1. 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:

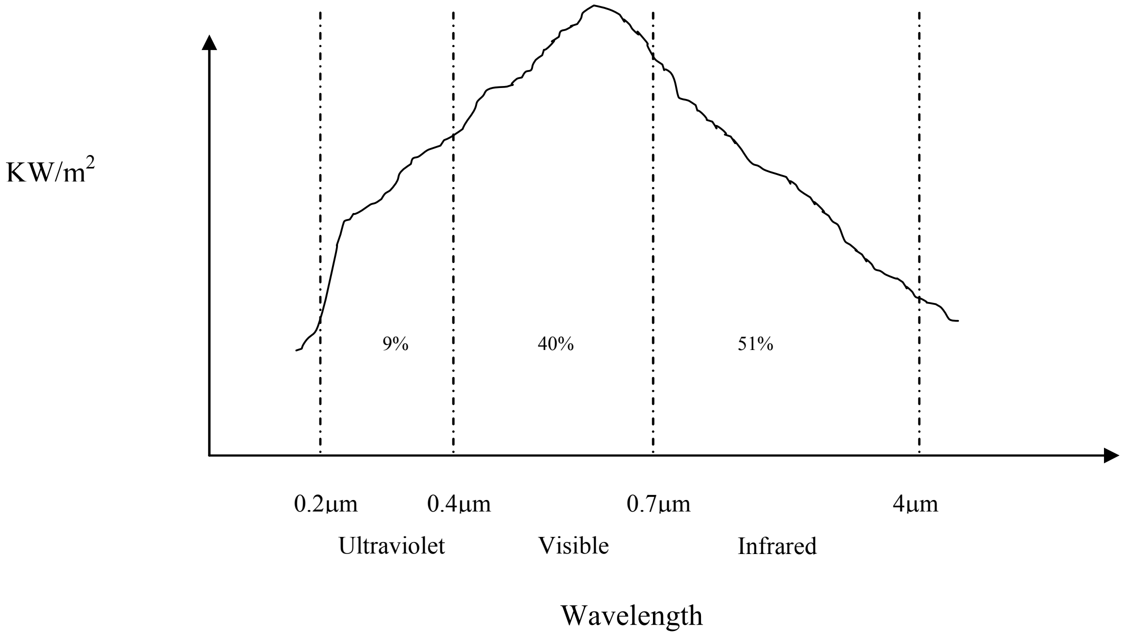
Latitude of the location, day (time in the year) also affects the amount of solar energy received by the place.

The above mentioned factors determine the amount of power falling on the surface.

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 1 m^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 '.

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.



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 1 kW/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 '.

Now we know the definition of two basic terms commonly used in design of a photovoltaic systems. Of course, these terms are often used interchangeably. Hence, one has to be careful in looking at the unit that has been used. In designing a photovoltaic system, it is important to know the amount of insolation available to us at a given time so that the power can be captured using solar panels and convert it into electricity. Depending on the requirement, the size of the panel can be then designed.

2. Radiation Measurement

We know that the atmosphere is made up of ions and other particles including clouds. Hence, 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. 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.

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:

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

   $$SunPosition = f(\phi, \varpi, \delta)$$

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

   $$H_O = f(SunPosition)$$

3. 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.

   $$H_{OA} = K_T H_O$$

4. 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:

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

$$N = 1 \rightarrow 365$$

$\delta = 23.45 * \sin\left(\frac{2\pi(N-80)}{365}\right)$ Degrees, N = 1 on Jan 1st, N = 365 on Dec 31st

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

$I_O = I_{SC}\left(1 + 0.033\cos\left(\frac{360N}{365}\right)\right)$ KW/m2

$H_{ot} = \frac{24 I_O}{\pi} * (\cos(\phi-\beta)\cos\delta\cos\omega_{sr} + \omega_{sr}\sin(\phi-\beta)\sin\delta)$ KWh/m^2/day on a tilted surface with no atmospheric effects.

$H_o = \frac{24 I_O}{\pi} * (\cos(\phi)\cos\delta\cos\omega_{sr} + \omega_{sr}\sin(\phi)\sin\delta)$ kWh/m^2/day

$K_T = (curve \cdot fitting \cdot data)$ - Clearness Index

$R_D = K_R(1-K_D) + K_D\left(\frac{1+\cos\beta}{2}\right) + \rho\left(\frac{1-\cos\beta}{2}\right)$ - Tilt Factor where ρ is the reflection factor which ranges between 0.2 to 0.7.

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

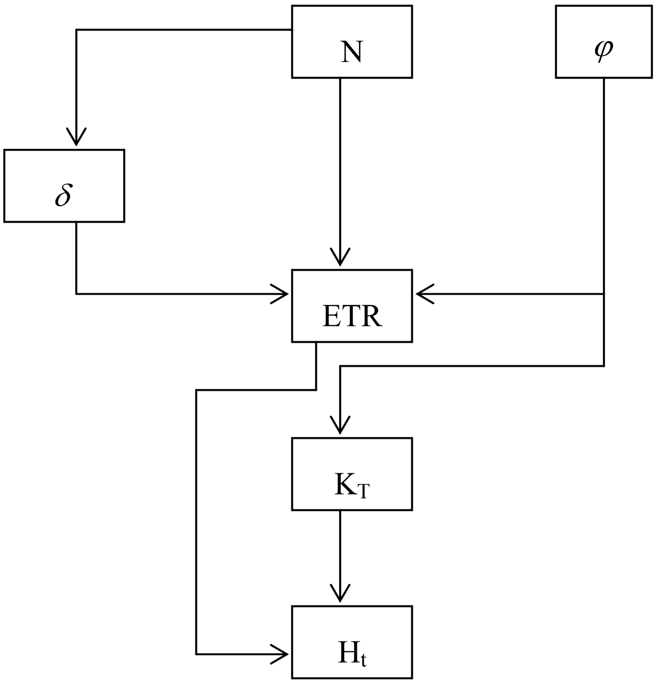
This algorithm can be translated into any of the programming languages like C, C++ or MATLAB. Entering the known parameters, it becomes convenient to find out the solar energy available at any geographical location.

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:

a. Day of the year (N)
b. Latitude of the location (φ)
c. Tilt angle (β)
d. Angle of declination (δ)
e. Clearness Index (K_T)
f. Reflection co-efficient (varies from 0.2 to 0.7)

Following flow chart gives an idea for developing the algorithm:



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:

$$\delta = Ao + A_1 \cos t + A_2 \cos 2t + A_3 \cos 3t + B_1 \sin t + B_2 \sin 2t + B_3 \sin 3t \qquad \text{where}$$

$$t = \frac{360}{365}(N - 80) \text{ degrees}$$

A0, A1…B3 = ?

ETR can be calculated from the following expression:

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

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

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

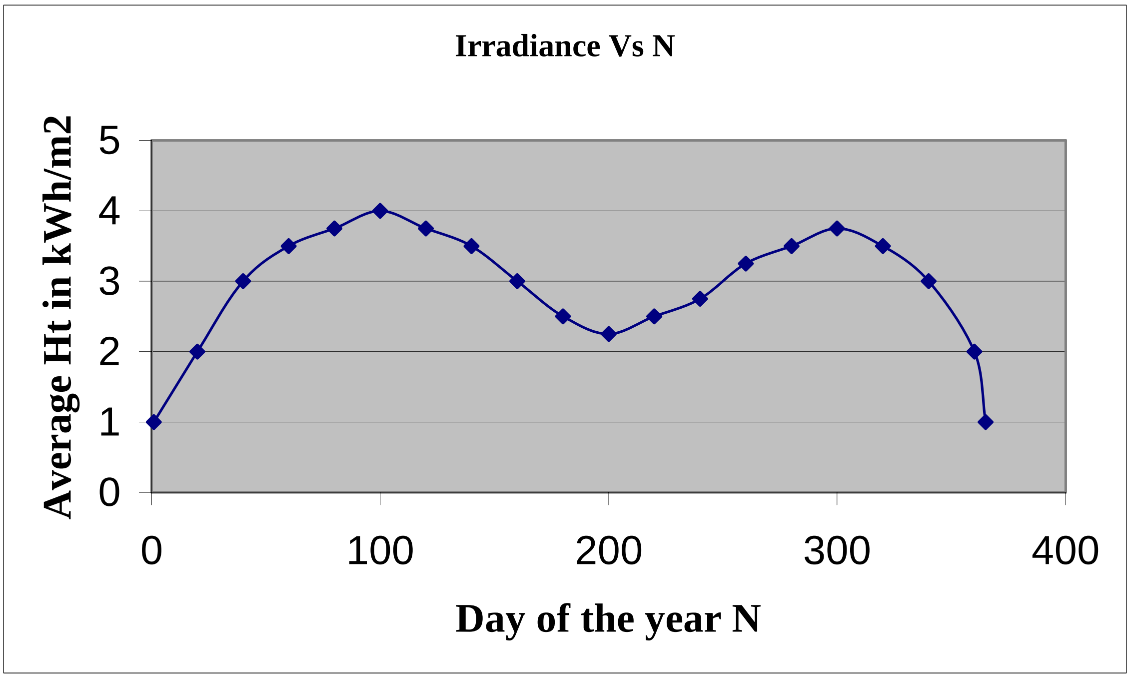
φ = latitude in degrees/radians

δ = declination angle in degrees/radians

ω_{sr} =hour angle at sunrise in degrees/radians = $\cos^{-1}(-\tan\varphi\tan\delta)$

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



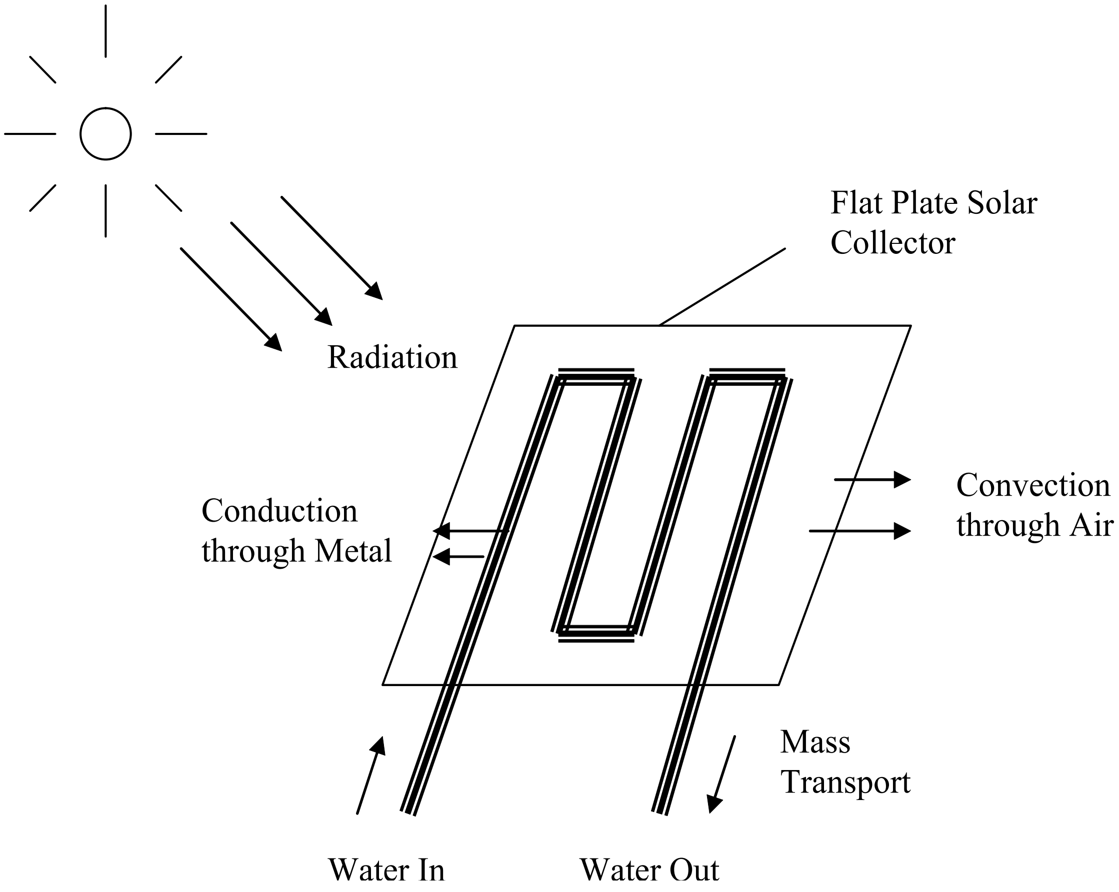
We can see that the level varies with the day of the year. It may reach a peak at some day of the year and reach a bottom on some other day of the year. The peaks and valleys are the direct result of the amount of irradiance reaching the earth. This is a graph that gives us the irradiance level over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

3. Heat Transfer Concepts

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

a) Radiation
b) Conduction
c) Convection
d) 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.

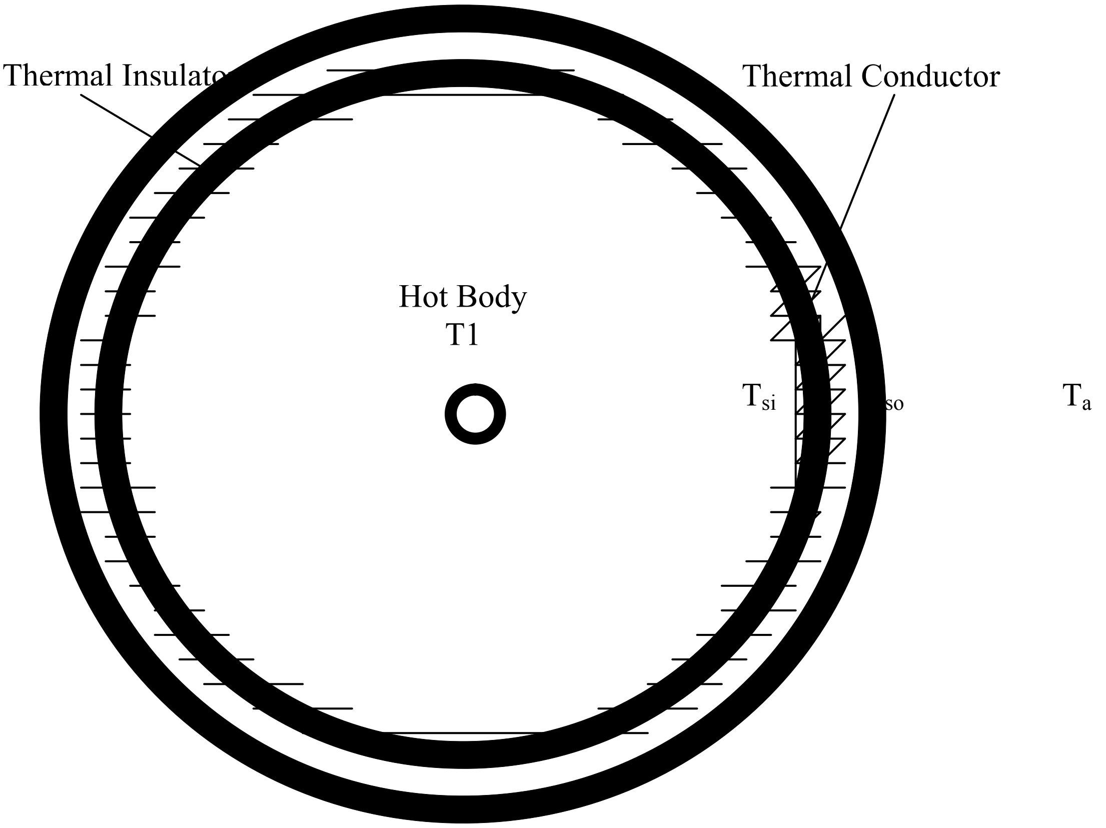


In the above figure it can be seen that the heat is transferred from Sun to the flat plate solar collector by radiation. Radiation is the process of heat transfer from source to the target directly. The plate gets heated and transfers part of the heat to the copper tubes carrying water by conduction. 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.

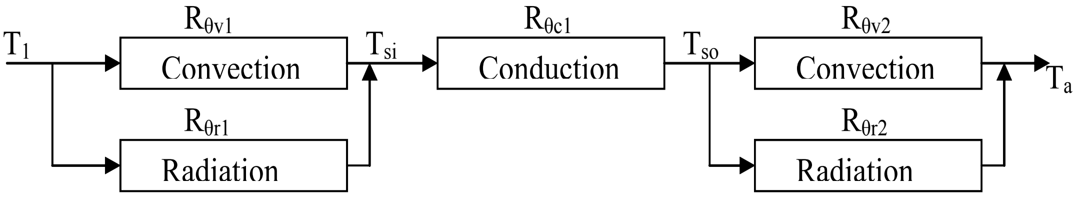
Convection is a process of heat transfer from solids to the surroundings via fluids. The heat transferred to the copper tube gets eventually transferred to the water flowing through the tubes by mass transport. Mass transport is a process of heat transfer similar to convection with little difference. 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:



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



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, and T_a is the ambient temperature. Also, $R_{\theta v1}$ 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, $R_{\theta c1}$ 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, and $R_{\theta r2}$ 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 · r). That is effort = flow x resistance. 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

$$R_{\theta v1} = \frac{(T_1 - T_{si})}{P_{\theta v1}} \text{ , °C/W}$$

Power transmitted through convection is given by

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

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

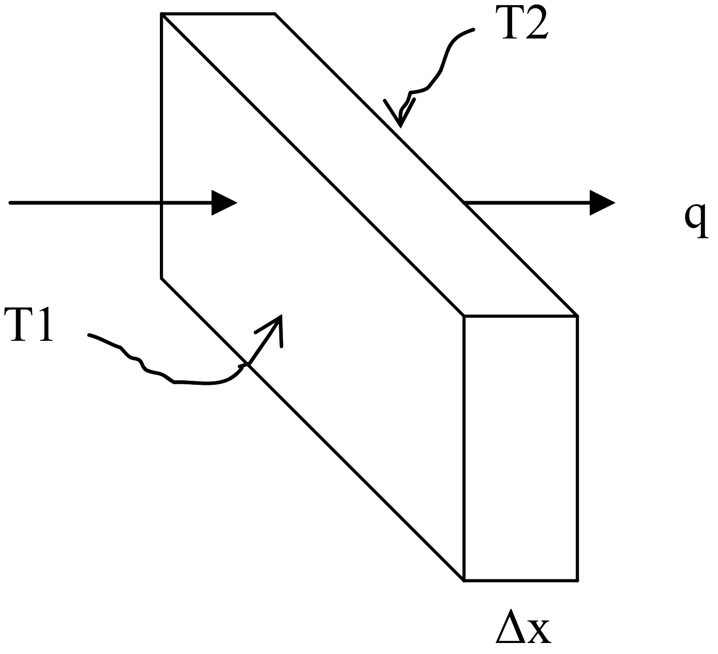
In general we can write

$$q = \frac{\Delta T}{r_\theta} = h \cdot \varDelta T$$

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:



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. T1 is the temperature of the hotter side of the slab and T2 is the temperature of the colder side of the slab. We have seen earlier that the heat flux is proportional to the temperature difference (T1 – T2). That is

q A (T1 – T2).

Hence, we can write

$q = h \cdot \Delta T$

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

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 m^2) · m]; [W/°C m]

Hence, we can write

$$h = \frac{k}{\Delta x}$$

Substituting this in the expression for heat flux, we get

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

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.

a) Thermal resistance R_θ = ˚C/W or ˚K/W
b) Thermal resistivity r_θ = ˚C· m^2/W or ˚K· m^2/W
c) Thermal co-efficient h = W/˚C· m^2 or W/˚K· m^2
d) Thermal conductivity k = W/˚C· m or W/˚K· m

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

a) Thermal conductivity = k
b) Thermal co-efficient $h = \frac{k}{\Delta x}$
c) Thermal resistivity $r_\theta = \frac{\Delta x}{k}$
d) Thermal resistance $R_\theta = \frac{\Delta x}{k \cdot A}$

Thermal conductivity is an important property of material and plays an important role in the conduction process. The k values for different materials are given in the following table:

Material	**k value in W/˚C/m**
Copper	385
Aluminum	211
Steel	47.6
Glass	1.05
Brick	0.6

Concrete	1.7
Asbestos	0.32
Polyurethane	0.025
Polystyrene	0.035
Still air	0.026

Problem:

Calculate Thermal resistance of the path if

a) The slab is made up of glass having area of 1 m^2 and thickness of 5 mm.
b) The slab is made up of brick having area of 1 m^2 and thickness of 220 mm.

Solution:

We know that the expression for thermal resistance is given by $R_\theta = \dfrac{\Delta x}{k \cdot A}$

a) $\Delta x = 5$ mm $= 5 \times 10^{-3}$ m; k = 1.05; A = 1 m^2

$$R_\theta = \frac{5x10^{-3}}{1.05 \cdot 1} = 0.004762 \text{ °C/W}$$

b) $\Delta x = 220$ mm $= 220 \times 10^{-3}$ m ; k = 0.6 ; A = 1 m^2

$$R_\theta = \frac{220x10^{-3}}{0.6 \cdot 1} = 0.366667 \text{ °C/W}$$

A typical example of heat transfer by conduction is the case of heat dissipation in semiconductor devices such as junction transistors (BJT and FET). Any device that has a voltage across it and current through it simultaneously dissipates power. This power is equal to the product of the voltage and the current. We know that the power is the rate at which energy is converted from one form to another. In semiconductor devices, the energy changes from electrical energy to heat energy.

Now, heat energy can be compared to current and temperature to voltage. When current flows in a semiconductor device, a voltage is produced and when heat energy flows in any substance, the temperature rises. The thermal resistance measured in ˚C/W of the substance determines how much the temperature rises when heat energy flows in it.

The maximum operating temperature of a semiconductor junction is about 200 ˚C. Depending upon the type of case material, any given semiconductor device may have a lower maximum operating temperature. If this maximum temperature is exceeded, the device gets destroyed. An important part of the design process for large signal semiconductor circuit is making sure that the junction does not rise to a destructive temperature. To safeguard this, heat sinks are frequently used with semiconductor devices. Thermal resistance of the heat sink is the one that controls the temperature. We have seen earlier that the thermal resistance R_θ can be given by the following expression:

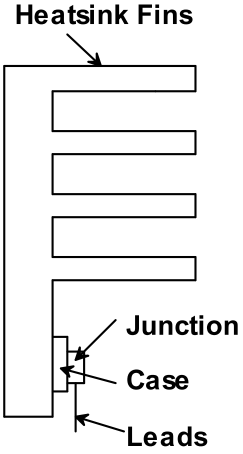
$$R_\theta = \frac{\Delta x}{k \cdot A}$$

Here, the thermal resistance depends on the thickness of the heat sink material, thermal conductivity of the material and the area of the heat sink material. Normally, the thickness of the material is almost standardized and the thermal conductivity is the property of the material. That leaves the flexibility of varying only the surface area of the heat sink to vary the thermal resistance of the heat sink. 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:

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

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

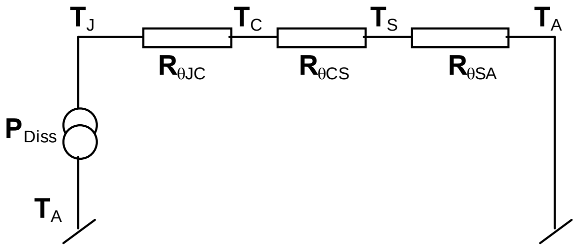
Following figure shows how a semiconductor device is mounted on to a heat sink.



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

1. $R_{\theta JC}$ 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.
2. $R_{\theta CS}$ 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.
3. $R_{\theta SA}$ 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.

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:



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

Substituting for Rot 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:

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

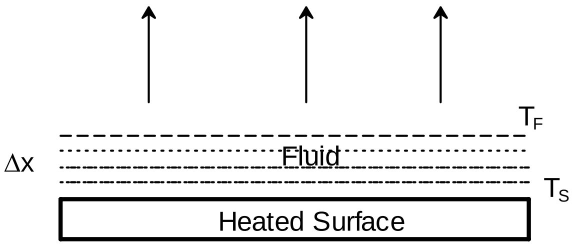
Convection

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.

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. This region of the fluid is known as the velocity boundary layer. Also, if the surface and flow temperature differ, there will be a region of the fluid through which the temperature varies from T_S at the surface to T_F in the outer flow. This layer is called the thermal boundary layer. If $T_S > T_F$, convection heat transfer will occur between the surface and the outer flow.

The convection heat transfer mode is sustained both by random molecular motion and by the bulk motion of the fluid within the boundary layer. The contribution due to random molecular motion dominates near the surface where the fluid velocity is low. The contribution due to bulk fluid motion originates from the fact that the boundary layer grows as the flow progresses in the x direction. In effect, the heat that is conducted into this layer is swept downstream and is eventually transferred to the fluid outside the boundary layer.

Convection heat transfer may be classified into the following types:

1. Free Convection: Here the flow is induced by buoyancy forces, which arise from density differences, caused by temperature variations in the fluid.

2. 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:

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

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

Here most of the parameters are measurable except the fluid thickness, by. It can vary with surroundings. Hence, 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:

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

X = Characteristic dimension

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

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

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

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

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

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

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

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

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

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

$$q = h_{\theta v} \cdot \Delta T\text{; W/m}^2$$

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

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

Nusselt Number for different classes of convection is different. They are called

1. **Rayliegh Number** for free convection. It is represented by $\mathcal{A}$ and is given by the following expression:

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

2. **Reynolds Number** for forced convection. It is represented by $\mathcal{R}$ and is given by the following expression:

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

$\mathcal{N} = f(\mathcal{A}, \mathcal{R})$

The boundary layer in convection mode of heat transfer can be any of the following:

- **Laminar**: In the laminar boundary layer, fluid motion is highly ordered and it is possible to identify streamlines along which particles move. Since the velocity component u is in the direction normal to the surface, it can contribute significantly to the transfer of momentum and energy through the boundary layer.

- **Turbulent**: In the turbulent boundary layer, fluid motion is highly irregular and is characterized by velocity fluctuations. These fluctuations enhance the transfer of momentum and energy and hence increase surface friction as well as convection transfer rates.

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

For Rayliegh Number:

a) $A \geq 10^5$: Turbulent flow
b) $10^3 \leq A \leq 10^5$: Laminar flow
c) $A < 10^3$: Free convection is not possible

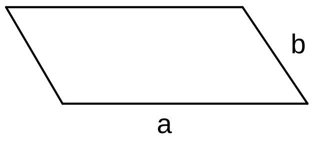
For Reynolds Number:

a) $R \geq 2300$:Turbulent flow
b) $R < 2300$: Laminar flow

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.

Free Convection - Rayliegh Number:

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



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

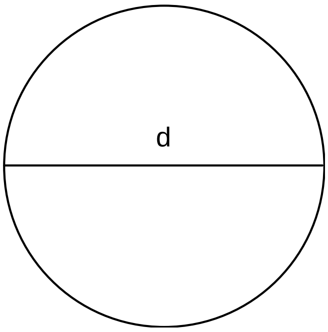
For Laminar Flow:

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

For Turbulent Flow:

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

Circular plate with diameter ‘d’ as shown in the following figure:



Characteristic Dimension: $X = d$

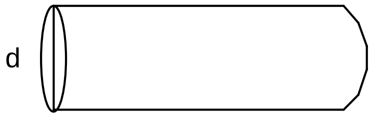
For Laminar Flow:

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

For Turbulent Flow:

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

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



Characteristic Dimension X = d

For Laminar Flow:

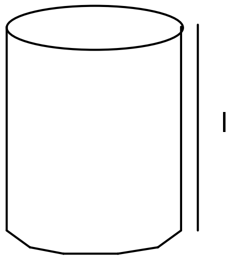
- $10^4 < \mathcal{A} < 10^9$

- $\mathcal{N} = 0.47\, \mathcal{A}^{0.25}$

For Turbulent Flow:

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

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



Characteristic dimension X = l

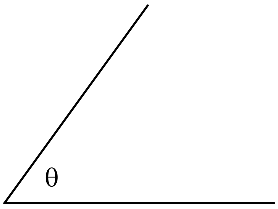
For Laminar Flow:

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

For Turbulent Flow:

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

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



Characteristic Dimension X = Distance between parallel plates

For $\theta < 50°$

For Laminar Flow:

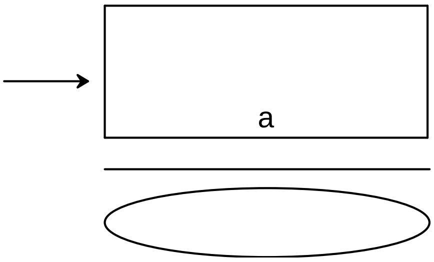
- Not possible

For Turbulent Flow:

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

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

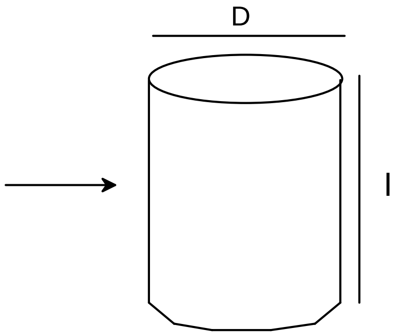
For Laminar Flow:

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

For Turbulent Flow:

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

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

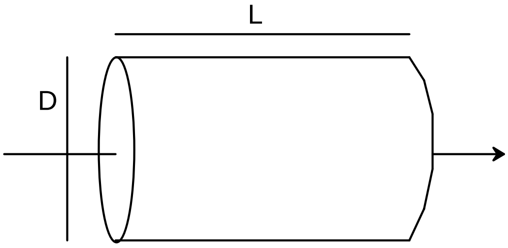
For Laminar Flow:

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

For Turbulent Flow:

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

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:

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

For Turbulent Flow:

- $\mathcal{R} > 2300$

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

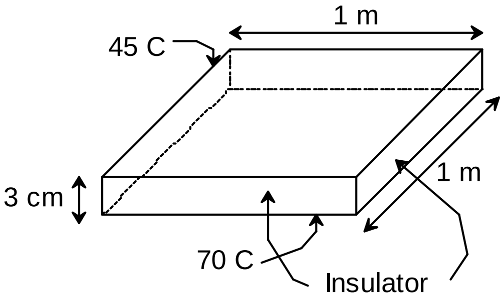
Application of Convection Principles

Problem 1:

Consider two conducting square plates measuring 1 m on each side, placed parallel to each other, separated by a distance of 3 cm. Let air is the medium of their separation. Let the vertical sides formed by the plates are thermally insulated so that no heat flows through them. Let the bottom plate is at 70 ˚C and the top plate is 45 ˚C. Calculate the heat flow in watts from the bottom plate to the top plate by convection through the air separating the plates.

Solution:

Following figure explains the problem.



We have seen earlier that the expression for the power flow P is given by the following expression:

$$P = A \cdot \frac{N \cdot k}{X} \cdot \Delta T \text{ , W, where}$$

A = Area of the surface perpendicular to the heat flow = 1 m^2

$\mathcal{N}$= Nusselt number

k = Thermal conductivity of the fluid (air) = 0.028 W/m˚K

X = Characteristic dimension = Vertical distance between the plates for parallel plates.

ΔT = Temperature difference between the plates

Let us assume free convection. Hence we need to first find Rayliegh Number to evaluate Nusselt number. The Rayliegh Number, $\mathcal{A}$, is given by the following expression:

$$\mathcal{A} = \frac{g \cdot \beta \cdot X^3 \cdot \Delta T}{\delta \cdot \upsilon}$$, where

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

β = Coefficient of thermal expansion of the fluid (air) = $\frac{1}{330^\circ K}$

X = Characteristic dimension for parallel plates = 3 cm = 0.03 m

ΔT = (273 + 70) °K – (273 + 45) °K = 25 °K

δ = Thermal diffusivity of the fluid (air) = 2.6 x 10^{-5} m^2/s

υ = Kinemetic viscosity of the fluid (air) = 1.8 x 10^{-5} m^2/s

Substituting the above values we can evaluate the value of Rayliegh number as:

$$\mathcal{A} = \frac{\left(9.81 m/s^2\right)\cdot\left(1/330^\circ K\right)\cdot\left(0.03 m\right)^3 \cdot 25^\circ K}{\left(2.6x10^{-5} m^2/s\right)\cdot\left(1.8x10^{-5} m^2/s\right)}$$

$\mathcal{A}$ = 0.42876 x 10^5

Since $\mathcal{A}$ > 10^5, the flow is laminar. Hence, the Nusselt Number is given by the following expression:

$\mathcal{N}$ = 0.062 $\mathcal{A}^{0.33}$

$\mathcal{N}$ = 0.062 x (0.42876 x 10^5)$^{0.33}$

$\mathcal{N}$ = 2.09422

Now, substituting the value of Nusselt Number in the expression for heat flow, P, we get:

$$P = 1m^2 \cdot \left(\frac{2.09422}{0.03m}\right) \cdot \left(0.028W/m^\circ K\right) \cdot \left(25^\circ K\right)$$

$P = 48.865$ W

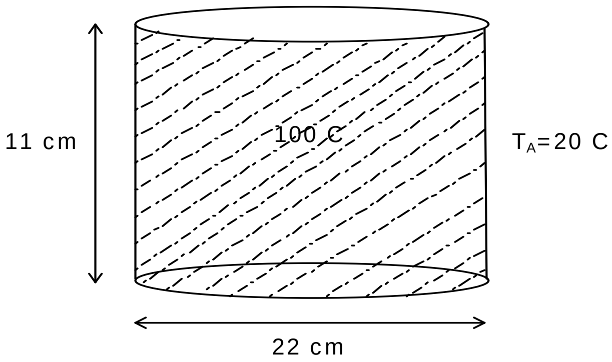
Problem 2:

Consider a cylindrical pot having a diameter of 22 cm. Let the pot is filled with water to a height of 11 cm. Let the ambient temperature be 20 ˚C. Calculate the energy required to maintain boiling temperature of the pot at 100 ˚C under the following conditions:

a) If the pot is sheltered from wind
b) If the pot is exposed to breeze traveling at 3 m/s

Solution:

Following figure shows the cylindrical pot.



a) The pot is sheltered from the wind:

Since there is no wind involved here, it is the case of free convection. Hence, Rayliegh Number needs to be evaluated to calculate Nusselt Number. The energy from the pot is lost due to convection in two directions, viz., through the top portion of the pot and through the sides of the pot. This energy needs to be refurbished so that the pot is maintained at the boiling temperature. Hence, the solution to calculate energy required to keep the pot at 100 ˚C for an hour has two components:

- Energy lost from the top of the pot
- Energy lost from the sides of the pot

It is assumed that the body of the pot has negligible thermal resistance. To calculate the energy lost due to convection, we need to first calculate Rayliegh Number, then the Nusselt Number and finally the power flow or the heat flow. Following are the steps:

i) **Top portion of the pot:** Top portion can be considered as a circular plate. The Rayliegh Number can be calculated from the following expression:

$\mathcal{A}$ (top) = $\dfrac{g \cdot \beta \cdot X^3 \cdot \Delta T}{\delta \cdot \upsilon}$, where X, the characteristic dimension of the

circular plate is the diameter of the plate.

Substituting the known values we get:

$$\mathcal{A}\text{ (top)} = \frac{\left(9.81 m/s^2\right)\cdot\left(1/330^\circ K\right)\cdot\left(0.22 m\right)^3\cdot\left(80^\circ K\right)}{\left(2.6x10^{-5} m^2/s\right)\cdot\left(1.8x10^{-5} m^2/s\right)}$$

$\mathcal{A}$ (top) = $5.41087 \text{ x } 10^7$

Since $\mathcal{A} > 10^5$, the Nusselt Number is calculated from the following expression:

$\mathcal{N} = 0.14\,\mathcal{A}^{0.33}$

$\mathcal{N} = 0.14\,(5.41087 \text{ x } 10^7)^{0.33}$

$\mathcal{N} = 49.901$

Now the expression for heat flow is given by the following expression:

$$P = A \cdot \frac{N}{X} \cdot k \cdot \Delta T \text{, W}$$

Here, A is the surface area of the circular plate given by $A = \frac{\pi}{4} \cdot (d)^2$, d being the diameter of the plate.

Substituting the known values we get the following:

$$P = \left(\frac{\pi}{4}\right) \cdot (0.22m)^2 \cdot \left(\frac{49.901}{0.22m}\right) \cdot \left(0.028W/m^\circ K\right) \cdot \left(80^\circ K\right)$$

P (top) = 19.3139 W

ii) **Side portion of the pot:** Side portion of the pot can be considered as a vertical cylinder, where the characteristic dimension X is the length of the cylinder. Substituting the know values, we get the following:

$$\mathcal{A}\text{ (side)} = \frac{\left(9.81m/s^2\right) \cdot \left(1/330^\circ K\right) \cdot (0.11m)^3 \cdot \left(80^\circ K\right)}{\left(2.6x10^{-5} m^2/s\right) \cdot \left(1.8x10^{-5} m^2/s\right)}$$

$\mathcal{A}$ (side) = $6.7636 \text{ x } 10^6$

Since $10^4 < \mathcal{A} < 10^9$, the Nusselt Number can be found from the following expression:

$\mathcal{N} = 0.56\, \mathcal{A}^{0.25}$

$\mathcal{N} = 0.56 \text{ x } (6.7636 \text{ x } 10^6)^{0.25}$

$\mathcal{N} = 28.5583$

We have seen that the expression for the heat flow is given by:

$$P = A \cdot \frac{N}{X} \cdot k \cdot \Delta T \text{, W}$$

Here A is the surface area of the side of the cylinder given by $A = \pi\, d\, h$, where d is the diameter of the cylinder rim and h is the height. Substituting the known values, we get the value of heat flow as:

$$P = \left(\pi \cdot 0.22m \cdot 0.11m\right) \cdot \left(\frac{28.5583}{0.11m}\right) \cdot \left(0.028W / m^{\circ}K\right) \cdot \left(80^{\circ} K\right)$$

P (side) = 44.2133 W

The total heat flow is the sum of the above two. That is

P (total) = P (top) + P (side)

P (total) = 19.3139 W + 44.2133 W

P (total) = 63.5272 W

Hence, the energy required to maintain the pot at the boiling temperature of 100 ˚C for one hour is = 63.5272 W x 1 h = 63.5272 Wh.

b) Wind flows across the pot at an average velocity of 3 m/s:

The convection here is the forced convection and hence Reynolds Number needs to be calculated to find Nusselt Number. Expression for Reynolds Number is given by the following expression:

$\mathcal{R} = \frac{u \cdot X}{\upsilon}$, where

u is the average velocity in m/s

X is the characteristic dimension in m

υ is the kinemetic viscosity of the fluid in m^2/s

As in the case of free convection, the loss of energy is in two directions, top and sides. The loss of energy in each direction can be found as follows:

i) **Top portion of the pot:** Top portion can be considered as a circular flat. The characteristic dimension X of the circular plate is its diameter. The Reynolds number for this plate can calculated as follows:

$$\mathcal{R}= \frac{(3m/s)\cdot(0.22m)}{\left(1.8x10^{-5}m^2/s\right)}$$

$\mathcal{R}$= 0.3667 x 10^5

Since $\mathcal{R}$< 5 x 10^5, the flow is laminar. Now the Nusselt Number can be found from the following expression:

$\mathcal{N}$=0.664 x $\mathcal{R}^{0.5}$ x $(\upsilon/\delta)^{0.33}$, where

δ is the thermal diffusivity of the fluid

Substituting the known values, we get the Nusselt Number as follows:

$$\mathcal{N}= (0.664)\cdot\left(0.3667x10^5\right)^{0.5}\cdot\left(\frac{1.8x10^{-5}m^2/s}{2.6x10^{-5}m^2/s}\right)^{0.33}$$

$\mathcal{N}$= 112.622

Having the Nusselt Number, we can calculate the heat flow from the following expression:

P (top) = $A\cdot\frac{N}{X}\cdot k\cdot\Delta T$, where

A is the area of the circular plate = $\pi\cdot\frac{D^2}{4}$, m^2

K is the thermal conductivity of the fluid

ΔT is the temperature difference

Substituting the known values, we get the value of heat flow as:

$$P\ (top) = \left(\frac{\pi}{4}\right)\cdot(0.22m)^2\cdot\left(\frac{112.622}{0.22m}\right)\cdot\left(0.028W/m^{\circ}K\right)\cdot\left(80^{\circ}K\right)$$

P (top) = 43.5897 watts

ii) **Side portion of the pot:** Side portion constitutes a vertical cylinder. The characteristic dimension X for this case is the diameter of the cylinder. Hence the Reynolds Number in this case also would be same. That is:

$\mathcal{R}$= 0.3667 x 10^5 or 3.667 x 10^4

Since 1000 < $\mathcal{R}$< 5 x 10^4, the flow is turbulent. The Nusselt Number is evaluated from the following expression:

$\mathcal{N}$= 0.26 R $^{0.6}$ $(\upsilon/\delta)^{0.3}$

$$\mathcal{N}= (0.26)\cdot\left(3.667x10^4\right)^{0.6}\cdot\left(\frac{1.8x10^{-5}m^2/s}{2.6x10^{-5}m^2/s}\right)^{0.3}$$

$\mathcal{N}$= 127.541

Having the Nusselt Number, the heat flow can be calculated by following expression:

P (side) = $A\cdot\frac{N}{X}\cdot k\cdot\Delta T$, W, where

A = Surface area of the cylinder = $\pi\cdot D\cdot h$, m^2

$$P\ (side) = \left(\pi\cdot 0.22m\cdot 0.11m\right)\cdot\left(\frac{127.541}{0.22m}\right)\cdot\left(0.028W/m^{\circ}K\right)\cdot\left(80^{\circ}K\right), \text{W}$$

P (side) = 98.728 watts

Hence the total heat flow is the sum of the heat flow through the top and through the sides.

P (total) = (43.5897 + 98.728) watts

P (total) = 142.3177 watts

Hence, the energy required to maintain the pot at the boiling temperature of 100 ˚C for one hour is = 142.3177 W x 1 h = 142.3177 Wh.

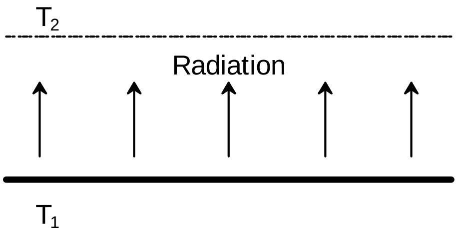
Comment:

We have calculated the energy required for keeping the pot at the boiling temperature of 100 ˚C for one hour for both free convection and forced convection separately at their worst case condition respectively. However, in real situations, the resultant convection flow would be the combination of both free and forced convection and would be difficult to predict or calculate accurately. Ideal design process would be to take the worst-case results of each type and sum them up to get the total energy lost.

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. In fact, radiation transfer occurs most efficiently in a vacuum.

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:

$P = h_r \cdot A \cdot \Delta T$, 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} $W/m^2/°K^4$

Eeff = effective emittance

φ = Shielding factor

The shielding factor o for parallel plates is zero. The emittance depends on the properties such as surface type and the color of the material. Following table gives the emittance of some of the materials:

Material Type	**Emittance**
Anodized Aluminum (Black)	0.800
Polished Aluminum	0.095
Rough Surface Aluminum	0.180
Rough Surface Iron	0.170
Tungsten at 1500 C	0.330
Brick	0.930
Concrete	0.940
Glass	0.940
Wood	0.900

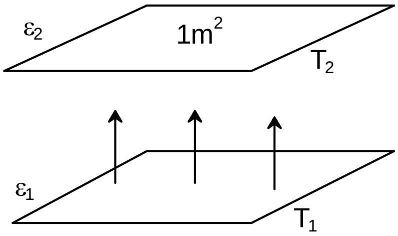
A material, which has emittance of 1.000, it is called a black body and is a perfect radiator. It also means that the material cannot retain any heat and the heat would lose completely over a period. Such materials would be useless in applications where heat retention is required. To understand the concept, let us solve the following problem.

Problem:

There are two parallel plates each having area of 1 m^2. Let the first plate is made up of glass and kept at a temperature of 350 ˚K. Let the second plate is made up of rough surfaced aluminum. Let the temperature of the second plate is at 300 ˚K. Find the radiation heat flow from first plate to the second plate.

Solution:

Let us consider the following figure to understand the problem:



The bottom plate is a glass plate which is at 350 K and from the table the emittance of glass is e1 = 0.940. The top plate is made up of rough surfaced aluminum having emittance of 0.18. The temperature at that plate is 300 K. The radiation heat flow is from plate 1 to plate 2. The radiation thermal coefficient of the path between plate 1 and plate 2 can be calculated from the following expression:

$$h_r = 4 \cdot \sigma \cdot \varepsilon_{eff} \cdot (1-\phi) \cdot \left(\frac{T_1 + T_2}{2} \right)^3$$, W/m²/°K, where

σ = Boltzman's constant = 5.67 x 10^{-8} W/m²/°K^4

φ = Shielding factor = 0 for parallel plates

$$\varepsilon_{eff} = \frac{\varepsilon_1 \cdot \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \cdot \varepsilon_2}$$

Substituting the known values we get:

$$h_r = 4 \cdot \left(5.67x10^{-8} W/m^2/^\circ K^4 \right) \cdot \left(\frac{(0.94)\cdot(0.18)}{0.94 + 0.18 - (0.94)\cdot(0.18)} \right) \cdot (1-0) \cdot \left(\frac{350^\circ K + 300^\circ K}{2} \right)^3$$

Hr = 1.3855 W/m²/°K

Hence, the radiation heat flow can now be calculated from the following expression:

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

P = (1.3855 W/m^2/˚K) · (1m^2) · (350 ˚K – 300 ˚K)

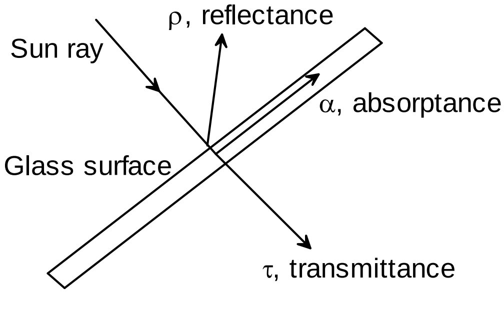
P = 69.275 watts

This implies that 69.275 watts of heat flow (power) is lost due to radiation from plate 1 to plate 2.

Whenever a wave of energy hits a surface, part of the energy gets reflected, part of energy is absorbed by the surface and part of the energy gets transmitted depending on the type of surface. The amount of energy that gets reflected depends on a constant called the reflectance of the surface denoted by ρ. The amount of energy that is absorbed depends on a constant called the absorptance of the surface denoted by α. The amount of energy that gets transmitted depends on a constant called transmittance of the surface denoted by τ. For any surface, the following relationship holds good:

$\rho + \alpha + \tau = 1$

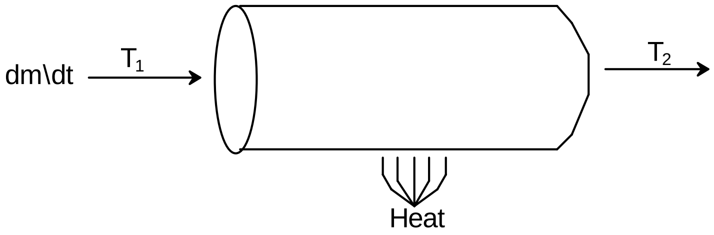
The relationship is called the conservation of energy and these constants depend on the type of surface. Following figure shows the distribution of energy when it strikes a glass surface.



For a glass surface, α is almost equal to 0, τ is equal to 0.92 and ρ is equal to 0.08. And the sum is equal to 1, satisfying the above relationship.

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

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

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

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

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

Here temperature is not a driving function for the heat transfer unlike conduction, free convection and radiation. The heat flow is determined by external factors controlling the rate of mass flow, (dm/dot).

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 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:

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

(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:

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

4. Applications

1. Solar thermal power plants

The two main types of solar thermal power plants are

1. Concentrating Solar Power (CSP) plants.
2. Solar Chimneys

1.1 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.

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.

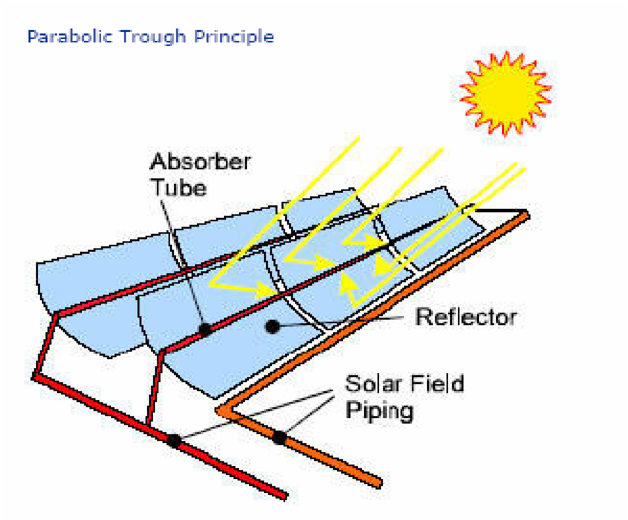
Concentrating solar power systems can be sized for village power (10 kilowatts) or grid-connected applications (up to 100 megawatts). Some systems use thermal storage during cloudy periods or at night. There are four CSP technologies being promoted internationally. For each of these, there exists various 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:

a. 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. 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.

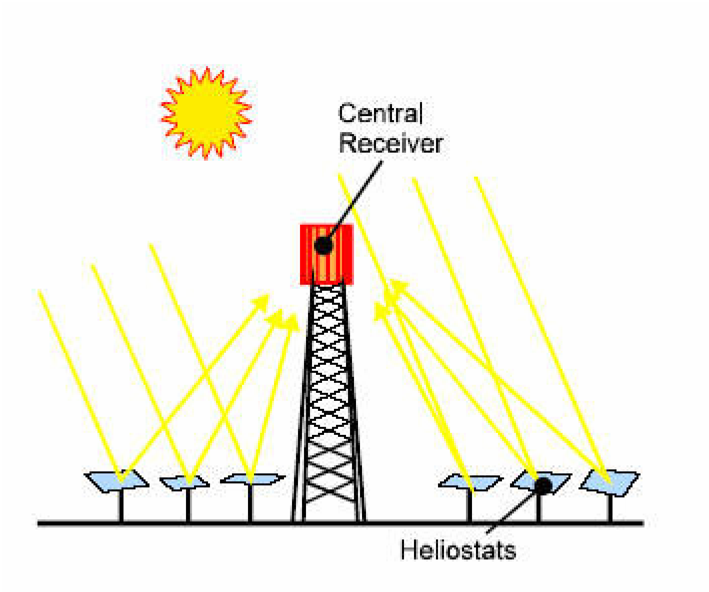
Trough designs can incorporate thermal storage—setting aside the heat transfer fluid in its hot phase—allowing for electricity generation several hours into the evening.

Currently, all parabolic trough plants are "hybrids," meaning they use fossil fuel to supplement the solar output during periods of low solar radiation.

Another option under investigation is the approximation of the parabolic troughs by segmented mirrors according to the principle of Fresnel.

B. Power Tower Systems:

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

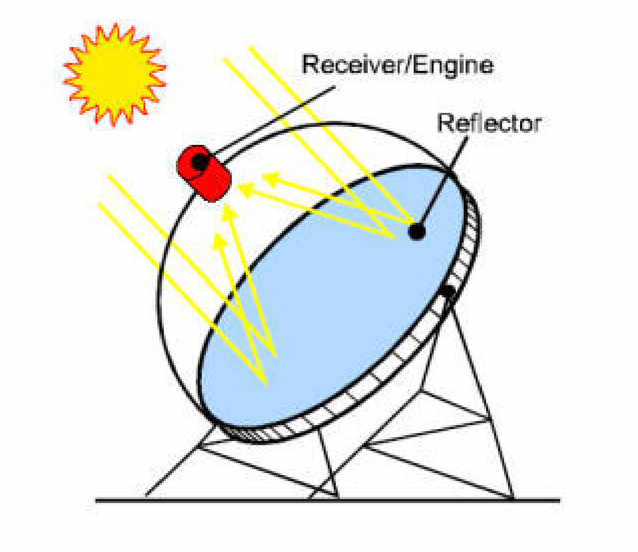


Early power towers (such as the Solar One plant) utilized steam as the heat transfer fluid; current designs (including Solar Two, shown in fig) utilize molten nitrate salt because of its superior heat transfer and energy storage capabilities. Current European designs use air as heat transfer medium because of its high temperature and its good hand ability.

Individual commercial plants will be sized to produce anywhere from 50 to 200 MW of electricity.

c. 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. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun.

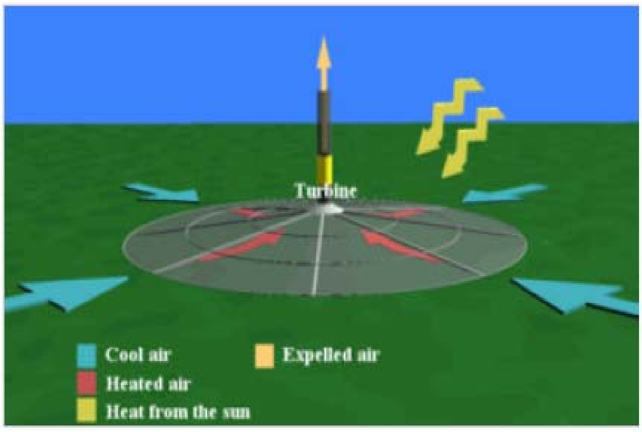


The collected heat is typically utilized directly by a heat engine mounted on the receiver moving with the dish structure. Stirling and Brayton cycle engines are currently favored for power conversion.

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.

1.2 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); 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.



General concept of proposed solar chimney power station

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. 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. Carnot's theorem greatly restricts the efficiency of conversion in these circumstances.

2. Water heating

Water heating is required in most countries of the world for both domestic and commercial use. There are a wide variety of solar water heaters available. 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. There are two common simple configurations for such a system and they are outlined below.

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

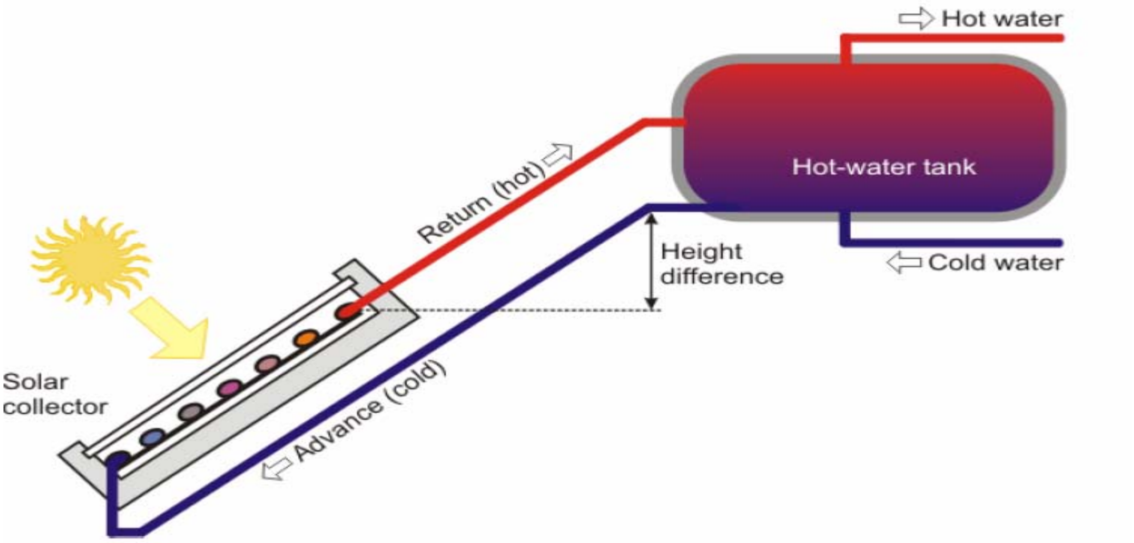


FIGURE 4. A thermosyphon system

b. ***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.

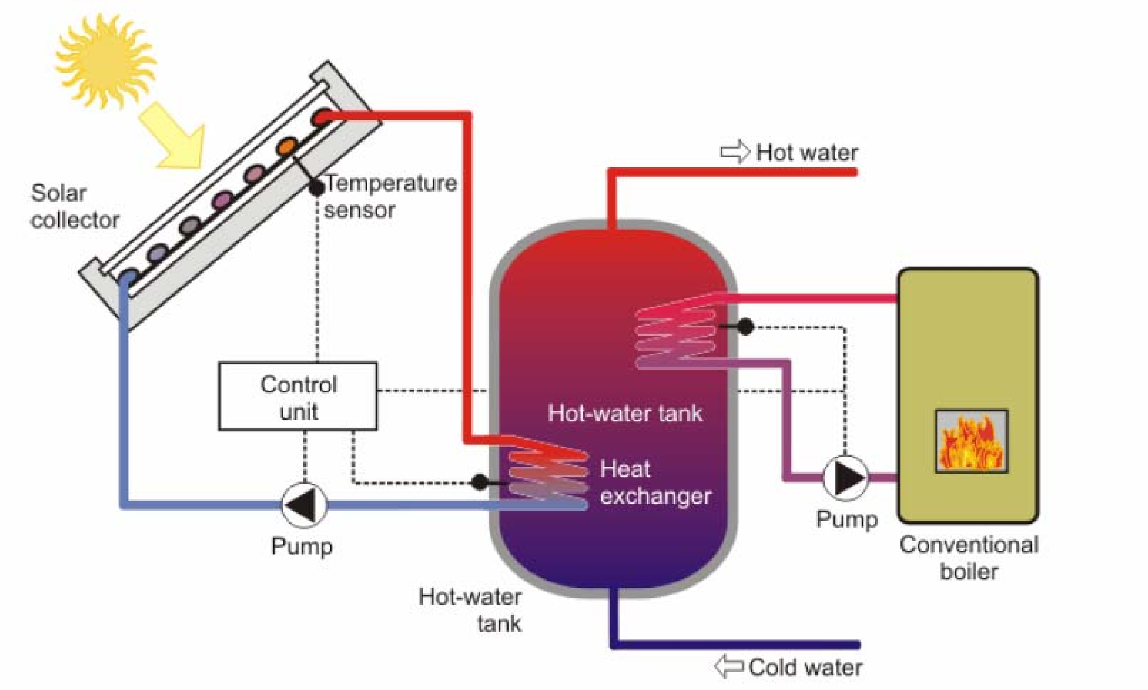


FIGURE 5. A double-cycle system with forced circulation with a conventional boiler for back-up heating

2.1 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. There are higher piping losses with a central tank, but some solar district heating demonstration systems have already been successfully tested.

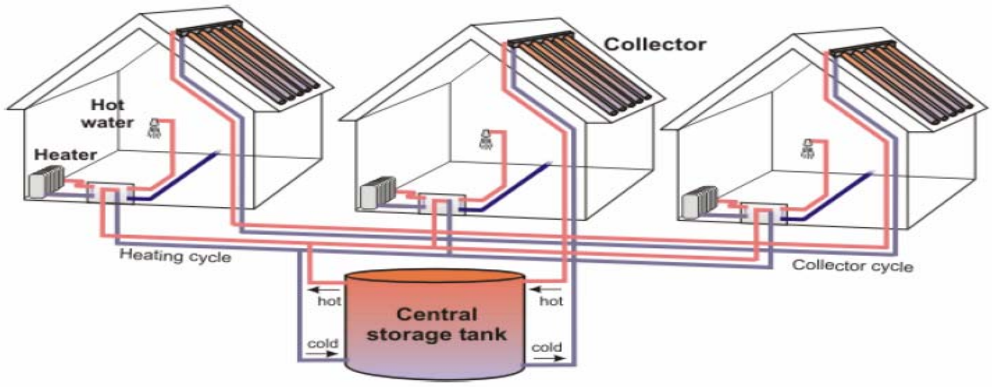


FIGURE 6. A solar district heating system

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. The **life-cycle cost** of energy of saved electrical energy is Rest. 5600 per year at the point of end-user. If the SWH is purchased as an add-on to an existing geyser, the simple payback period for the consumer would be 5.45 years. If the SWH is purchased instead of a conventional geyser, the payback period for the consumer would reduce to 3.58 years.

3. 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. The vapor produced is carried away by air moving past the material, the air motion being due either to natural convection resulting from contact with the heated material or to winds.

This process has several disadvantages

Disadvantages of mechanical and artificial drying:

1. Spoilage of product due to adverse climatic condition like rain, wind etc
2. Loss of material due to birds and animals
3. Deterioration of the material by decomposition, insects and fungus growth
4. 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 is a very useful device for

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

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. 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.

1. Solar cabinet dryer
2. Solar green house dryers
3 Indirects sonars drayer

4. 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. 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. Provision has been made to fill water in the still basin. A window is provided in the basin to clean the basin from inside. Water is charged in to the basin in a thin layer.

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

1. Produces pure water
2. No prime movers required
3. No conventional energy required
4. No skilled operator required
5. Local manufacturing/repairing
6. Low investment
7. Can purify highly saline water (even sea water)

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.

The operation of Solar Still is very simple and no special skill is required for its operation and maintenance. Solar stills is an useful devise to get fresh/ distilled water which is required in Industries for industrial processes Hospitals and Dispensaries for sterilization Garages and Automobile Workshop for radiator and battery maintenance Telephone Exchange for battery maintenance Laboratory Use for analytic work Marshy and costal area To get fresh potable water

5. 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:

1. Outer Box: The outer box of a solar cooker is generally made of G.I. or aluminum sheet or fiber reinforced plastic.

2. 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.

3. 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.

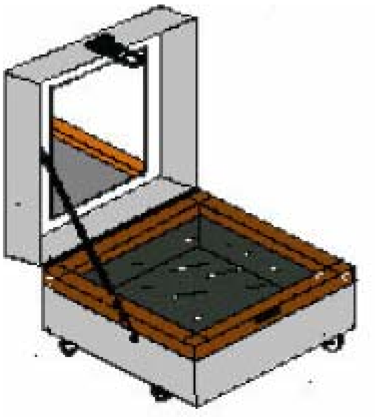
4. Thermal Insulator: The space between the outer box and inner tray including bottom of the tray is packed with insulating material such as glass wool pads to reduce heat losses from the cooker. This insulating material should be free from volatile materials.

5. 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.

6. 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.

The solar box cooker typically reaches a temperature of 90 °C; not as hot as a standard oven, but still enough to warm food over an hour. Because it doesn't reach too high a temperature, food can be safely left in it all day without burning. The cooker is often used to make a large pot of food in the morning, and then people eat servings or snack from it all day. The cooker is usually used to warm food and drinks but can also be used to pasteurize milk and sanitize water.

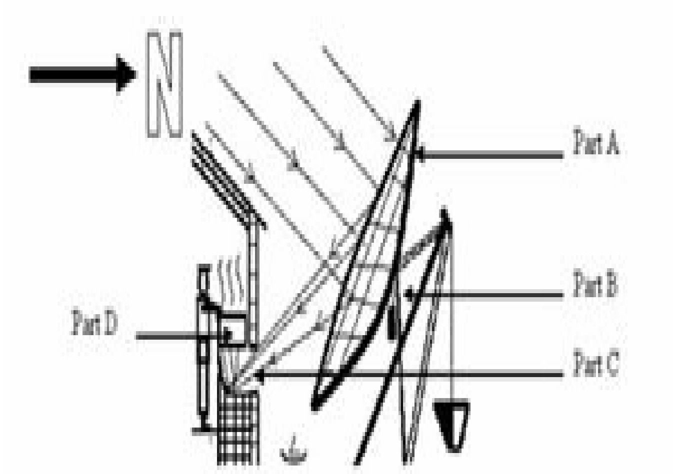
Horace de Assure, a Swiss naturalist, invented solar cookers as early as 1767



We can cook a large number of items, like pulses, rice, cheer etc. The time taken to cook will depend upon the type of the food, time of the day and solar intensity. However, the time taken to cook some of the dishes in a solar cooker is as follows:

1. Rice (45 minutes to one hour),
2. Vegetables (about one to two hours),
3. Black gram and Raja (about two hours),
4. Cake (one hour).

6. Community Solar Cooker:



Numerous households all over the country are using ‘**Surry**’ Cooker to cook their meals. 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. The canteen size solar cookers are just larger in size and can cook for 10-15 persons. For meeting still larger demands a large Community Solar Cooker has been developed with Solar Concentrator technology. It is an ideal cooking device for hostels, guesthouses etc.

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. The implications of utilizing such inefficient devices are higher fuel consumption & environment pollution. As a result more trees are felled each year for meeting the ever-increasing energy demands. This leads to rapid deforestation and environment degradation. In addition, the smoke from chelas causes serious health hazard to kitchen workers. The Community Solar Cooker, in contrast, poses no such health hazards as it utilizes ‘the freely available eco-friendly solar energy from nature.

This Community Solar Cooker employs a parabolic reflecting concentrator that can cook large quantities of food at much faster rate. The best part is that the cooking can take place within an

Enclosed kitchen. It can replace LPG, kerosene and firewood which are either cumbersome to use, very expensive or which are in short supply. This Cooker is technologically far superior to the box-type community cooker, having overcome a number of shortcomings of the box type cooker.

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.

7. 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. When providing water vapor or steam, it is stored in the porous storage medium (adsorption) and simultaneously heat is released.

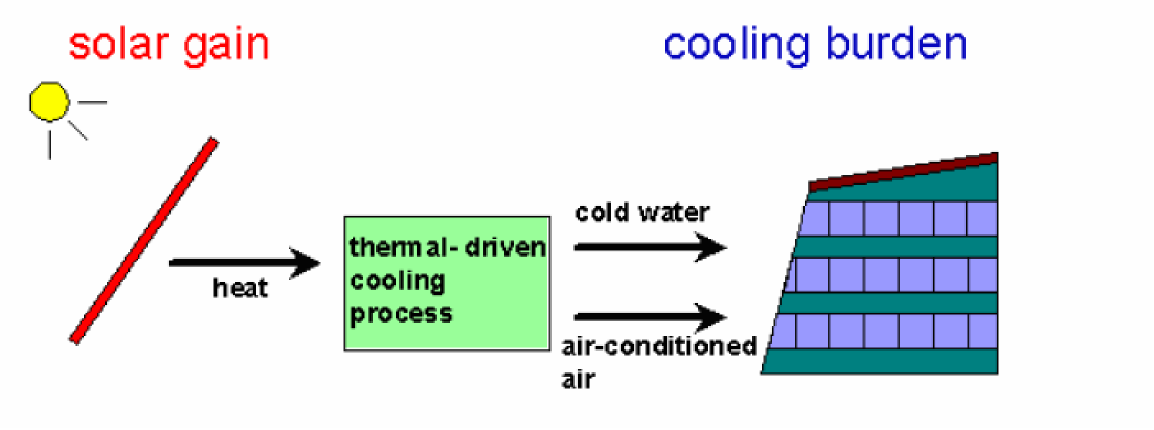
Processes are differentiated between closed refrigerant circulation systems, for producing

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. The latter is used

For dehumidification and evaporative cooling

Basic structure of a solar air conditioning system:



8. 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, so 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.

Another problem is the dangers involved in transmitting such high power radiations through the atmosphere.

Case study:

1. 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.

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. The other external

Walls, the ground and the roof are insulated to retain the heat and reduce the heat loss.

The insulation value of the traditional construction materials (mud, stone) is not sufficient and other local materials have to be selected as insulator such as straw, sawdust, leaves, dung... The east, west and north walls are cavity walls constructed by mud brick and the air layer is filled with the insulator.

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.

During the winter, the education, the handicraft, the gathering activities are limited by the coldness, the lack of fuel wood and the space heating cost. The integration of passive solar architecture can facilitate these activities. The internal temperature of these buildings is never below 13°C during the day or 8°C during the night when the external temperature is -20°C.

The fuel wood required is reduced by more than 90%. Even if the weather is cloudy, enough energy is stored in the walls to maintain a comfortable temperature during 4 days. The over cost of the solar passive architecture is 10 to 15% of the cost of a traditional building

The passive solar technology have been implemented in many areas, some examples are:

1. 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.

2. It has also been implemented in Administration buildings (e.g. Latah Autonomous Hill Council).

3. Handicrafts center (LEHO has constructed 3 villages training center in Dakar,

Chicot and Diskette to facilitate the production of Patina shawl during the winter period.)

4. Community halls

5. Hospital and dispensary: The comfort and hygiene conditions are very good compared with the usual system. In maternity wards and operating theatres, the passive solar technology can be combined with a radiant floor heating to optimize the hygiene condition.

6. 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.

2. 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. This system produces 54000 liters of hot water at 60 °C. Hot water produced by Solar System is used as pre heated boiler feed water and helps to save about 200 lit of furnace oil per day. 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. This is the single largest solar water heating system in Gujarat installed in a Dairy Industry.

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:

The capital subsidy for solar water heating systems was abolished in 1994 and provisions were made for soft loans. Indian Renewable Energy Development Agency (IREDA) and six other designated banks provide the financing for solar thermal systems.

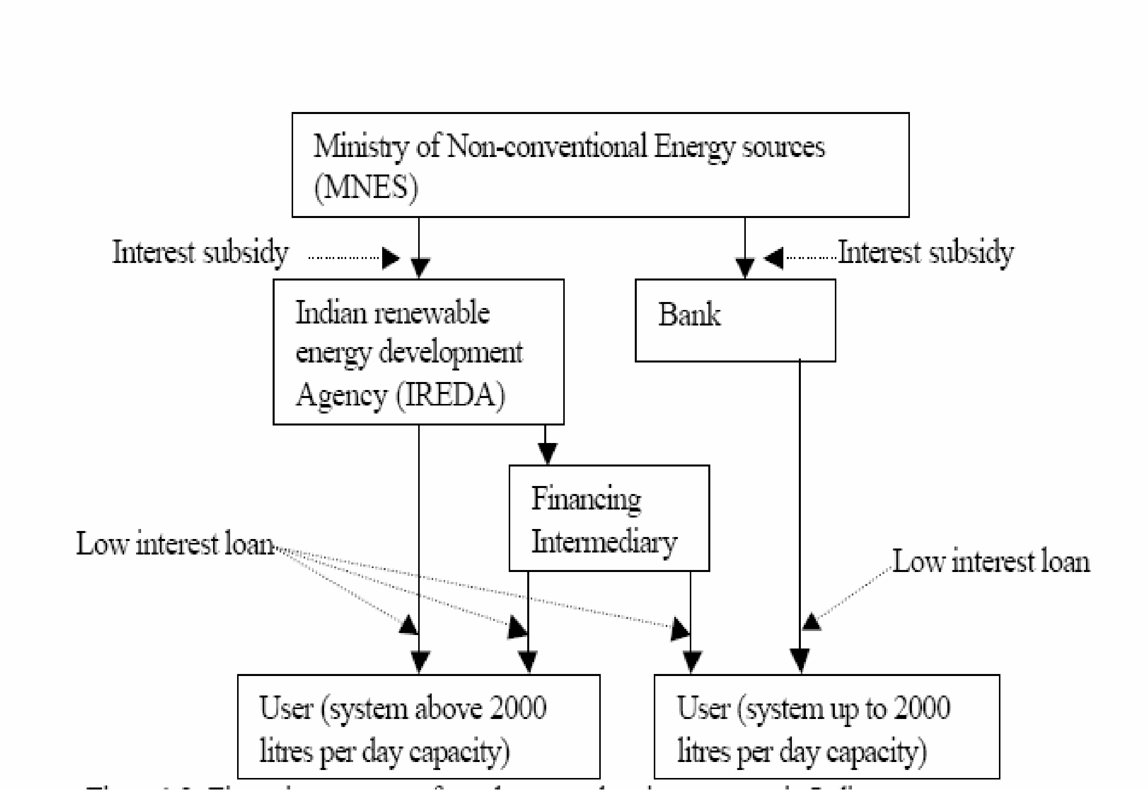


Fig. Financing structure for solar water heating systems in India

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

Could be solved by connecting the plant to the grid. The power flow in either direction can be metered separately. With all these features and opportunities in hand the percentage contribution of Solar energy to Global energy demand could be increased in near future thus reducing stress on the use of fossil fuels.

References:

1. www.globalresourceoptions.com
2. http://www.consumerenergycenter.org/renewable/basics/solarthermal/thermal.html#top
3. http://www.southface.org/solar/solar-roadmap/solar_how-to/solar-how_solar_works.htm
4. http://www.itdg.org/docs/technical_information_service/solar_thermal_energy.pdf
5. http://www.geda.org.in/solar/so_slr_hmlight.htm
6. http://en.wikipedia.org/wiki/Solar_power
7. http://www.volker-quaschning.de/articles/fundamentals4/index_e.html
8. http://www.ieiglobal.org/ESDVol1No1/solarwater.pdf
9. http://www.solarserver.de/solarmagazin/artikeljuni2002-e.html
10. http://www.teri.res.in/teriin/opet/reports/solarthermal.pdf
11. Renewable Energy World 02/2004 pp. 95-99
12. Lecture notes “Design of Photovoltaic systems”, Dr L Umanand, CEDT IISc Bangalore.