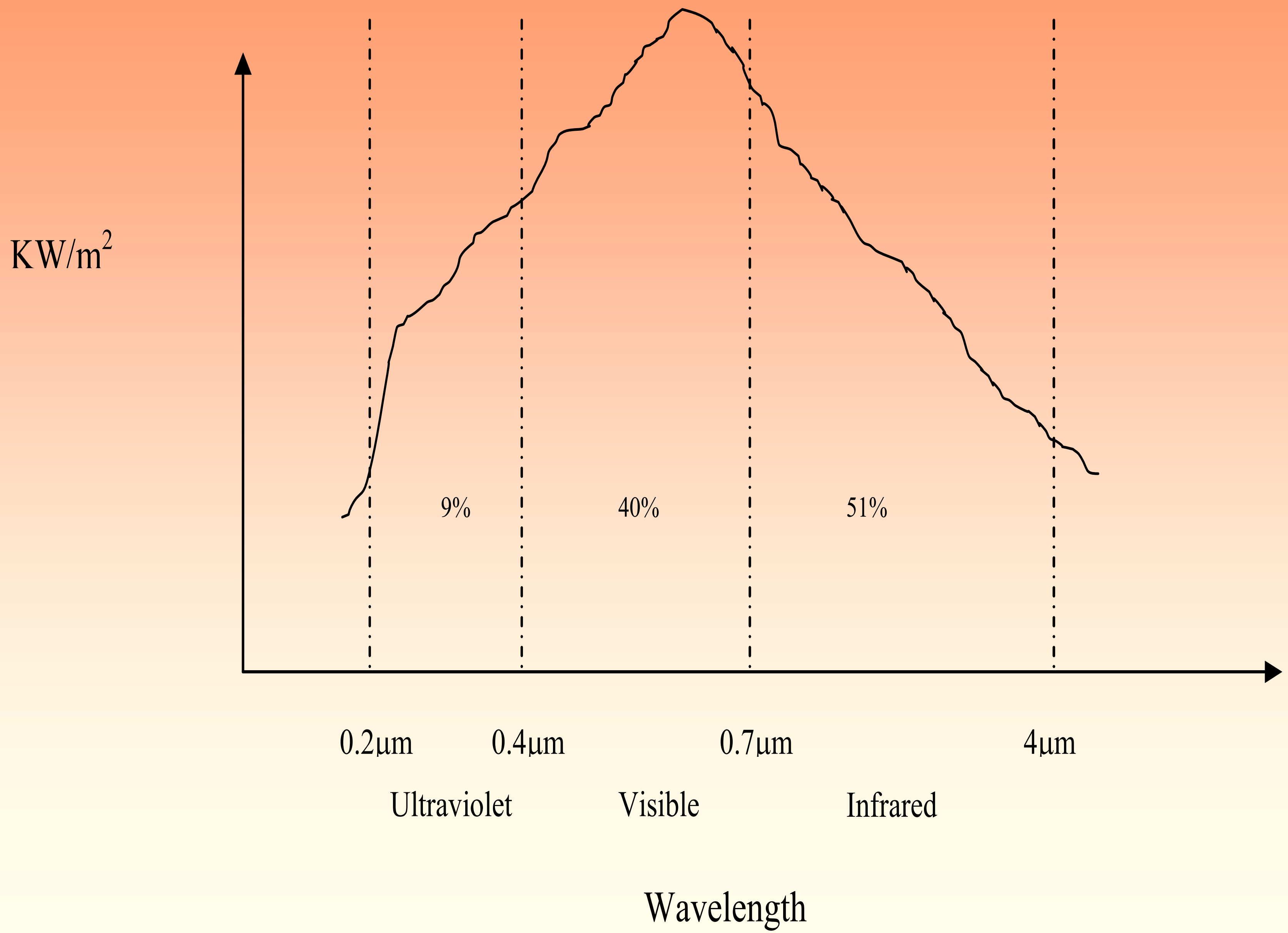
Insolation

- It is a quantity indicating the amount of incident solar power on a unit surface, commonly expressed in units of kW/m^2 .
- At the earth's outer atmosphere, the solar insolation on a $1m^2$ surface oriented normal to the sun's rays is called SOLAR CONSTANT and its value is 1.37 kW/m^2 .
- Due to atmospheric effects, the peak solar insolation incident on a terrestrial surface oriented normal to the sun at noon on a clear day is on the order of 1 kW/m^2.
- A solar insolation level of 1 kW/m^2 is often called PEAK SUN. Solar insolation is denoted by ' I '.

Insolation-1

- The graph shown gives the amount of power present in different wavelengths of radiation.
- It can be seen from the graph that 50% of solar energy is in the form of thermal energy .
- Solar PV captures the energy in visible region. Solar thermal captures energy in infrared region.

Insolation-2



Irradiance

- It is an amount of solar energy received on a unit surface expressed in units of kWh/m^2 .
- Solar irradiance is essentially the solar insolation (power) integrated with respect to time.
- When solar irradiance data is represented on an average daily basis, the value is often called PEAK SUN HOURS (PSH) and can be thought of as the number of equivalent hours/day that solar insolation is at its peak level of $1kW/m^2$.
- The worldwide average daily value of solar irradiance on optimally oriented surfaces is approximately 5 kWh/m^2 or 5 PSH. Solar irradiance is denoted by ' H '.

Radiation Measurement

- We know that the atmosphere is made up of ions and other particles including clouds.
- when the incident radiation passes through the atmosphere, some radiation penetrates and falls directly on to the panel, some radiation diffuses in atmosphere and travels to the panel and some radiation gets reflected from the surroundings of the panel and reaches the panel, the effect being called albedo effect.

Radiation Measurement-1

- It becomes extremely important to know the amount of energy that has reached the panel through all the paths.
- There are several factors on which this energy is dependent. They are as follows:
- Latitude and longitude of the geographical location.
- Climatic conditions such as presence of clouds, water vapor etc.
- Time of the day.
- Time of the year.
- Angle of tilt.
- Collector design.

Radiation Measurement-2

Now, let us see how we make use of this information in calculating the solar energy available at the panel. The steps are as follows:

- Find the sun position with respect to the location. This is a function of latitude (φ), hour angle (ω) and declination angle (δ)

$$\text{SunPosition} = f(\phi, \varpi, \delta)$$

- Find the available solar energy or irradiance with no atmosphere, H_O. This is a function of sun position.

$$H_O = f(\text{SunPosition})$$

- Find the solar energy available on horizontal surface with atmospheric effects, H_{OA}. This is a function of H_O and clearness index K_T

$$H_{OA} = K_T H_o$$

Radiation Measurement-3

- Find the actual solar energy available at the panel, H_t. this is a function of H_{OA} and the tilt factor R_D.

$$H_t = R_D H_{OA}$$

- All the above mentioned steps can be written as an algorithm so that the moment available data is fed, the actual solar energy available at the panel can be calculated instantly. The algorithm would involve the following equations:

$$Enter \quad \phi, \beta$$

$$N = 1 \rightarrow 365$$

$$\delta = 23.45 * \sin\left(\frac{2\pi(N - 80)}{365}\right)$$

$$\text{Degrees}, \text{N} = 1 \text{ on jan } 1^{st}, \text{N} = 365 \text{ on dec } 31^{st}$$

Radiation Measurement-4

$$\omega_{sr} = \cos^{-1}\left(-\tan\phi \cdot \tan\delta\right)$$

$$I_O = I_{SC}\left(1 + 0.033\cos\left(\frac{360N}{365}\right)\right) \text{ KW/m}^2$$

$$H_{ot} = \frac{24 I_O}{\pi} * \left(\cos(\phi-\beta)\cos\delta\cos\omega_{sr} + \omega_{sr}\sin(\phi-\beta)\sin\delta\right)$$

$KWh/m^2/day$ on a titled surface with no atmospheric effects

Radiation Measurement-5

$$H_o = \frac{24 I_O}{\pi} * \left(\cos(\phi)\cos\delta\cos\omega_{sr} + \omega_{sr}\sin(\phi)\sin\delta\right)$$

$$\mathrm{KWh/m^2/day}$$

$$K_T = \left(curve \cdot fitting \cdot data\right)$$

Clearance index

$$R_D = K_R\left(1 - K_D\right) + K_D\left(\frac{1+\cos\beta}{2}\right) + \rho\left(\frac{1-\cos\beta}{2}\right)$$

Tilt Factor

Radiation Measurement-6

where is the reflection factor which ranges between 0.2 to 0.7.

$$H_t = K_T * R_D * H_o \quad \text{kWh/m}^2\text{/day}$$

This algorithm can be translated into any of the programming languages like C, C++ or MATLAB. Entering the known parameters, it becomes convenient to find out the solar energy available at any geographical location.

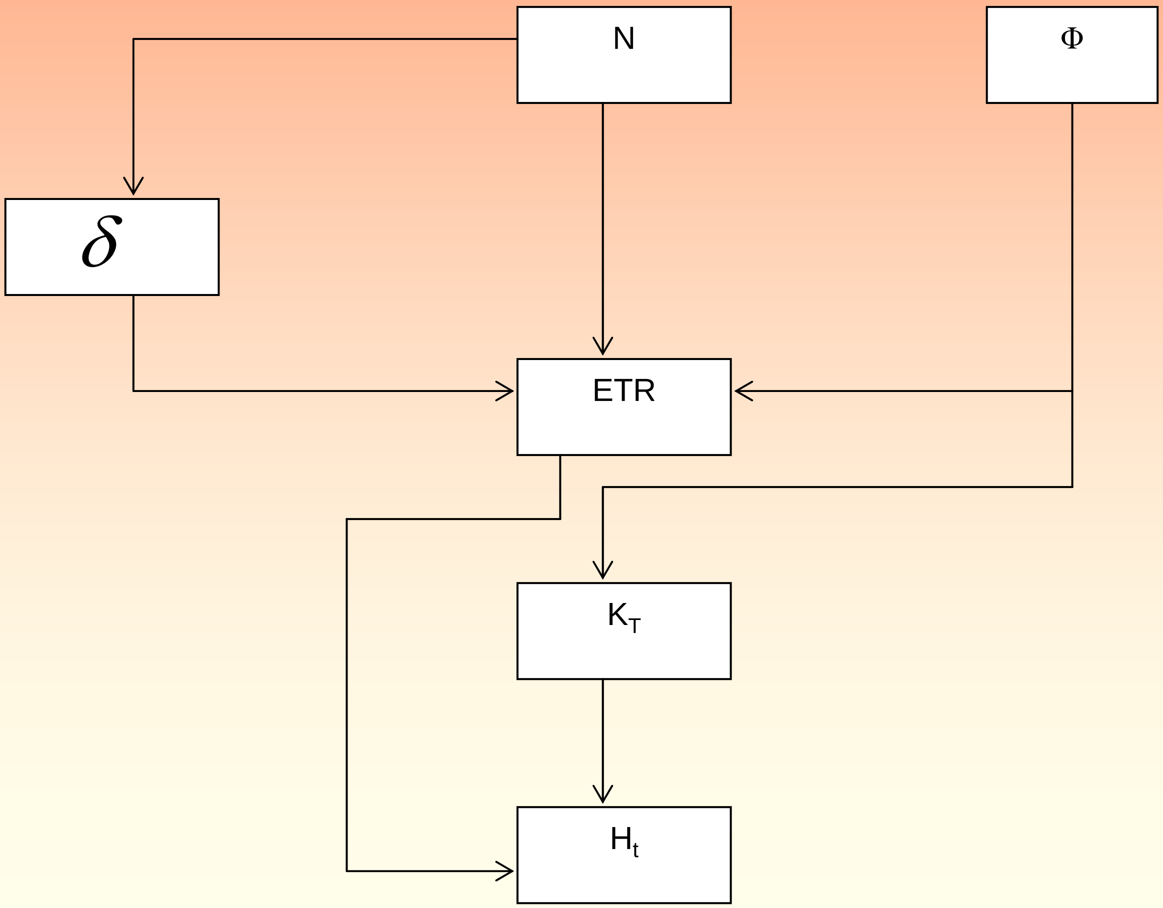
Insolation at any location

We need to develop an algorithm, which calculates insolation (H_t) in kWh/m^2 at any place, once we input the following parameters:

- Day of the year (N)
- Latitude of the location (φ)
- Tilt angle (β)
- Angle of declination (δ)
- Clearness Index (KT)
- Reflection co-efficient (varies from 0.2 to 0.7)

Insolation at any location-1

Following flow chart gives an idea for developing the algorithm:



Insolation at any location-2

We can see that once δ, N and φ are input, Extra Terrestrial Radiation (ETR) can be determined. Δ, the declination angle of the sun is assumed to be the same every year and δ = 0 in March 21st.

Following Fourier series can be used to calculate δ:

$$\delta = Ao + A_1 \cos t + A_2 \cos 2t + A_3 \cos 3t + B_1 \sin t + B_2 \sin 2t + B_3 \sin 3t$$

where $t = \frac{360}{365}(N - 80)$ degrees   A0, A1…B3 = ?

ETR can be calculated from the following expression:

$$ETR = 24 \cdot k \cdot I_{SC} \left(\cos\phi \cos\delta \sin\varpi_{sr} + \varpi_{sr} \sin\phi \sin\delta \right) \text{ kWh/m}^2$$

where $k = \left[1 + 0.033 \cos\left(\frac{360\, N}{365} \right) \right]$

Insolation at any location-3

I_{SC} = mean solar constant = 1.37 kW/m^2

φ = latitude in degrees/radians

δ = declination angle in degrees/radians

ω_{sr} =hour angle at sunrise in degrees/radians =cos-1(-tanφtan δ)

- The next parameter that needs to be known is K_T, the clearness index.
- It is one of the most important and difficult factors to be determined since it depends on atmospheric conditions such as absorption, pressure, cloud-cover at the place etc., which are not constant at a given place.

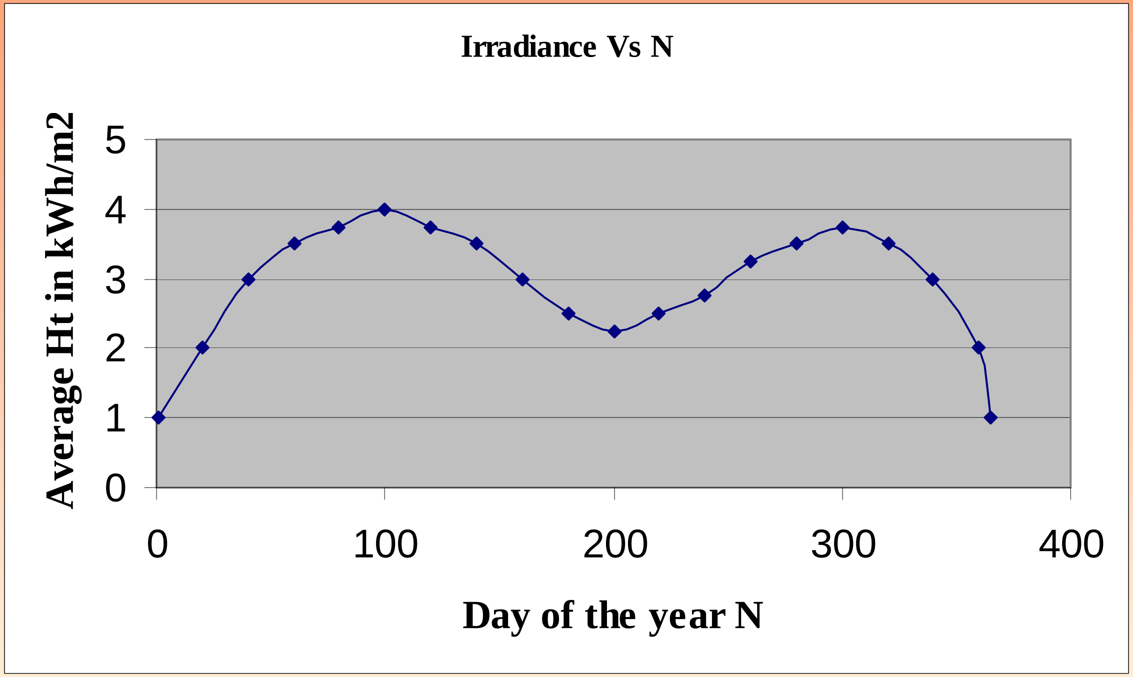
Insolation at any location-4

However, a model for K_T could be developed based on the irradiance level (H) measured at different places and using the relationship $K_T = H/ETR$.

- K_T was initially modeled using linear polynomial regression and multiple regression techniques.
- Since the results obtained with these models were not very accurate, a model was developed using Fourier series techniques of curve fitting since K_T is a periodic function of period one year.
- We have seen earlier that the irradiance in kWh/m^2 can be calculated for any location by inputting latitude of the location, declination angle, day number of the year for a given tilt angle using algorithm.

Insolation at any location-5

- The plot of irradiance as a function of the year is shown in the following figure



- We can see that the level varies with the day of the year. It may reach a peak at some day of the year and reach a bottom on some other day of the year. The peaks and valleys are the direct result of the amount of irradiance reaching the earth. This is a graph that gives us the irradiance level over one year period.

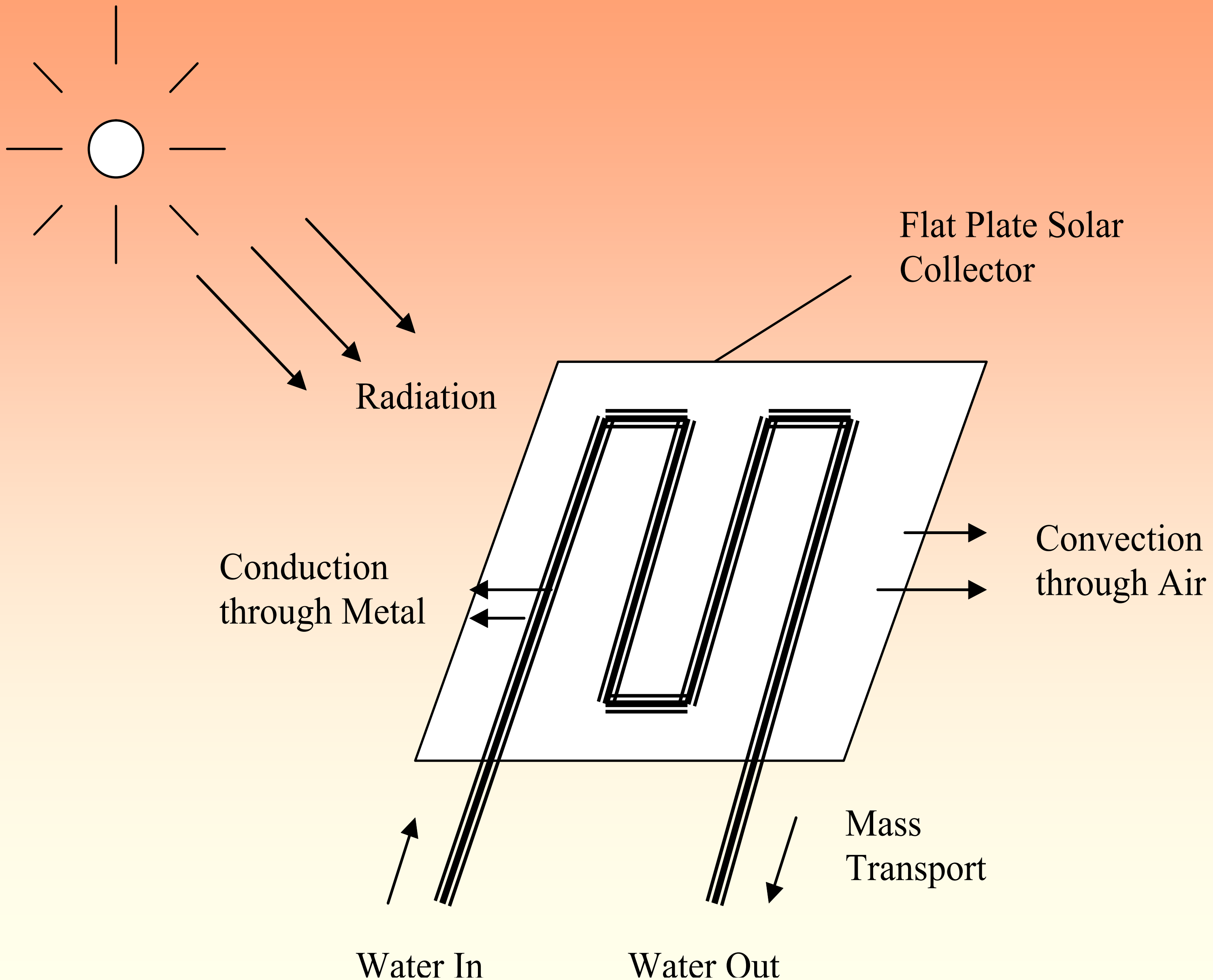
Heat Transfer Concepts

The important terminology one needs to know to understand the heat transfer mechanism is the following:

- Radiation
- Conduction
- Convection
- Mass transport

- To understand the meaning of each of these terms, let us take an example.
- Let us consider a typical flat plate solar collector that is used in solar water heater system and shown in the following figure.

Heat Transfer Concepts-1



Heat Transfer Concepts-2

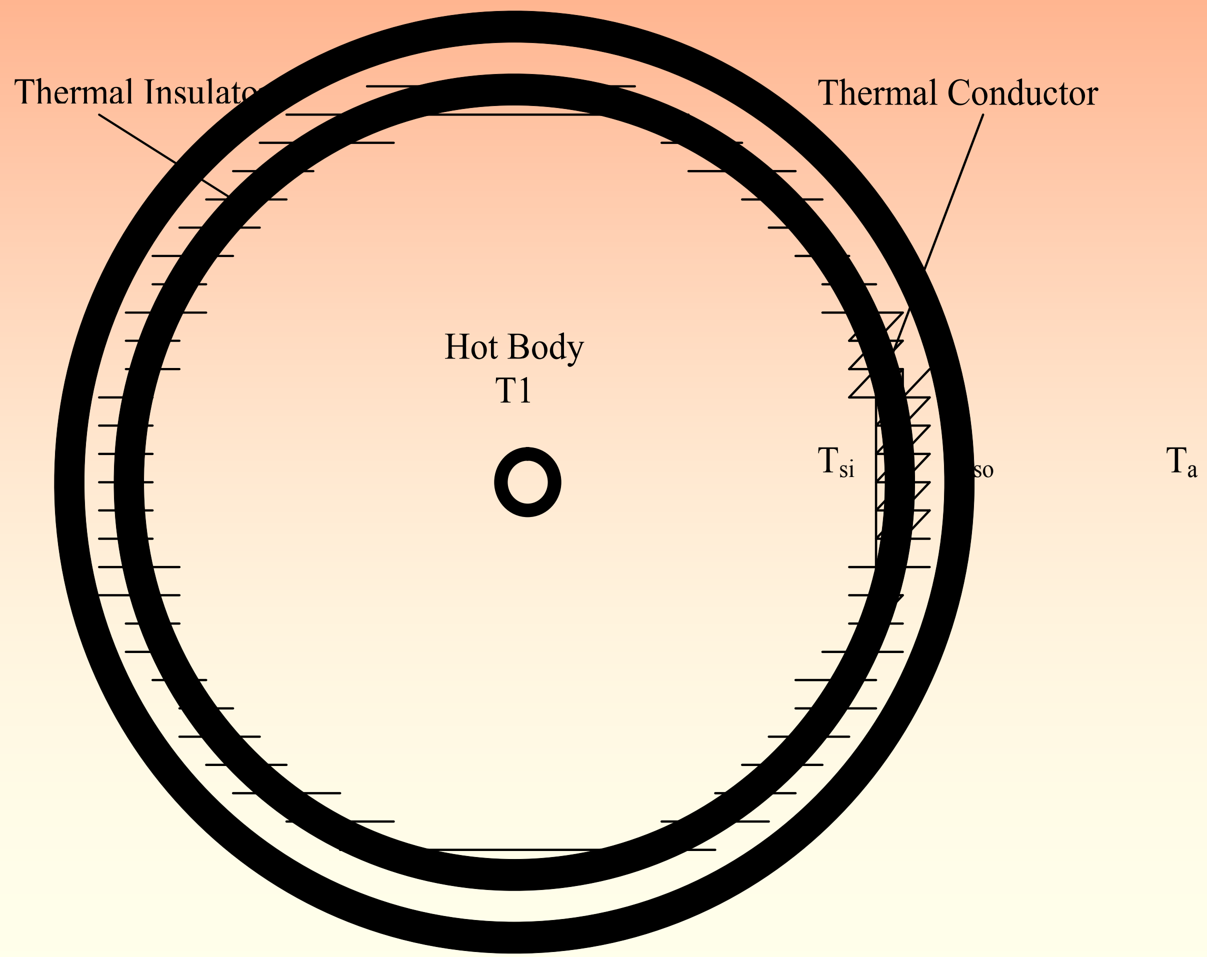
- In the above figure it can be seen that the heat is transferred from Sun to the flat plate solar collector by radiation.
- Radiation is the process of heat transfer from source to the target directly.
- The plate gets heated and transfers part of the heat to the copper tubes carrying water by conduction .
- Conduction is a process of heat transfer between two metals or solids. Part of the heat from the plate gets lost due to convection of heat.

Heat Transfer Concepts-3

- Convection is a process of heat transfer from solids to the surroundings via fluids. The heat transferred to the copper tube gets eventually transferred to the water flowing through the tubes by mass transport.
- Mass transport is a process of heat transfer similar to convection with little difference.
- Convection is an uncontrolled process where as mass transport is a controlled process where the discharge rate of the fluid can be controlled.
- It is important to note at this point that the above-mentioned heat transfer processes are all dependent on the properties of materials.

Modeling of Heat transfer system

To understand modeling concept, let us consider a spherical space as shown in the following figure



Modeling of Heat transfer system-1

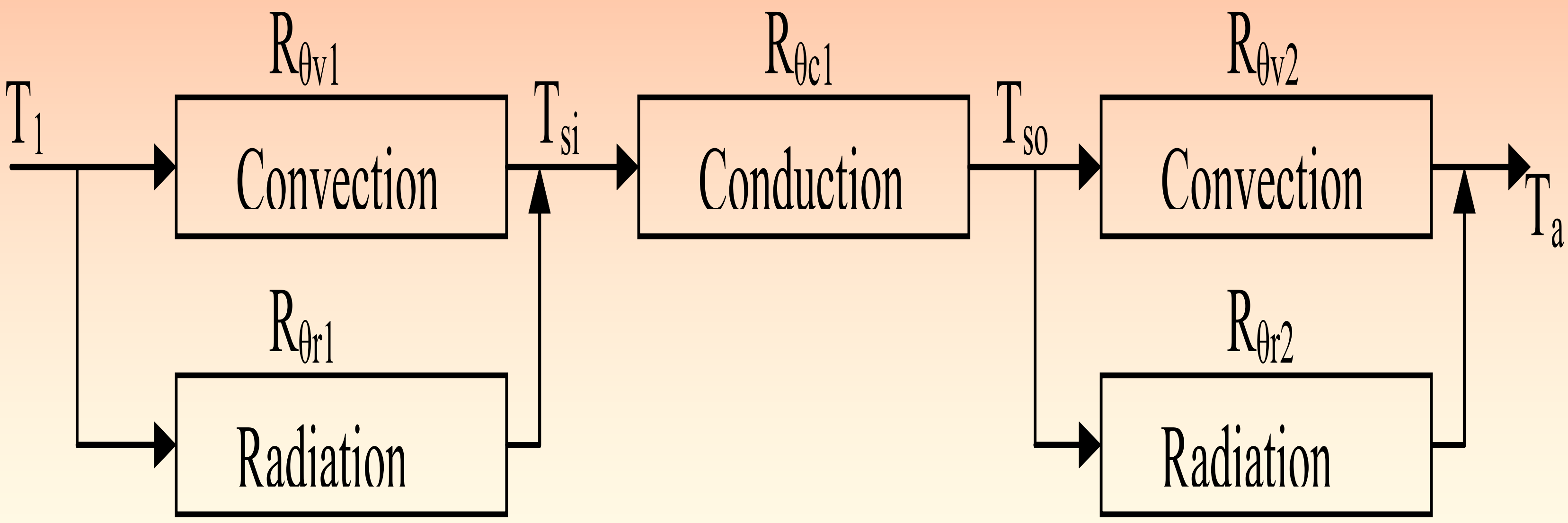
- Most part of the spherical space is enclosed by a thermal insulating material such as thermo-foam.
- The balance part is covered by a thermal conducting material.
- Let a hot body at temperature T_1 is placed at the middle of the space.
- The heat from the hot body flows outwards towards the boundary of the space by radiation and convection .
- Let the temperature at the inner surface of the conductive window of the space be T_{si}.

Modeling of Heat transfer system-2

- The heat flows through the thermal conductive window.
- Let the temperature at the outer surface of the window be T_{so}.
- The heat further flows into the atmosphere by convection and radiation.
- Let the ambient temperature outside the surface be T_a. It can be observed that $T_1 > T_{si} > T_{so} > T_a$.
- The decrease of temperatures during the outflow is attributed to the loss of heat in the process of convection, radiation and conduction of heat.

Modeling of Heat transfer system-3

The following block diagram can represent the outward flow of heat from the hot body to ambient:



Modeling of Heat transfer system-4

- In the block diagram, T_1 is the temperature of the hot body.
- T_{si} is the temperature at the inner surface of the thermal conductor window.
- T_{so} is the temperature at the outer surface of the thermal conductor window.
- T_a is the ambient temperature .
- $R_{\theta v1}$ is the thermal resistance of the convection path between hot body and the inner surface of the thermal conductor.
- $R_{\theta r1}$ is the thermal resistance of the radiation path between hot body and the inner surface of the thermal conductor.

Modeling of Heat transfer system-5

- $R_{\theta c1}$ is the thermal resistance of the conduction path between inner and out surface of the thermal conductor window.
- $R_{\theta v2}$ is the thermal resistance of the convection path between outer surface of the thermal conductor and the ambient.
- $R_{\theta r2}$ is the thermal resistance of the radiation path between outer surface of the thermal conductor and the ambient.
- The heat flow from the hot body to the ambient is analogous to ohms law ($v = I \cdot r$)
- That is effort = flow x resistance .

Modeling of Heat transfer system-6

- With reference to the heat flow, effort is the temperature difference, flow is the power and resistance is the thermal resistance of the path. Hence, we can write

$$T = P \times R_{\theta}.$$

- Based on this analogy, let us find the following terms:
- Thermal Resistance of the convection path is given by

$$R_{\theta v1} = \frac{(T_1 - T_{si})}{P_{\theta v1}} \quad {}^{o}C/W$$

- Power transmitted through convection is given by

$$P_{\theta v1} = \frac{(T_1 - T_{si})}{R_{\theta v1}} \quad , W$$

Modeling of Heat transfer system-7

- Normalizing the power transmitted through convection by dividing it by unit area, we get

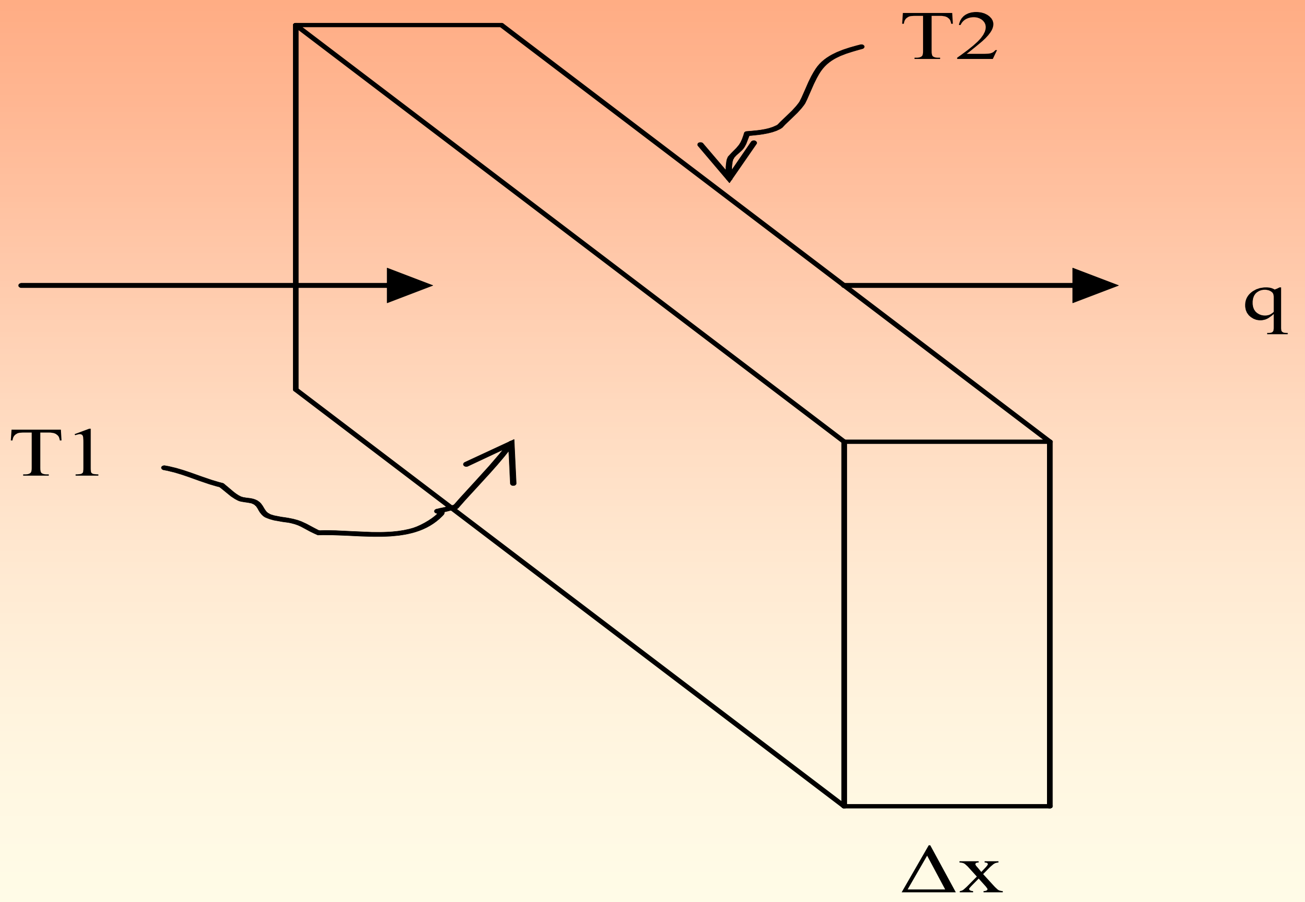
$$\frac{P_{\theta v1}}{A} = \frac{\Delta T}{r_{\theta v1}} = q$$

- Where $r_{\theta v1} = R_{\theta v1} \times A$ = Thermal Resistivity measured in °C m^2/W
- In general we can write $$q = \frac{\Delta T}{r_\theta} = h \cdot \Delta T$$
- Here h is called the Thermal Coefficient, one of the most important terms in heat transfer.

Conduction

- Conduction is a mode of heat transfer in which transfer of energy takes place from the more energetic to the less energetic particles of a substance due to interactions between the particles.
- Heat transfer processes by conduction can be quantified in terms of rate equation known as Fourier's law.
- Let us consider a thin rectangular solid slab as shown in the following figure:

Conduction-1



Conduction-2

- In the figure, q is the heat flux and is the rate of heat transfer in the x direction per unit area perpendicular to the direction of transfer .
- T_1 is the temperature of the hotter side of the slab .
- T_2 is the temperature of the colder side of the slab .
- We have seen earlier that the heat flux is proportional to the temperature difference $(T_1 - T_2)$. That is,

$$q \alpha (T_1 - T_2).$$

Hence, we can write $q = h \cdot \Delta T$

- Where h is the thermal coefficient in W/°C m^2

Conduction-3

- Now, let us define another constant called thermal conductivity, k, in terms of thermal coefficient and the thickness of the slab Δx. That is,

- $k = h \cdot \Delta x$ [(W/°C m²) · m]; [W/°C m]

Hence, we can write $h = \dfrac{k}{\Delta x}$

Substituting this in the expression for heat flux, we get

$$q = k \cdot \frac{\Delta T}{\Delta x}$$

Conduction-4

- Thermal conductivity, k, is a transport property and is the characteristic of the slab material.
- Now, if A is the area of the slab then the heat rate by conduction, P is the product of heat flux and the area. That is

$$P = q \cdot A = k \cdot \frac{\Delta T}{\Delta x} \cdot A$$

- Let us summarize the units of various constants we have considered so far.
- Thermal resistance $R\theta$ = ˚C/W or ˚K/W
- Thermal resistivity $r\theta$ = ˚C· m2/W or ˚K· m2/W
- Thermal co-efficient h = W/˚C· m2 or W/˚K· m2
- Thermal conductivity k = W/˚C· m or W/˚K· m

Conduction-5

Also, we can write expression for all the above-mentioned constants in terms of thermal conductivity as follows:

- Thermal conductivity $= k$
- Thermal co-efficient $h = \dfrac{k}{\Delta x}$
- Thermal resistivity $r_\theta = \dfrac{\Delta x}{k}$
- Thermal resistance $R_\theta = \dfrac{\Delta x}{k \cdot A}$

Conduction-6

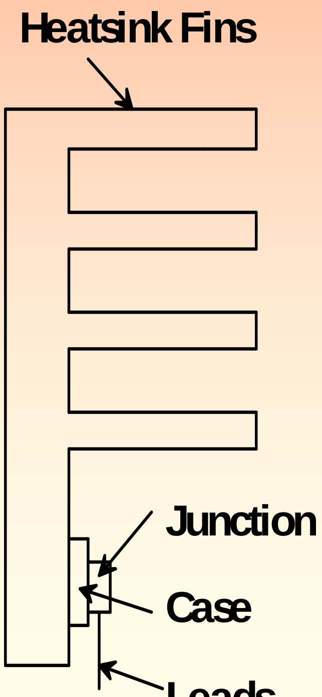
- To design heat sink with appropriate surface area, we need to know the maximum allowable temperature for the junction and the ambient temperature .
- The temperature of a piece of the material depends upon both the temperature rise caused by heat energy flowing in a thermal resistance and the temperature of the surrounding air. Stated mathematically:

$$Temperature = T_A + P_{Diss} R_{\theta t}$$

$$R_{\theta t} = \frac{T_{J\max} - T_A}{P_{Diss,\max}}$$

Conduction-7

Following figure shows how a semiconductor device is mounted on to a heat sink.



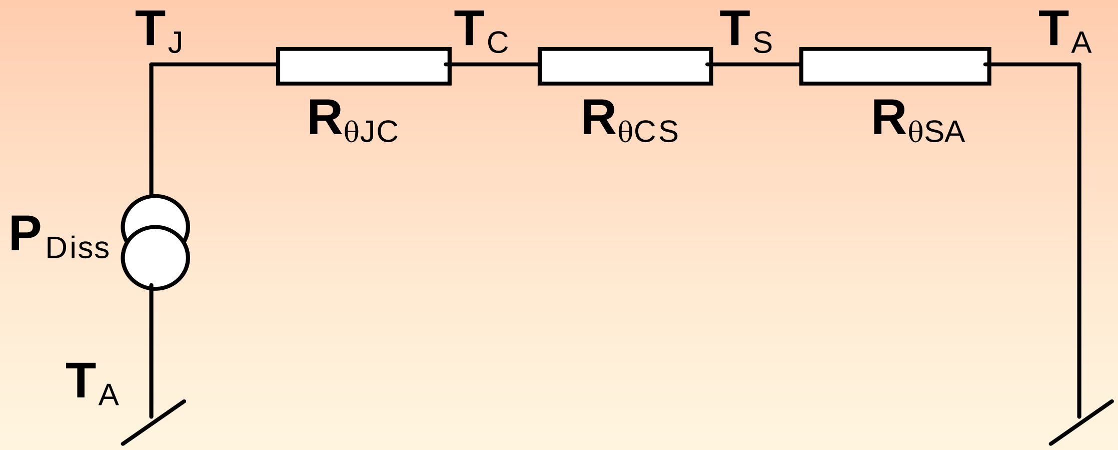
Conduction-8

The thermal resistance of the whole unit is made up of the following three parts:

- $R_{\theta JC}$ is the thermal resistance from junction of the device to case of the device. This specifies how many degrees hotter than the case the semiconductor junction will become for each watt dissipated.
- $R_{\theta CS}$ is the thermal resistance from case to heat sink. It specifies how many degrees hotter than the heat sink the case of the device will become for each watt dissipated.
- $R_{\theta SA}$ is the thermal resistance from heat sink to ambient. It specifies how many degrees hotter than the surrounding air the heat sink will become for each watt dissipated.

Conduction-9

Since all three thermal resistances appear in series with the flow of heat energy, the total thermal resistance is the sum of the three as shown in the following figure:



Conduction-10

$$R_{\theta t} = R_{\theta JC} + R_{\theta CS} + R_{\theta SA}$$

Substituting for $R_{\theta t}$ in the above equation we get the following:

$$R_{\theta JC} + R_{\theta CS} + R_{\theta SA} = \frac{T_{J\max} - T_A}{P_{Diss,\max}}$$

Normally, $R_{\theta JC}$ is provided in the data sheet of any device and $R_{\theta CS}$ can be assumed to be 1˚C/W. Hence, the thermal resistance of the heat sink can be calculated by rearranging the terms as follows:

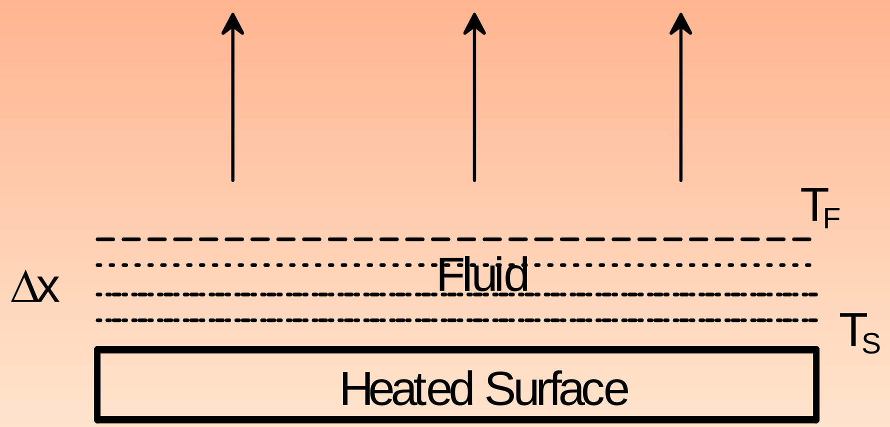
$$R_{\theta SA} = \frac{T_{J\max} - T_A}{P_{Diss,\max}} - R_{\theta JC} - R_{\theta CS}$$

Convection

- Convection is a mode of heat transfer between a solid and a fluid when there is a temperature difference between a fluid and a solid.
- The convection heat transfer mode is comprised of following two mechanisms:
- Energy transfer due to random molecular motion (diffusion).
- Energy transferred by the bulk motion of the fluid.
- Such motion in the presence of a temperature gradient contributes to heat transfer.

Convection-1

Let us consider a fluid flow over a heated surface as shown in the following figure:



The interaction between the fluid and the heated surface results in the development of a region in the fluid through which the velocity varies from zero at the surface to a finite value associated with the flow .

Convection-2

Convection heat transfer may be classified into the following types:

- **Free Convection:** Here the flow is induced by buoyancy forces, which arise from density differences, caused by temperature variations in the fluid.
- **Forced Convection:** Here the flow is caused by external means such as fan, pump or atmospheric winds.

Let us derive expressions for convective thermal resistance, convective thermal resistivity, convective thermal conductivity and convective thermal coefficient . We have seen in earlier that the expression for power (heat flow) is given by the following:

Convection-3

$$P = k \cdot \frac{\Delta T}{\Delta x} \cdot A$$ W; where

k = Thermal conductivity

A = Cross sectional area perpendicular to the heat flow

$\Delta T = T_S - T_F$ = Temperature difference between surface and outer flow

Δx = Thickness of the fluid

An additional parameter is added which is measurable and the fluid thickness is taken as a fraction of the measurable parameter as given by the following expression:

Convection-4

$$P = k \cdot \frac{X}{\Delta x} \cdot \frac{\Delta T}{X} \cdot A$$ W; where X = Characteristic dimension

The ratio of Characteristic dimension to the fluid thickness is called as the Nusselt number, a dimensionless quantity represented by N. Hence

$$P = k \cdot \mathrm{N} \cdot \frac{\Delta T}{X} \cdot A \quad ;\mathrm{W}$$

Rearranging the terms, we can get the expression for heat flow rate/unit area (heat density) and convective thermal resistance as

$$\frac{P}{A} = q = k \cdot \mathrm{N} \cdot \frac{\Delta T}{X} \quad ;\mathrm{W/m^2}$$

$$R_{\theta v} = \frac{\Delta T}{P} = \frac{X}{k \cdot \mathrm{N} \cdot A} \quad ;{}^{\circ}\mathrm{C/W}$$

Convection-5

Now, we know that the thermal resistivity is the product of thermal resistance and area.

$$r_{\theta v} = \frac{X}{k \cdot \mathrm{N} \cdot A} \cdot A = \frac{X}{k \cdot \mathrm{N}} \quad ; \ ^{\circ}\mathrm{Cm}^2/\mathrm{W}$$

From the above expression, we can write the expression for convective thermal coefficient (reciprocal of thermal resistivity) as

$$h_{\theta v} = \frac{k \cdot \mathrm{N}}{X} \quad ; \ \mathrm{W}/^{\circ}\mathrm{C}/\mathrm{m}^2$$

Substituting for convective thermal coefficient in the expression for heat density and heat flow rate we get the following expressions:

$$q = h_{\theta v} \cdot \Delta T \quad ; \ \mathrm{W/m2}$$

$$P = h_{\theta v} \cdot \Delta T \cdot A \ ; \ \mathrm{W}$$

Determination of Nusselt Number

- Nusselt Number is a dimensionless number that can be determined experimentally only .
- In convection mode of heat transfer, we need to know the following for determining the Nusselt Number:
- Speed of the fluid flow.
- Property of the fluid.
- Geometry of the solid.

Determination of Nusselt Number-1

- **Rayliegh Number** for free convection. It is represented by A and is given by the following expression:

$$A = \frac{g \cdot \beta \cdot X^3 \cdot \Delta T}{\delta \cdot \nu} \quad ; \text{where}$$

g = Acceleration due to gravity = 9.81 sec/m^2

β = Coefficient of thermal expansion

X = Characteristic Dimension

δ = Thermal diffusivity

υ = Kinemetic viscosity of fluid

Determination of Nusselt Number-2

Reynolds Number for forced convection. It is represented by R and is given by the following expression:

$$R = \frac{u \cdot X}{\nu} \quad \text{; where}$$

u = mean velocity of flow

X = Characteristic dimension

υ = Kinemetic viscosity of fluid

We can see that the Nusselt number is a function of both Rayliegh Number and Reynolds Number, that is

N = f(A, R)

Determination of Nusselt Number-3

- The boundary layer can be classified into laminar or turbulent based on the Rayliegh Number and Reynolds Number.

For Rayliegh Number:

- $A \geq 10^5$: Turbulent flow
- $10^3 \leq A \leq 10^5$: Laminar flow
- $A < 10^3$: Free convection is not possible

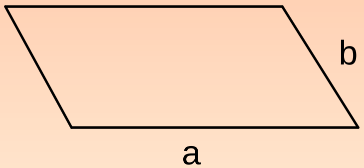
For Reynolds Number:

- $R \geq 2300$:Turbulent flow
- $R < 2300$: Laminar flow

Free Convection - Rayliegh Number -4

- Let us find expressions for Nusselt number for various shapes and for Laminar & Turbulent flows in terms of either Rayliegh Number or Reynolds Number for free convection and forced convection respectively.

Horizontal flat plate of length 'a' and breadth 'b' as shown in the following figure:



Characteristic Dimension: $X = \frac{(a+b)}{2}$

For Laminar Flow: $10^2 < A < 10^5$

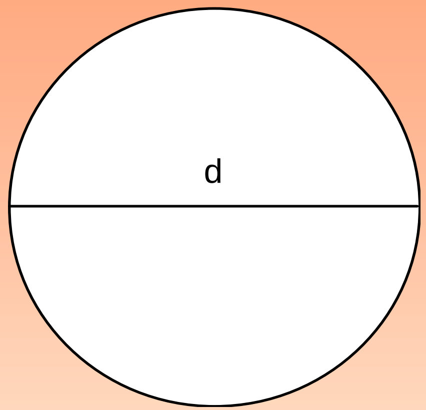
$N = 0.54\ A^{0.25}$

For Turbulent Flow: $A > 10^5$

$N = 0.14\ A^{0.33}$

Free Convection - Rayliegh Number-5

- ***Circular plate*** with diameter 'd' as shown in the following figure:



Characteristic Dimension: $X = d$

For Laminar Flow:

- $10^2 < A < 10^5$
- $N = 0.54\ A^{0.25}$

For Turbulent Flow:

- $A > 10^5$
- $N = 0.14\ A^{0.33}$

Free Convection - Rayliegh Number-6

Horizontal cylinder with diameter ‘d’ as shown in the following figure:

Characteristic Dimension X = d

For Laminar Flow:

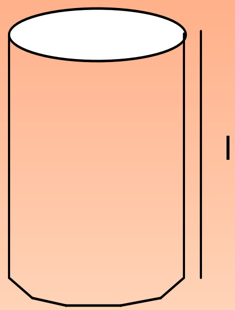
- $10^4 < A < 10^9$
- $N = 0.47\ A^{0.25}$

For Turbulent Flow:

- $A > 10^9$
- $N = 0.10\ A^{0.33}$

Free Convection - Rayliegh Number-7

Vertical cylinder with length ‘l’ as shown in the following figure:



Characteristic dimension X = l

For Laminar Flow:

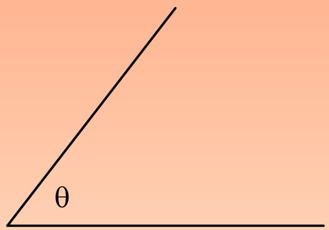
- $10^4 < A < 10^9$
- $N = 0.56\ A^{0.25}$

For Turbulent Flow:

- $10^9 < A < 10^{12}$
- $N = 0.20\ A^{0.4}$

Free Convection - Rayliegh Number-8

Parallel plates at an angle ‘θ’ as shown in the following figure:



Characteristic Dimension X = Distance between parallel plates

For $\theta < 50^\circ$

For Laminar Flow:

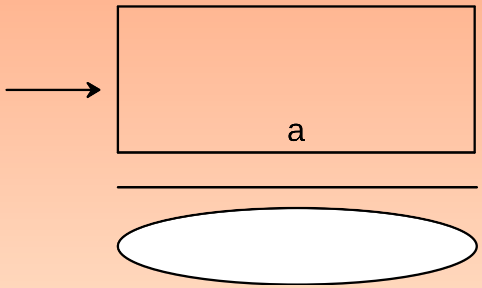
- Not possible

For Turbulent Flow:

- $A > 10^5$
- $N = 0.062\ A^{0.33}$

Forced Convection – Reynolds Number

Flat plate of length ‘a’ or ***Circular plate*** of diameter ‘a’ as shown in the following figure:



Characteristic Dimension X = a

For Laminar Flow:

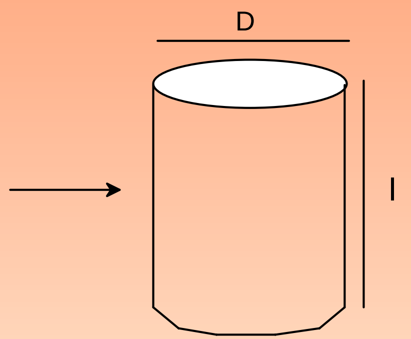
- $R < 5 \times 10^5$
- $N = 0.664 \times R^{0.5} \times (\upsilon/\delta)^{0.33}$

For Turbulent Flow:

- $R > 5 \times 10^5$
- $N = 0.37 \times R^{0.8} \times (\upsilon/\delta)^{0.33}$

Forced Convection - Reynolds Number-1

Vertical cylinder with length 'l' and diameter 'D' where the flow is over the cylinder as shown in the following figure:



Characteristic Dimension X = Diameter, D

For Laminar Flow:

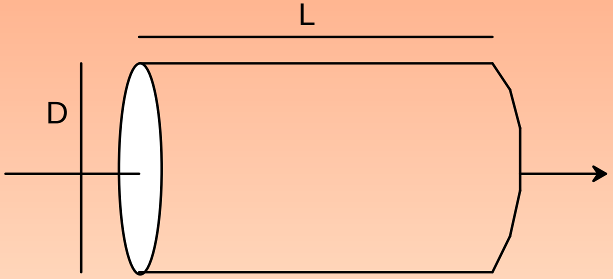
- $0.1 < R < 1000$
- $N = (0.35 + 0.56\ R^{0.52}) \times (\upsilon/\delta)^{0.3}$

For Turbulent Flow:

- $1000 < R < 5 \times 10^5$
- $N = 0.26\ R^{0.6} \times (\upsilon/\delta)^{0.3}$

Forced Convection - Reynolds Number-2

Horizontal cylinder with diameter 'd' where the flow is into the cylinder as shown in the following figure:



Characteristic Dimension X = Length, L

For Laminar Flow:

- $R < 2300$
- $N = 1.86\ (R \times \upsilon/\delta \times D/L)^{0.33}$

For Turbulent Flow:

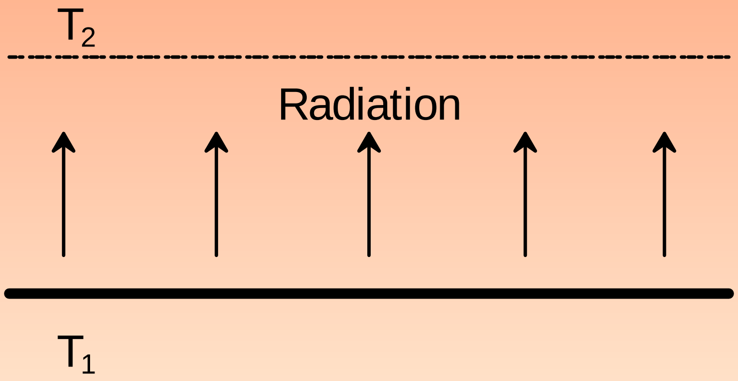
- $R > 2300$
- $N = 0.027 \times R^{0.8} \times (\upsilon/\delta)^{0.33}$

Radiation

- Thermal radiation is energy emitted by matter that is at a finite temperature.
- The emission may be attributed to changes in the electron configurations of the constituent atoms or molecules.
- The energy of the radiation field is transported by electromagnetic waves.
- The transfer of energy by radiation does not require the presence of a material medium.

Radiation-1

Let us consider a hot body at temperature T_1 as shown in the following figure:



Let T_2 be the temperature at some horizontal surface parallel to the radiating body such that $T_2 < T_1$.

We have seen in the earlier heat flow modes that the expression for heat flow is given by the following expression:

Radiation-2

$$P = h_r \cdot A \cdot \Delta T$$ W, where

- h_r is the radiation thermal coefficient
- A is the surface area perpendicular to the flow of radiation
- ΔT is the temperature difference between the radiating body and the reference point

Now the radiating thermal coefficient is given by the following expression:

$$h_r = 4 \cdot \sigma \cdot \varepsilon_{eff} \cdot (1-\phi) \cdot \left(\frac{T_1 + T_2}{2}\right)^3$$, where

σ = Stefan Boltzman's constant = 5.67 x 10^{-8} W/m^2/°K^4

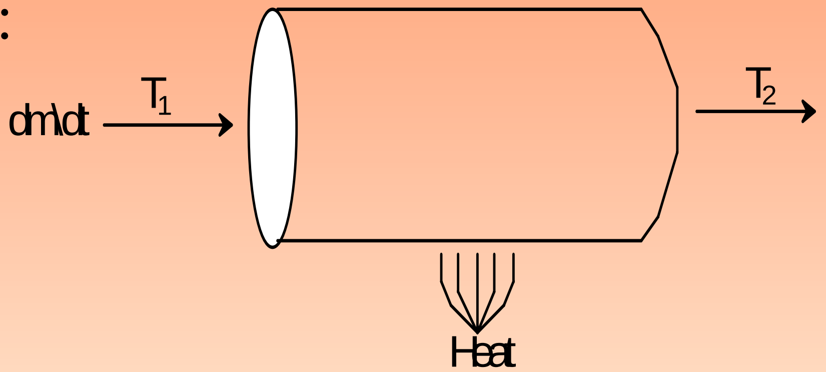
E_{eff} = effective emittance

φ = Shielding factor

- The shielding factor for parallel plates is zero.

Heat transfer by mass transport

- Let us consider the fluid flow through a heated pipe as shown in the following figure:



- Let T_1 is the temperature at the entry point and at ambient temperature.
- Let T_2 is the temperature at the exit point such that $T_1 < T_2$.
- Let m be the mass of the fluid in Kg, flowing through the pipe and (dm/dot) is the mass flow rate in Kg/s.

Heat transfer by mass transport-2

- Hence the net heat flow due to the mass transfer P_m is given by the following expression:

$$P_m = \frac{dm}{dt} \cdot s \cdot (T_2 - T_1) \quad \text{W, where}$$

- S is called the specific heat of the fluid given in J/Kg/°K.
- This is a constant for a given fluid.
- Now the thermal resistance of the process can be found from the following basic relationship:

$$(T_2 - T_1) = P_m \cdot R_m$$

Hence $R_m = \frac{(T_2 - T_1)}{P_m}$, °K/W

Heat transfer by mass transport-3

Substituting the value of P_m from the above expression, we get the expression for thermal resistance as:

$$R_m = \frac{(T_2 - T_1)}{(dm/dt) \cdot s \cdot (T_2 - T_1)} = \frac{1}{(dm/dt) \cdot s} \quad , \ ^\circ K/W$$

- The most effective means of heat transfer is as latent heat of vaporization .
- Latent heat of vaporization is the amount of energy required to vaporize 1 Kg of water that is already at 100 ˚C. It is denoted by Λ.
- To vaporize 1 Kg of water, 2.4 MJ of heat is required where as to heat water through 100 ˚C, only 0.42 MJ is required.

Heat transfer by mass transport-4

- Heat taken from the heat source at T_1 is carried to wherever the vapor condenses at T_2. The associated heat flow is given by:

$$P_m = \frac{dm}{dt} \cdot \Lambda \quad \text{W, where}$$

- (dm/dot) is the rate at which fluid is being evaporated and Λ is the latent heat of vaporization.
- Now the associated thermal resistance can be given by the following expression:

$$R_m = \frac{(T_1 - T_2)}{P_m} = \frac{(T_1 - T_2)}{(dm/dt) \cdot \Lambda} \quad {}^\circ\text{K/W}$$

Applications

Solar thermal power plants

The two main types of solar thermal power plants are

- Concentrating Solar Power (CSP) plants.
- Solar Chimneys

Concentrating Solar Power (CSP) plants

- Solar thermal power plants generally use reflectors to concentrate sunlight into a heat absorber.
- Such power plants are known as Concentrating Solar Power (CSP) plants.

Applications-1

Concentrating Solar Power (CSP) plants

- Concentrating solar power plants produce electric power by converting the sun's energy into high-temperature heat using various mirror configurations.
- The heat is then channeled through a conventional generator.
- The plants consist of two parts, one that collects solar energy and converts it to heat, and another that converts heat energy to electricity.

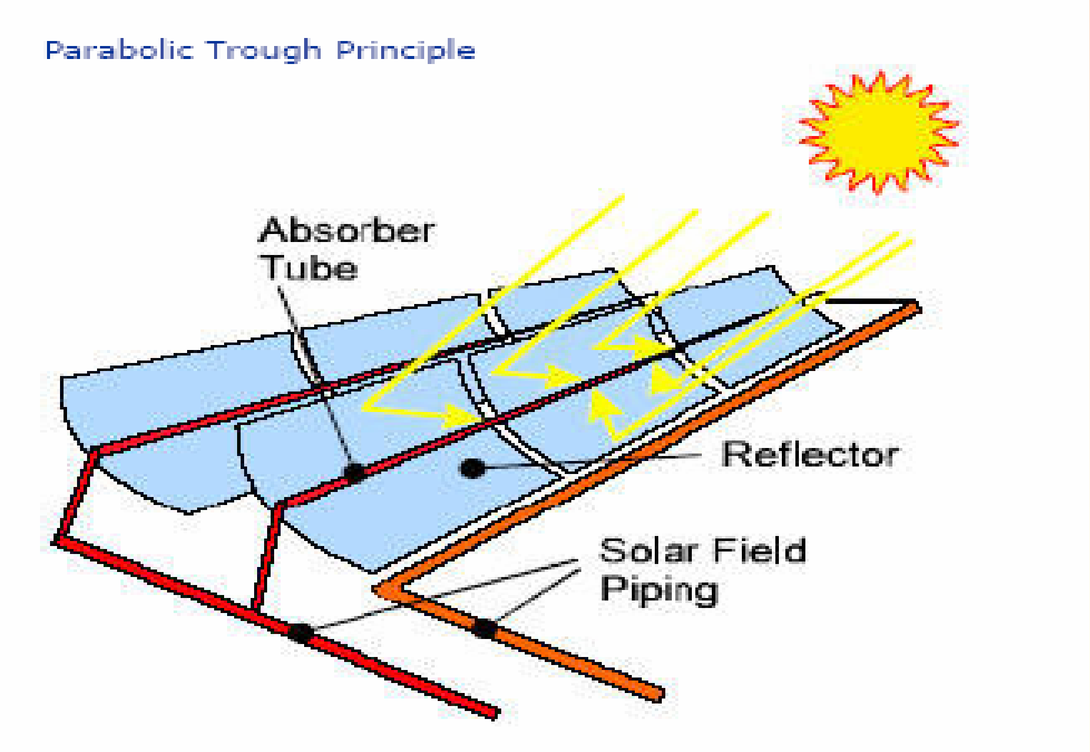
Applications-2

- Concentrating solar power systems can be sized for village power (10 kilowatts) or grid-connected applications (up to 100 megawatts).
- Some systems use thermal storage during cloudy periods or at night.
- There are four CSP technologies being promoted internationally.
- For each of these, there exists various design variations or different configurations.
- The amount of power generated by a concentrating solar power plant depends on the amount of direct sunlight.
- Like concentrating photovoltaic concentrators, these technologies use only direct-beam sunlight, rather than diffuse solar radiation.

Types of CSP plants

Parabolic Trough Systems

- The sun's energy is concentrated by parabolically curved, trough-shaped reflectors onto a receiver pipe running along the inside of the curved surface .

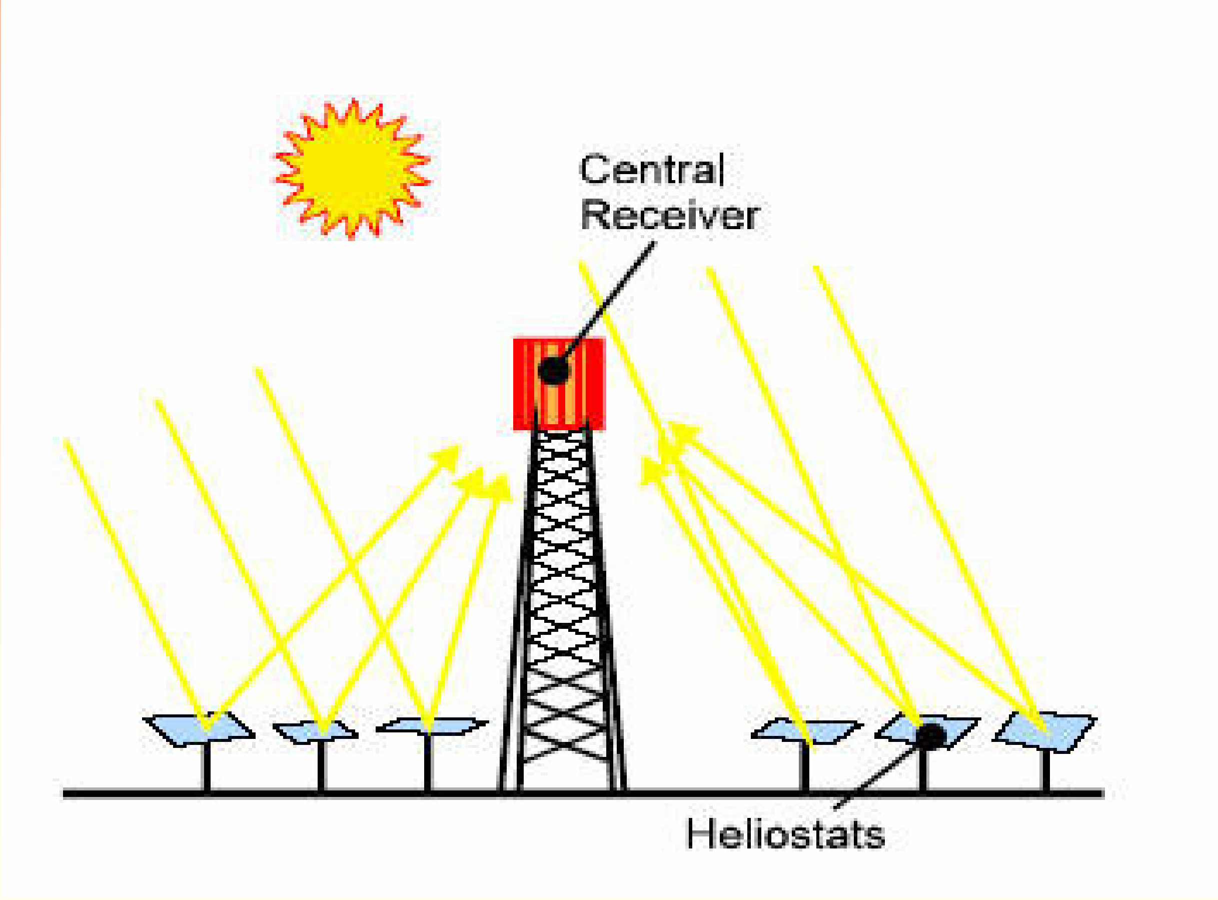


Types of CSP plants-1

- This energy heats oil flowing through the pipe and the heat energy is then used to generate electricity in a conventional steam generator.
- A collector field comprises many troughs in parallel rows aligned on a north-south axis.
- This configuration enables the single-axis troughs to track the sun from east to west during the day to ensure that the sun is continuously focused on the receiver pipes.
- Individual trough systems currently can generate about 80 megawatts of electricity .
- Another option under investigation is the approximation of the parabolic troughs by segmented mirrors according to the principle of Fresnel.

Power Tower Systems

A power tower converts sunshine into clean electricity for the electricity grids.

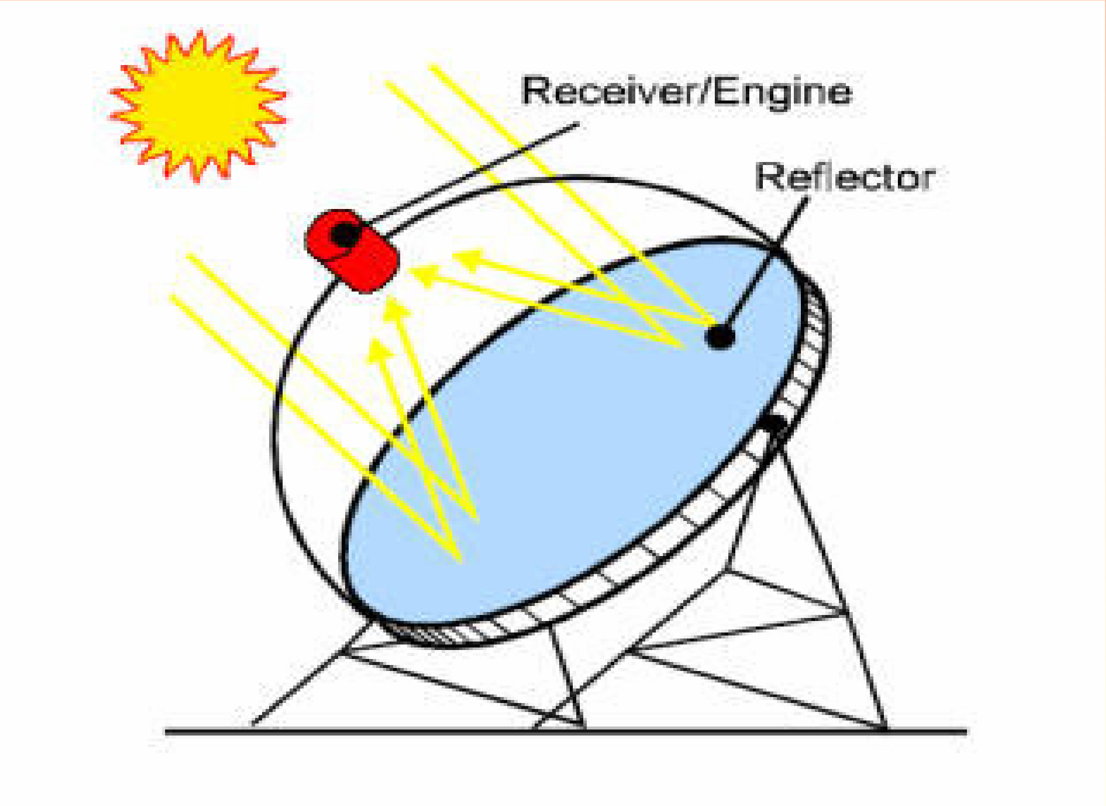


Power Tower Systems-1

- The technology utilizes many large, sun-tracking mirrors (heliostats) to focus sunlight on a receiver at the top of a tower.
- A heat transfer fluid heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine-generator to produce electricity.
- Early power towers (such as the Solar One plant) utilized steam as the heat transfer fluid; current designs (including Solar Two, shown in fig) utilize molten nitrate salt because of its superior heat transfer and energy storage capabilities.
- Individual commercial plants will be sized to produce anywhere from 50 to 200 MW of electricity.

Parabolic Dish Systems

- Parabolic dish systems consist of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point.

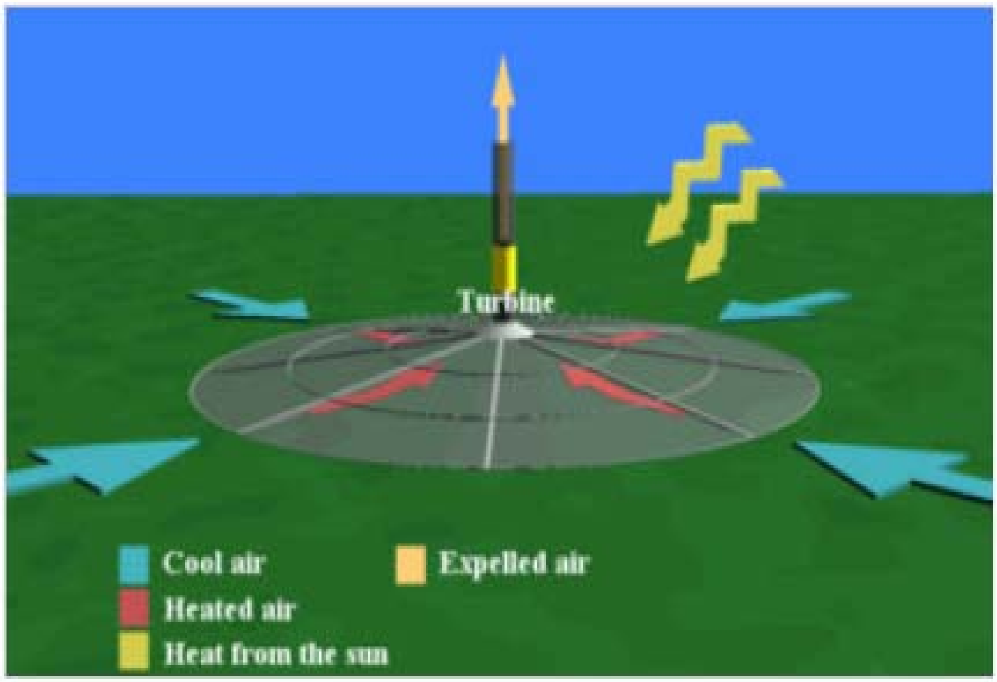


Parabolic Dish Systems-1

- These concentrators are mounted on a structure with a two-axis tracking system to follow the sun.
- The collected heat is typically utilized directly by a heat engine mounted on the receiver moving with the dish structure.
- Stirling and Brayton cycle engines are currently favored for power conversion.
- Projects of modular systems have been realized with total capacities up to 5 MW.
- The modules have max sizes of 50 kW and have achieved peak efficiencies up to 30% net.

Solar chimney

- A solar chimney is a solar thermal power plant where air passes under a very large agricultural glass house (between 2 and 30 kilometers in diameter).



General concept of proposed solar chimney power station

Solar chimney-2

- The air is heated by the sun and channeled upwards towards a convection tower.
- It then rises naturally and is used to drive turbines, which generate electricity.
- A **solar chimney** is an apparatus for harnessing solar energy by convection of heated air.
- In its simplest form, it simply consists of a black-painted chimney.
- During the daytime, solar energy heats the chimney and thereby heats the air within it, resulting in an updraft of air within the chimney.

Solar chimney-3

- The suction this creates at the chimney base can also be used to ventilate, and thereby cool, the building below .
- In most parts of the world, it is easier to harness wind power for such ventilation, but on hot windless days such a chimney can provide ventilation where there would otherwise be none.
- This principle has been proposed for electric power generation, using a large greenhouse at the base rather than relying on heating of the chimney itself.
- The main problem with this approach is the relatively small difference in temperature between the highest and lowest temperatures in the system.

Water heating

- Water heating is required in most countries of the world for both domestic and commercial use.
- The simplest solar water heater is a piece of black plastic pipe, filled with water, and laid in the sun for the water to heat up.
- Simple solar water heaters usually comprise a series of pipes, which are painted black, sitting inside an insulated box fronted with a glass panel. This is known as a solar collector.
- The fluid to be heated passes through the collector and into a tank for storage.
- The fluid can be cycled through the tank several times to raise the heat of the fluid to the required temperature.

Water heating-1

The ***thermosyphon*** system makes use of the natural tendency of hot water to rise above cold water.

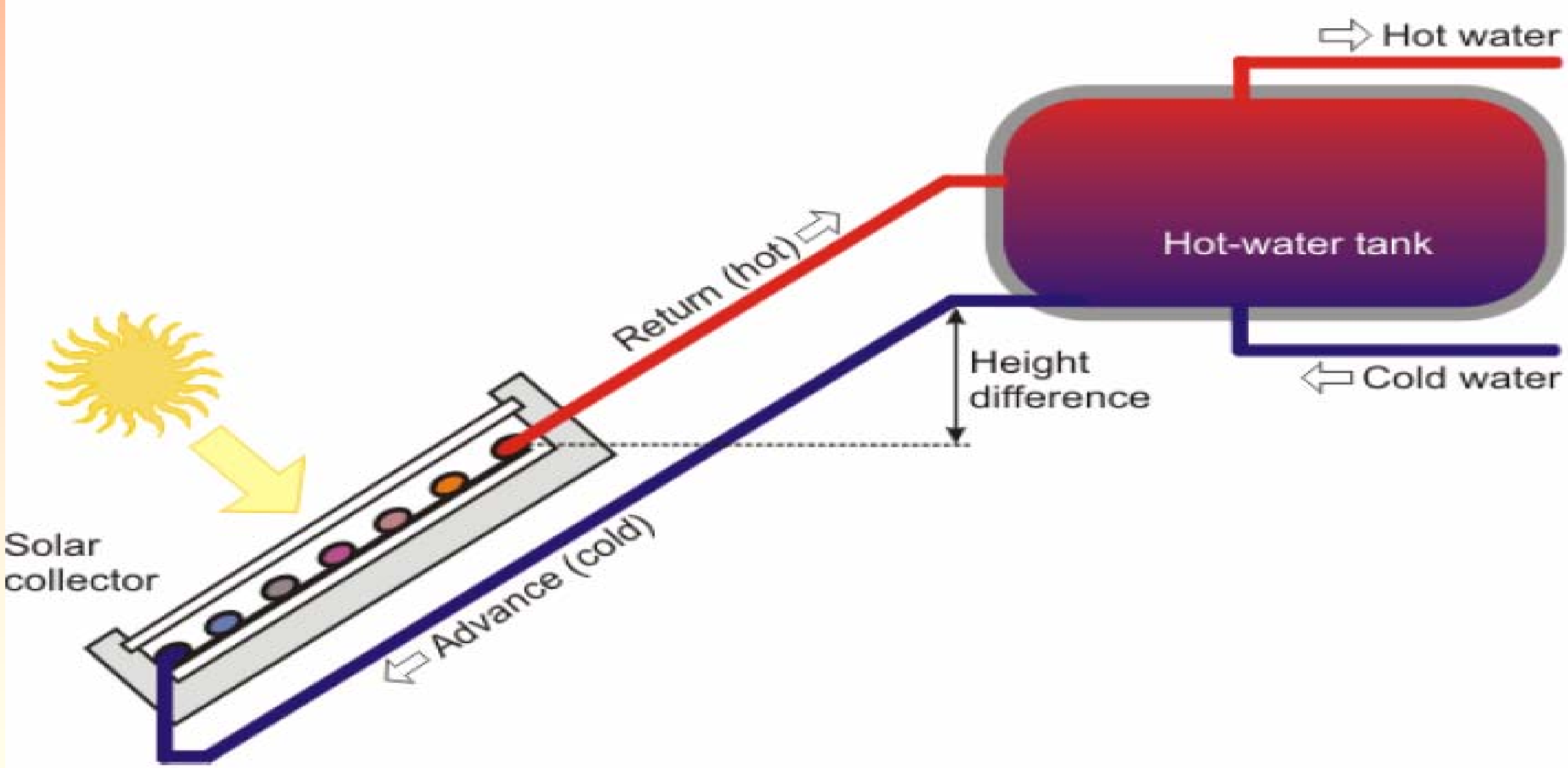


FIGURE 4. A thermosyphon system

Water heating-2

- The tank in such a system is always placed above the top of the collector and as water is heated in the collector it rises and is replaced by cold water from the bottom of the tank.
- This cycle will continue until the temperature of the water in the tank is equal to that of the panel.
- A one-way valve is usually fitted in the system to prevent the reverse occurring at night when the temperature drops.
- As hot water is drawn off for use, fresh cold water is fed into the system from the mains.
- As most solar collectors are fitted on the roofs of houses, this system is not always convenient, as it is difficult to site the tank above the collector, in which case the system will need a pump to circulate the water.

Water heating-3

- ***Pumped*** solar water heaters use a pumping device to drive the water through the collector.
- The advantage of this system is that the storage tank can be sited below the collector.
- The disadvantage of course is that electricity is required to drive the pump.
- Often the fluid circulating in the collector will be treated with an anti-corrosive and /or anti-freeze chemical.
- In this case a heat exchanger is required to transfer the heat to the consumers hot water supply.

Water heating-4

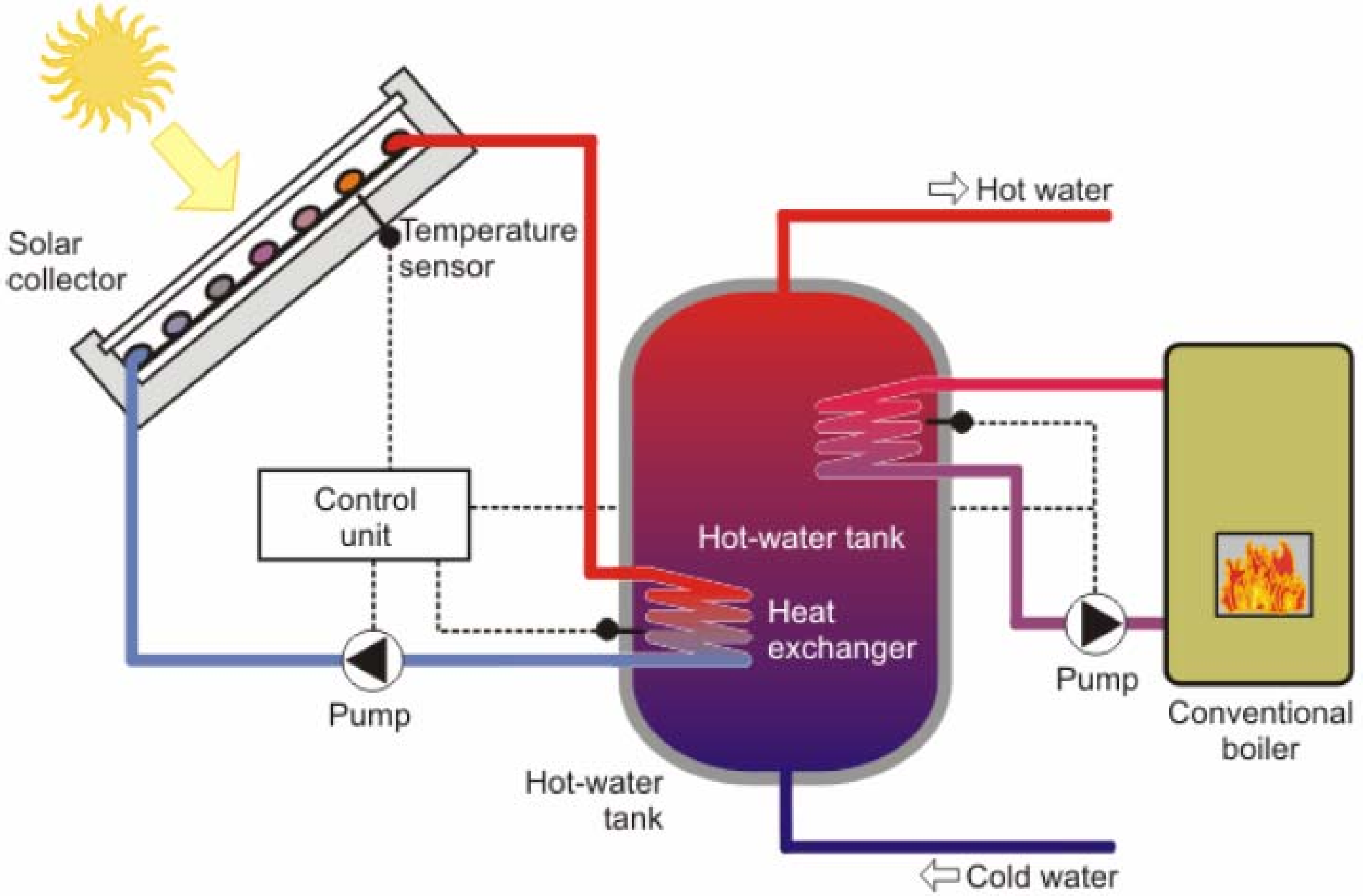


FIGURE 5. A double-cycle system with forced circulation with a conventional boiler for back-up heating

Solar District Heating

- If an entire housing estate should be fitted with solar systems, one solution is a solar district heating system (see Figure).
- The collectors are either distributed on the houses, or replaced by a large, central solar collector.
- The collectors then heat up a big central storage tank, from which much of the heat is distributed back to the houses.
- The surface-to-volume ratio of a central storage tank is much better than that for distributed storage systems, so the storage losses are much lower, and even permit seasonal heat storage.
- Solar district heating is also an option if room heating is to be covered by solar energy.

Solar District Heating-1

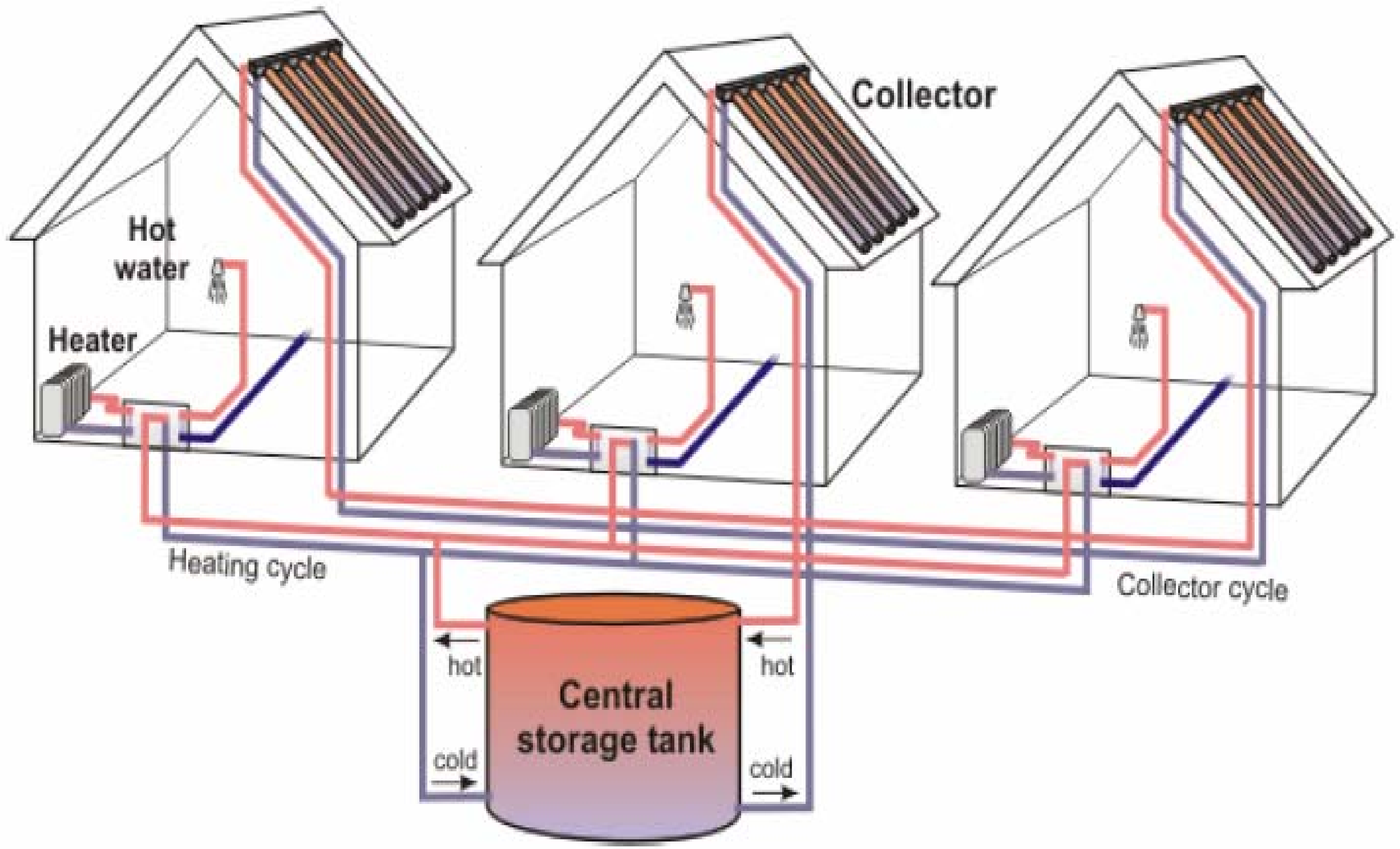


FIGURE 6. A solar district heating system

Cost Benefits of solar water heating system

- The most cost- effective way to install a solar geyser is to integrate the collector assembly, cold-water supply and piping with the design of a new house under construction.
- Solar geysers can easily be installed in group houses and apartments, especially during construction, if adequate provisions are made for piping, collector assembly and cold-water supply. Proper load matching is required to ensure that the capacity of the system installed is optimized to meet the daily hot water needs of the end-user.
- Current prices of domestic SWHs are around Rest. 20,000 for a 100 litres per day system.

Solar Dryer

- Controlled drying is required for various crops and products, such as grain, coffee, tobacco, fruits vegetables and fish.
- Their quality can be enhanced if the drying is properly carried out.
- Solar thermal technology can be used to assist with the drying of such products.
- Solar drying is in practice since the time imp-memorable for preservation of food and agriculture crops.
- This was done particularly by open sun drying under open the sky.
- In open air Solar drying the heat is supplied by direct absorption of solar radiation by material being dried.

Solar Dryer-1

This process has several disadvantages

Disadvantages of mechanical and artificial drying:

- Spoilage of product due to adverse climatic condition like rain, wind etc
- Loss of material due to birds and animals
- Deterioration of the material by decomposition, insects and fungus growth
- Highly energy intensive and expensive.
- Solar dryer make use of solar radiation, ambient temperature, relative humidity.
- Heated air is passed naturally or mechanically circulated to remove moisture from material placed in side the enclosure.

Solar Dryer-2

Solar dryer is a very useful device for

- Agriculture crop drying
- Food processing industries for dehydration of fruits, potatoes, onions and other vegetables,
- Dairy industries for production of milk powder, casein etc.
- Seasoning of wood and timber.
- Textile industries for drying of textile materials.

Solar Dryer-3

Working of solar dryer

- The main principle of operation is to raise the heat of the product, which is usually held within a compartment or box, while at the same time passing air through the compartment to remove moisture.
- The flow of air is often promoted using the 'stack' effect which takes advantage of the fact that hot air rises and can therefore be drawn upwards through a chimney, while drawing in cooler air from below. Alternatively a fan can be used.
- The size and shape of the compartment varies depending on the product and the scale of the drying system.

Solar Dryer-4

- Large systems can use large barns while smaller systems may have a few trays in a small wooden housing.
- Solar crop drying technologies can help reduce environmental degradation caused by the use of fuel wood or fossil fuels for crop drying and can also help to reduce the costs associated with these fuels and hence the cost of the product.

The principal types of solar dryers are enumerated below.

- Solar cabinet dryer.
- Solar green house dryers.
- Indirects sonars drayer.

Solar Distillation/De -salination

Solar Stills

- Solar still is a device to desalinate impure water like brackish or saline water.
- It a simple device to get potable/fresh distilled water from impure water, using solar energy as fuel, for its various applications in domestic, industrial and academic sectors .
- A solar still consist of shallow triangular basin made up of Fiber Reinforced Plastic (FRP).
- Bottom of the basin is painted black so as to absorb solar heat effectively.
- Top of the basin is covered with transparent glass tilt fitted so that maximum solar radiation can be transmitted in to the still.

Solar Distillation/De –salination-1

- Edges of the glass are sealed with the basin using tar tape so that the entire basin becomes airtight.
- Entire assembly is placed on a structure made of MS angle. Out let is connected with a storage container.

  Solar Stills have got major advantages over other conventional Distillation / water purification /de-mineralization systems as follows:

- Produces pure water
- No prime movers required
- No conventional energy required
- No skilled operator required
- Local manufacturing/repairing
- Low investment
- Can purify highly saline water (even sea water)

Solar Distillation/De –salination-2

Working of solar still

- Working of solar still is based on simple scientific principle of Evaporation and condensation.
- Brackish or saline water is filled in still basin, which is painted black at the bottom.
- Solar radiation received at the surface is absorbed effectively by the blacken surface and heat is transferred to the water in the basin.
- Temperature of the water increases that increases rate of evaporation.
- Water vapor formed by evaporation rises upward and condenses on the inner surface of the cover glass, which is relatively cold.
- Condensed water vapor trickles down in to troughs from there it is collected in to the storage container.

Solar box cooker

- A **solar box cooker** is an insulated transparent-topped box with a reflective lid.
- It is designed to capture solar power and keep its interior warm.
- The major parts of a solar cooker are enumerated below.

  Important Parts of Solar Cooker:

- **Outer Box:** The outer box of a solar cooker is generally made of G.I. or aluminum sheet or fiber reinforced plastic.
- **Inner Cooking Box (Tray):** This is made from aluminum sheet. The inner cooking box is slightly smaller than the outer box. It is coated with black paint so as to easily absorb solar radiation and transfer the heat to the cooking pots.

Solar box cooker-1

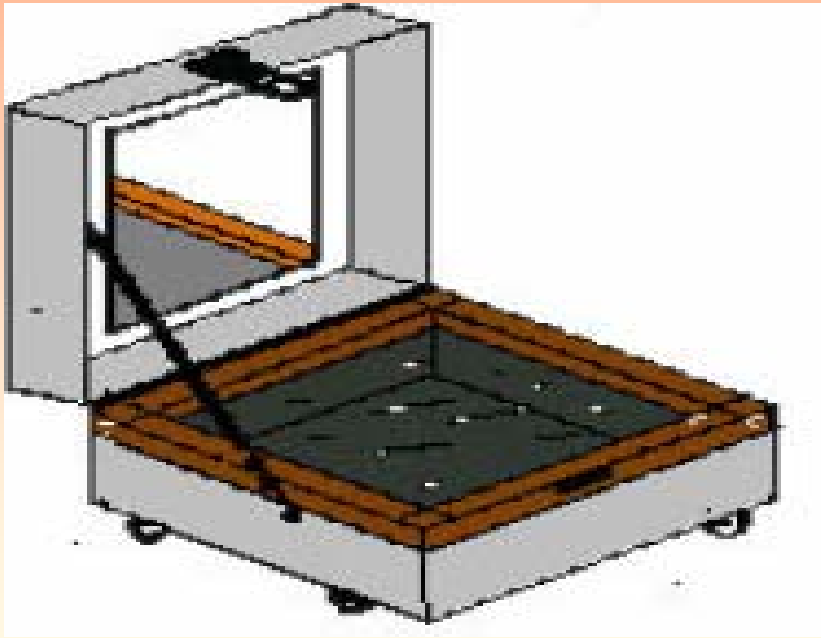
- **Double Glass Lid:** A double glass lid covers the inner box or tray. This cover is slightly larger than the inner box. The two glass sheets are fixed in an aluminum frame with a spacing of 2 centimeters between the two glasses.
- This space contains air which insulates and prevents heat escaping from inside. A rubber strip is affixed on the edges of the frame to prevent any heat leakage.
- **Thermal Insulator:** The space between the outer box and inner tray including bottom of the tray is packed with insulating material such as glass wool pads to reduce heat losses from the cooker.
- This insulating material should be free from volatile materials.

Solar box cooker-2

- **Mirror:** Mirror is used in a solar cooker to increase the radiation input on the absorbing space and is fixed on the inner side of the main cover of the box. Sunlight falling on the mirror gets reflected from it and enters into the tray through the double glass lid.
- This radiation is in addition to the radiation entering the box directly and helps to quicken the cooking process by raising the inside temperature of the cooker.
- Containers: The cooking containers (with cover) are generally made of aluminum or stainless steel.
- These pots are also painted black on the outer surface so that they also absorb solar radiation directly.

Solar box cooker-3

- ***Horace de Assure, a Swiss naturalist***, invented solar cookers as early as 1767.



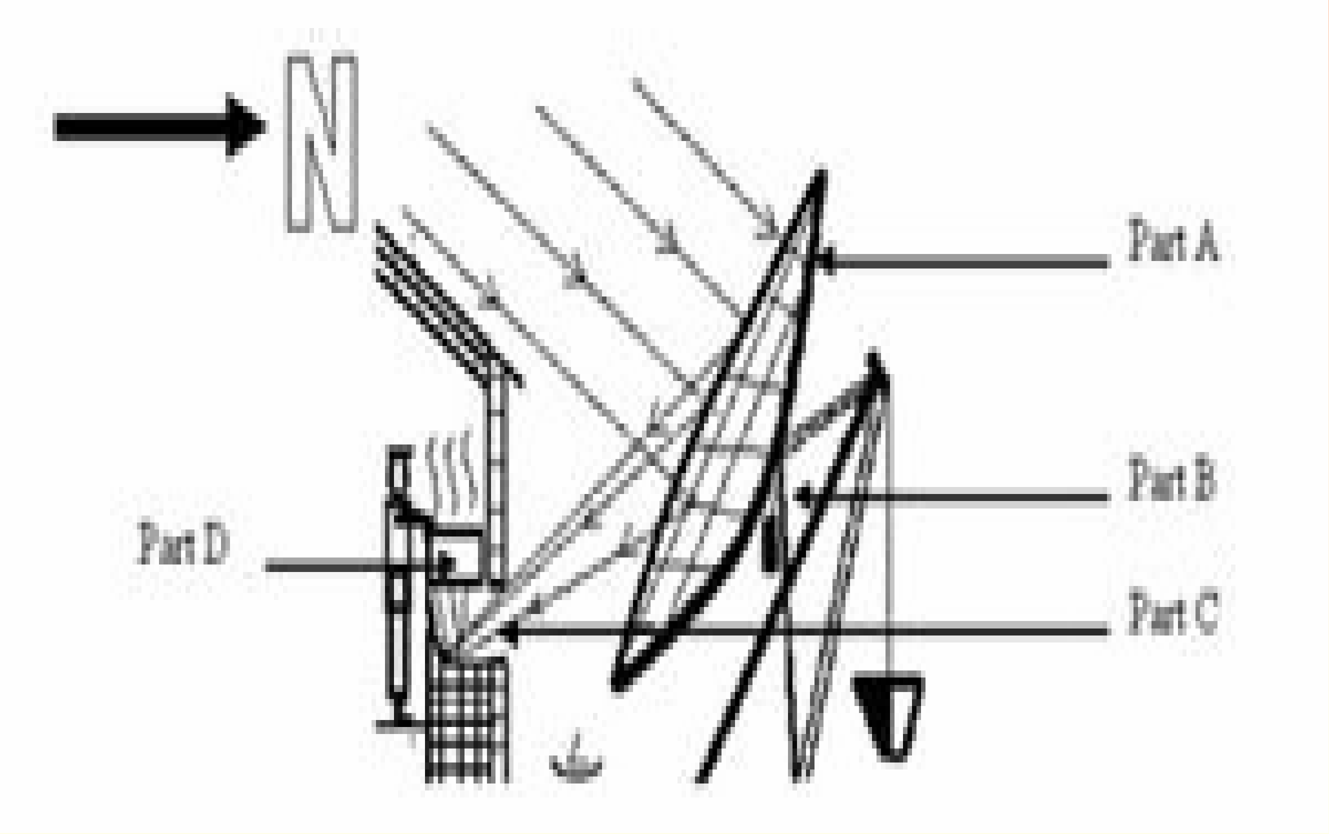
- We can cook a large number of items, like pulses, rice, cheer etc.

Solar box cooker-4

- The time taken to cook will depend upon the type of the food, time of the day and solar intensity.
- The time taken to cook some of the dishes in a solar cooker is as follows:
- Rice (45 minutes to one hour),
- Vegetables (about one to two hours),
- Black gram and Raja (about two hours),
- Cake (one hour).

Community Solar Cooker

- Numerous households all over the country are using '**Surry**' Cooker to cook their meals.



Community Solar Cooker-1

- This family-sized cooker can cook meals for 4-5 persons.
- A larger version of the family size box-type cooker was also developed and used for canteen application.
- Firewood is the most commonly used cooking fuel in community kitchens and traditional woodstove - a “Chula” are the most commonly used cooking device. These chelas have an efficiency of 5-10 % only.
- This Community Solar Cooker employs a parabolic reflecting concentrator that can cook large quantities of food at much faster rate.
- It can replace LPG, kerosene and firewood which are either cumbersome to use, very expensive or which are in short supply.

Community Solar Cooker-2

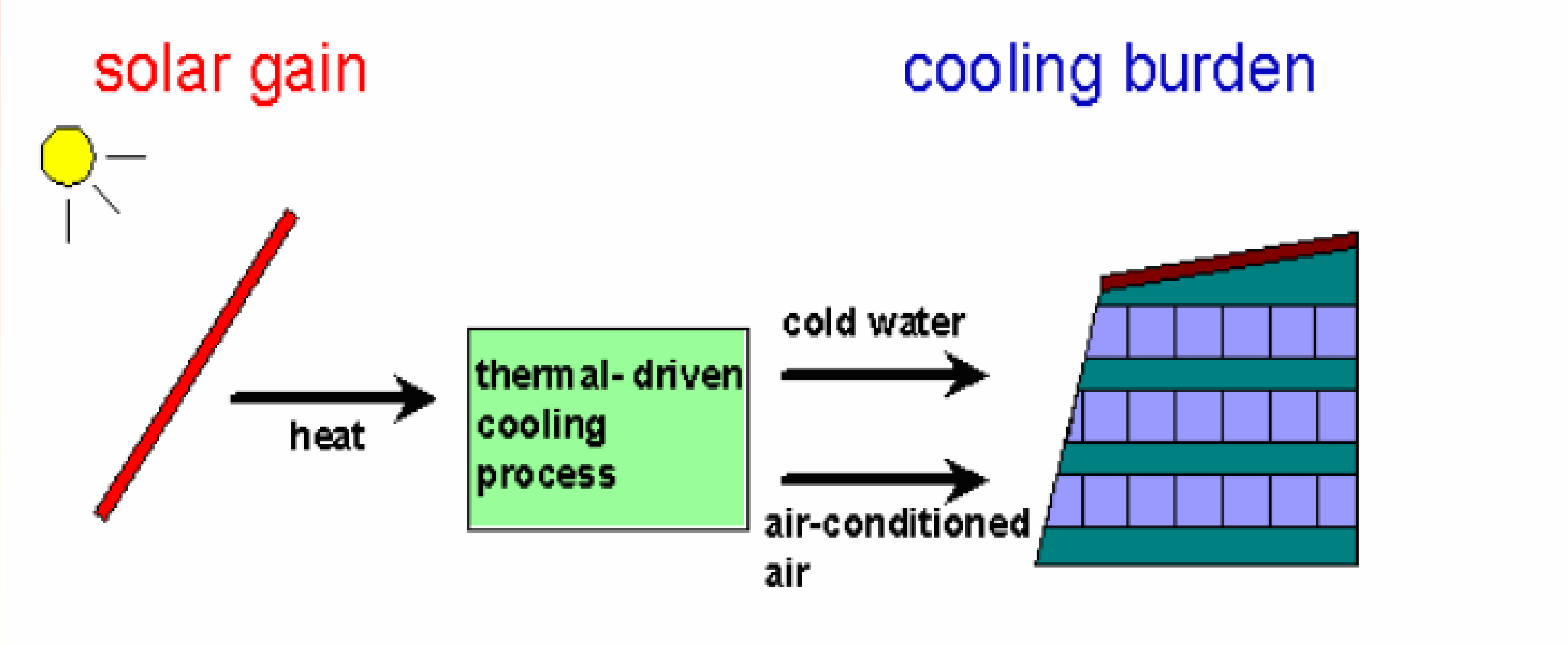
- This cooker is capable of achieving higher temperature unto 250°C as against 100-125 °C in box type cooker.
- This helps cooking much faster. The conventional cooking arrangement within the kitchen does not require to be changed and the cooking can be done inside the kitchen.
- Additionally roasting & frying can be done with this cooker, which is not possible in the old box type solar cooker.
- The **cost of Cooker**, inclusive of all attachments and installation charges is about Rest. 55,000.

Solar Air conditioning

- The basic principle behind solar thermal driven cooling is the thermo-chemical process of Sorption: a liquid or gaseous substance is either attached to a solid, porous material called **Adsorption** or is taken in by a liquid or solid material called **Absorption**.
- The sorbet, silica gel, a substance with a large inner surface area is provided with heat from a solar heater and is dehumidified.
- After this "drying", the process can be repeated in the opposite direction. Processes are differentiated between closed refrigerant circulation systems, for producing cold water, and open systems according to the way in which the process is carried out. That is, whether or not the refrigerant comes into contact with the atmosphere.

Solar Air conditioning-1

Basic structure of a solar air conditioning system:



Proposed application

- A **solar power satellite**, or **SPS**, is a satellite built in high Earth orbit that uses microwave power.
- Transmission to beam solar power to a very large antenna on Earth where it can be used in place of conventional power sources.
- The advantage to placing the solar collectors in space is the unobstructed view of the Sun, unaffected by the day/night cycle, weather, or seasons.
- However, the costs of construction are very high.
- It is unlikely the SPS will be able to compete with conventional sources unless there is a big reduction in the costs associated with launching massive satellites into space, unless a space-based manufacturing industry develops and they can be built in orbit.

Passive solar buildings for cold areas of the Himalayan Range

- Latah is located in the Western Himalayan range of India closed to the Tibetan and Pakistan borders.
- It is a cold desert between 2,800 m and 4,500 m above sea level.
- The winter is very cold, sometimes below - 30°C.Under this extremely cold and dry climate, no trees can grow.
- Therefore, during the winter, the inhabitants, the Leachy, burn dung to cook and warm their homes. Due to the extreme coldness, the space heating needs during the winter are very high.

Passive solar buildings for cold areas of the Himalayan Range-1

- The concept used is Passive solar architecture Passive solar architecture is the way to construct a building so that its structure benefits as much as possible from the external climate to make the interior space as comfortable as possible.
- A passive solar building is an insulated building with a high thermal mass coupled with a solar gain component. It is build along an east-west axis.
- The solar radiations are collected trough the south face and trapped inside trough the glazing, greenhouse or any other passive solar component.
- This heat is stored during the day inside the walls and released during the night to maintain the atmosphere warm.

Passive solar buildings for cold areas of the Himalayan Range-2

- The building can be designed by some local NGOs (Ledge, Secom, Ledge, LEHO) or administration (PWD) sometimes assisted by resource organization such as TERI, GERES.
- As the thermal efficiency of a passive solar building depends on the quality of the construction, some skilled mason and carpenter have been trained the local and international NGOs.
- The over-cost of the passive solar components is 10 to 20% of the building investment. But no running costs are required and the maintenance is cheap and easy.

Passive solar buildings for cold areas of the Himalayan Range -3

- The passive solar technology have been implemented in many areas, some examples are:
- This technology has been implemented in more than 20 schools by the Leachy govt. The over cost of passive solar component is between 20, 000 Rest to 40, 000 Rest per classroom.
- It has also been implemented in Administration buildings (e.g. Latah Autonomous Hill Council).
- Handicrafts center (LEHO has constructed 3 villages training center in Dakar.
- Hospital and dispensary: The comfort and hygiene conditions are very good compared with the usual system.

Passive solar buildings for cold areas of the Himalayan Range-4

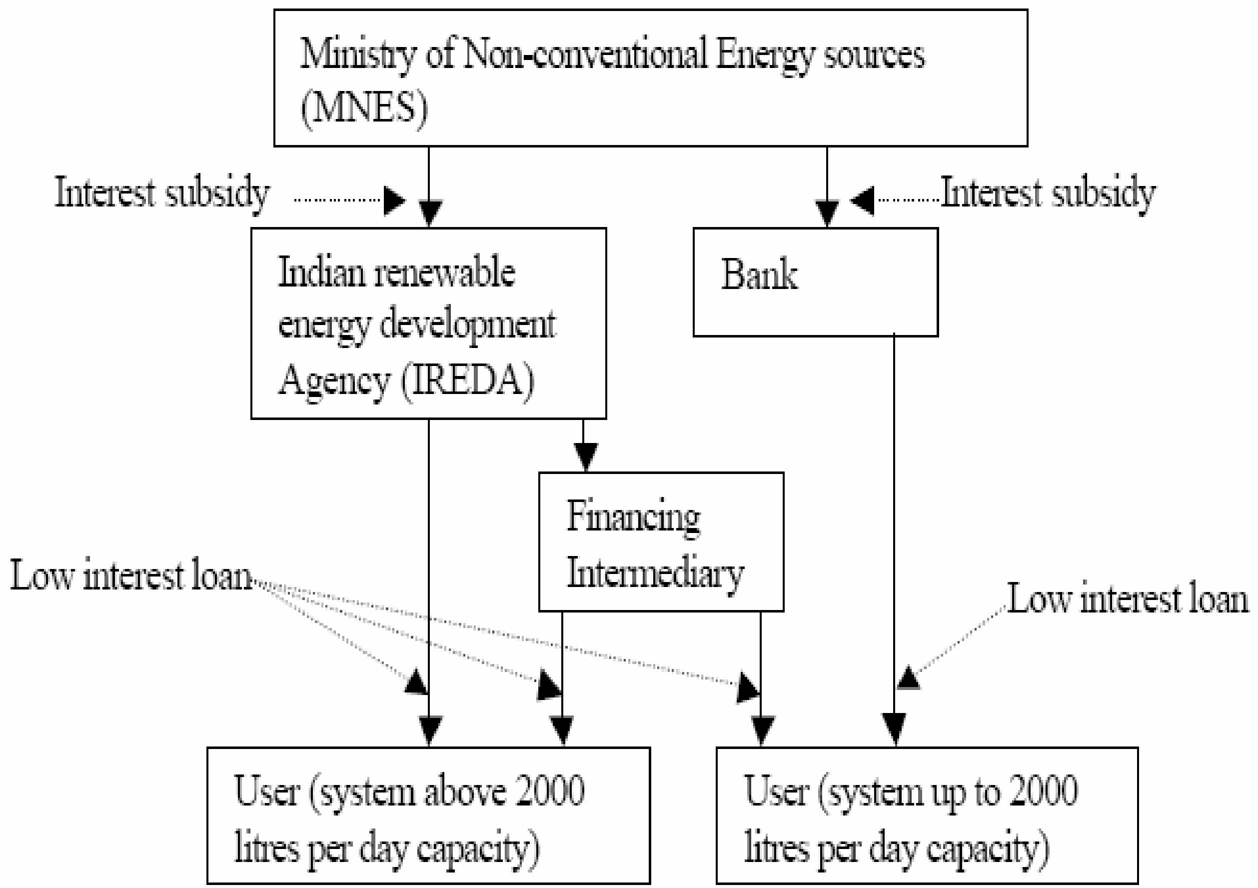
- In maternity wards and operating theatres, the passive solar technology can be combined with a radiant floor heating to optimize the hygiene condition.
- The domestic building can be heated with attached greenhouse or Thrombi wall on the south face. The investment to build an attached Greenhouse and to insulate the external walls of 2 south facing rooms is 20 000 Rest.
- The investment cost to construct 2 Thrombi walls and to insulate the external walls of 2 south facing rooms is 27 000 Rest.

Solar Water Heating System Installed at Cattle Feed Factory, Kantar

- A Solar Water Heating System of capacity 54000 Litres /Day has been installed and commissioned at Cattle feed Factory Kantar, a unit of AMUL Dairy Anand.
- The system consists of 361 Nos. of Solar Flat Plate Collectors, and insulated tank of 54000 lit capacity for storage of hot water.
- Controls are provided for automatic functioning of the system.
- Necessary instruments are provided for regular monitoring of the system.
- Cost of the system is Rest. 6, 10,000/- of which Gujarat Energy Dev. Agency has provided Rest 18, 05,000/- as subsidy.

Subsidies available

- Fig. Financing structure for solar water heating systems in India



Solar water heater at IISc New Hostel complex rooftop

Conclusion

- Solar energy offers many advantageous features over other alternative sources of energy and as shown in the paper the simple principle of heat energy can be applied in a variety of applications.
- Various other possible applications could be Solar Oven, Solar heating of swimming pools etc.
- But solar energy has its own drawbacks or limitations like high initial cost, dependence on weather, energy storage.
- Many government plans have come up under which they provide loans & subsidies as an effort towards promoting solar energy use.
- The energy storage problem especially power generation .