Solar Energy Conversion Technology

Flat Plate Collectors

Dr. Pankaj Kalita
Associate Professor
School of Energy Science and Engineering
Indian Institute of Technology, Guwahati

- Effect of various parameters on the performance of FPC
- Evacuated tube collector

Parameters influence the performance of FPC

- Design parameters
- Operational parameters
- Meteorological parameters
- Environmental parameters

Prominent parameters

- Selective surfaces
- Number of covers
- Collector tilt
- Cover transmissivity
- Fluid inlet temperature
- Dust on the top cover
- Spacing
- Shading

Selective Surfaces

- Absorber plate surfaces which exhibit the characteristics of a **high value of absorptivity for incoming solar radiation** and **a low value of emissivity for outgoing re-radiation** are called selective surfaces.
- **Desirable: because they maximize the absorption of solar energy and minimize the emission of the radiation loss.**
- Selective surfaces would yield higher collector efficiency than obtained when the absorptivity and emissivity are equal.

Selective Surfaces

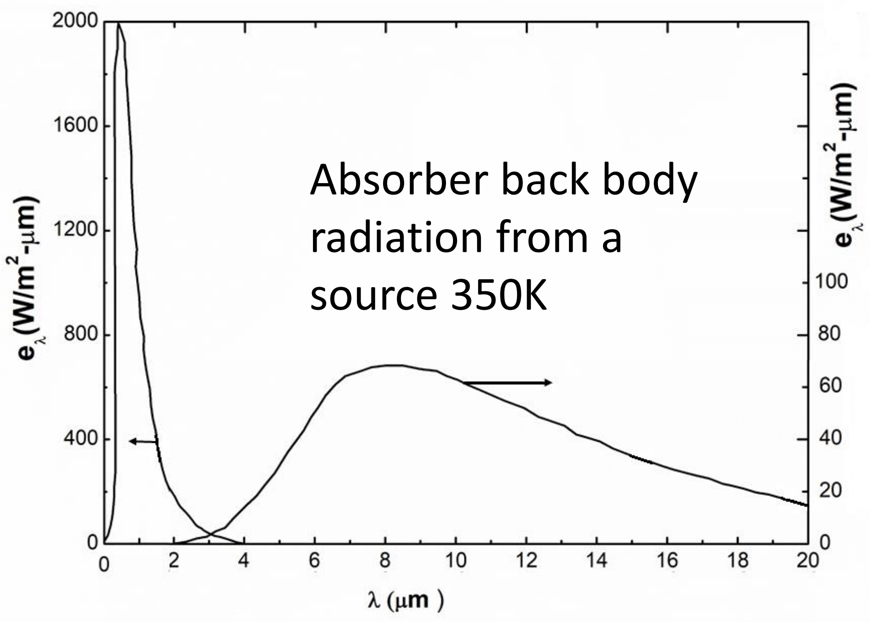
- ❖ **Possibility of having selective surface in FPC was suggested first by Tabor, Gier and Dunkle**

- ✓ If a surface that has a high absorptivity for wavelengths less than 4 µm and a low emissivity for wavelengths grater than 4 µm can be prepared, it would have the characteristics desirable for an absorber plate surface to act in a selective fashion.

Characteristics desired for an ideal selective surface:

$$\alpha_\lambda = \varepsilon_\lambda = 1 \text{ for } \lambda < 4\mu\text{m}$$

$$\alpha_\lambda = \varepsilon_\lambda = 0 \text{ for } \lambda > 4\mu\text{m}$$



Spectral distribution of extra-terrestrial solar radiation and black body radiation from a source at 350 K

- ✓ No over lap between the two spectrum
- ✓ Radiation coming out from the absorber plate is of large wavelengths with a maximum at 8.3 µm

Layer is less than 1 µm

Methods:

- ✓ Electroplating
- ✓ Chemical conversion
- ✓ Anode oxidation
- ✓ RF-magnetron sputtering
- ✓ Reactive DC magnetron Sputtering

Selective Surfaces

- Most of the commercialized selective surface coatings are metal dielectric composite coating known as **Cermets.**
- Consists of fine metal particles in a dielectric or ceramic matrix, or a porous oxides impregnated with metal.
- Thin films of these composites are transparent in the high wavelength region and strongly absorbing in the solar wavelength region. Thus they form a selective surface when deposited on a highly reflective metal surface.
- The coating developed include nickel-black, black chrome and nickel-pigmented alumina. Suitable for FPC applications up to 100 °C.

Absorptivity: 0.88 - 0.94, emissivity: 0.28 - 0.49

Effect of selective surfaces on performance of collector

- Selective surface

	Selective surface α= 0.94, ε_p=0.14	Non selective surface α= 0.94 ε_p=0.94	Selective surface α= 0.95, ε_p=0.085
T_{pm}(K)	351.2	346.2	351.9
U_l(W/m^2-K)	4.12	7.26	3.83
q_u(W)	888.3	642.0	924.1
T_{fo}(K)	344.1	341.1	344.6
η_i(%)	43.6	31.5	45.4

Data: Solar Energy Principles of Thermal Collection and Storage,2008, by S P. Sukhatme and J N Nayak, 3rd Edition, TataMcGraw Hill Education Privet Limited, New Delhi

Number of covers

Selective surface $\alpha = 0.94, \quad \varepsilon_P = 0.14$

	Number of covers		
	1	2	3
$(\alpha\tau)_b$	0.8041	0.6892	0.5932
$(\alpha\tau)_d$	0.7284	0.6008	0.5114
U_l(W^4/m^2-K)	4.12	2.68	1.99
η_i(%)	43.6	41.0	36.6

With the addition of more covers, efficiency of the collector goes on decreasing.

Number of covers

Non selective surface $\alpha = 0.94, \quad \varepsilon_P = 0.94$

	Number of covers		
	1	2	3
$(\alpha\tau)_b$	0.8041	0.6892	0.5932
$(\alpha\tau)_d$	0.7284	0.6008	0.5114
$U_l(W^4/m^2$-K)	7.26	4.04	2.75
η_i(%)	31.5	35.3	33.4

- As the number of covers increases, the values of beam and diffused transmissivity-absorptivity multiplication decreases. Thus, the flux **S** absorbed in the absorber plate decreases.
- The addition of more covers also decreases the value of **U_l**. For this reason, the useful heat gain goes through a maximum value with a certain number of covers.

Collector tilt

- FPC's are normally used in a fixed position and do not track the sun. Therefore the tilt angle at which they are fixed is very important.
- Optimum tilt depends on the nature of the application.

Morse and Czarnecki – extraterrestrial radiation falling on collector

Annual Insolation $= \sum_{n=1}^{365} I_{sc} \int_{-\omega_s}^{+\omega_s} \left(1+0.033\cos\frac{360n}{365}\right) \times \left(\sin\delta\sin\phi-\beta+\cos\delta\cos\omega\cos\phi-\beta\right) d\omega$

- ✓ Relative annual insolation = ratio of the annual insolation for given values of phi and beta to the annual Insolation for phi =0 and beta = 0.
- ✓ Latitude up to 30^o, small deviations of a degree or two from the optimum tilt will not cause much change in the relative insolation.

Collector tilt

- For winter the recommended a value of tilt is $\phi + 10^o$ or $\phi + 15^o$
  - Applications: water heating, space heating etc.
- For summer the recommended value of tilt is $\phi - 10^o$ or $\phi - 15^o$
  - Applications: Absorption refrigeration plant etc.

Monthly average value of the energy falling on a collector plane per unit area, kWh/sq. m

$$\bar{H}_b \frac{\sin\left(\bar{\alpha}_a + \beta\right)}{\sin\bar{\alpha}_a} + \bar{H}_d$$

$\bar{\alpha}_a$ = Monthly average altuitude angle at noon

Total flux falling on the collector over the year

$$\sum_{i=1}^{12} \bar{H}_{bi} \frac{\sin\left(\bar{\alpha}_{ai} + \beta\right)}{\sin\bar{\alpha}_{ai}} + \bar{H}_d$$

For annual flux to be maximum

$$\beta_{\text{opt}} = \tan^{-1}\left[\pm\left\{\sum_{i=1}^{12} \bar{H}_{bi} \tan\left|\phi - \delta_i\right|\right\} \Big/ \sum_{i=1}^{12} \bar{H}_{bi}\right]$$

Ex.1 The following radiations are measured for the place 8.48°N, 76.95°E. Calculate the maximum tilt of a flat plate collector for

(i) Insolation falling on the array over the whole year is to be maximized.

(ii) Insolation for the months of December, January and February is to be maximized.

(iii) Insolation for the months of April, May and June is to be maximized.

Month	$\bar{H}_b$ kWh/sq. m	n	δ	$\phi-\delta$	$\bar{H}_b \tan(\phi-\delta)$
January	4.162	16	-21.10	29.9	2.393
February	4.442	45	-13.62	22.42	1.833
March	4.486	75	-2.42	11.22	0.889
April	3.549	105	9.41	-0.61	-0.038
May	2.663	136	19.03	-10.23	-0.481
June	2.276	166	23.31	-14.51	-0.589
July	1.894	197	21.35	-12.55	-0.422
August	2.424	228	13.45	-4.65	-0.197
September	3.177	258	2.22	6.58	0.366
October	2.675	289	-8.97	17.77	0.857
November	2.69	319	-19.15	27.95	1.427
December	3.101	350	-23.37	32.17	1.951
	37.539				**7.989**

$$\phi = 8 + \frac{48}{60} = 8.8^o$$

$$\beta_{\text{opt}} = \tan^{-1}\left[\pm\left\{\sum_{i=1}^{12} \bar{H}_{bi} \tan\left|\phi-\delta_i\right|\right\} \Big/ \sum_{i=1}^{12} \bar{H}_{bi}\right]$$

$$\Rightarrow \beta_{\text{opt}} = \tan^{-1}\left[\frac{7.989}{37.539}\right] = 12.01^\circ$$

$$\beta_{\text{opt}} = \tan^{-1}\left[\frac{5.077}{16.639}\right] = 16.97^\circ$$

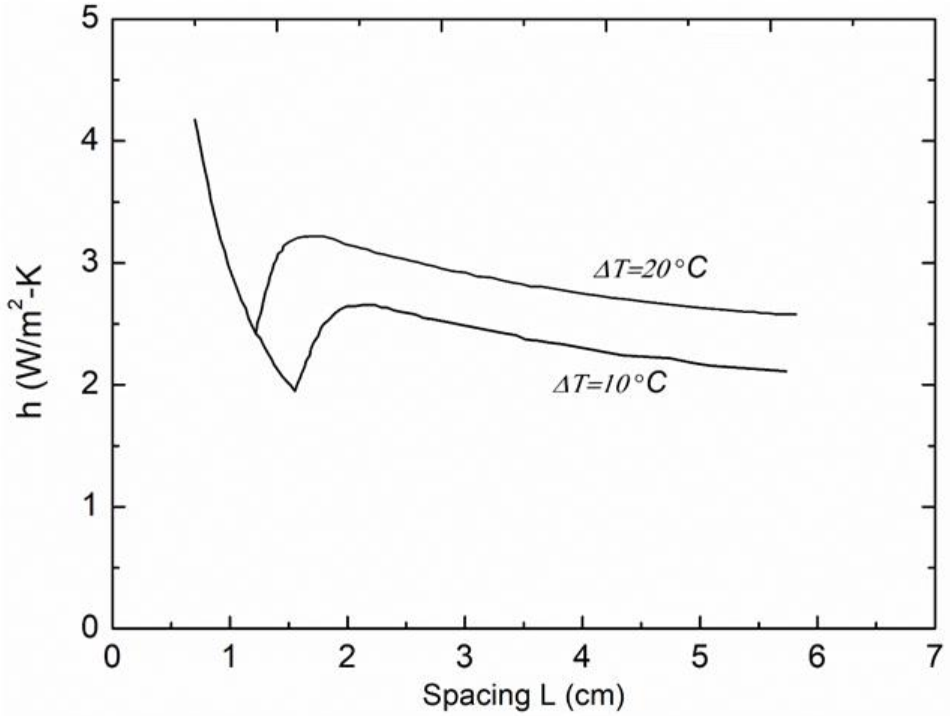
$$\beta_{\text{opt}} = 4.44^\circ$$

Spacing

- The spacing must be such that the values on the convective heat transfer coefficients are minimized.
- Spacing at which the minimum and maximum values occur vary with the temperature difference and tilt.
- An optimum value of spacing is difficult to specify
  - As the collectors are designed to operate at different locations with varying tilts and under varying service conditions.

Best to use a sufficiently large spacing away from the local minimum and maximum.

Variation of HTC with spacing



T_{mean}=70 °C

$\beta = 20^{\circ}$

- ✓ **Effect of Shading- important early morning and evening hours**
- ✓ **Shading reduces the radiation absorbed by about 3%**

$$Nu = 1; \text{ for } Ra\cos\beta < 1708$$

$$Nu = 1 + 1.446\left[1 - \frac{1708}{Ra\cos\beta}\right] \quad \text{for } 1708 < Ra\cos\beta < 5900$$

$$Nu = 0.229(Ra\cos\beta)^{0.252} \quad \text{for } 5900 < Ra\cos\beta < 9.23\times10^{4}$$

$$Nu = 0.157(Ra\cos\beta)^{0.285} \quad \text{for } 9.23\times10^{4} < Ra\cos\beta < 10^{6}$$

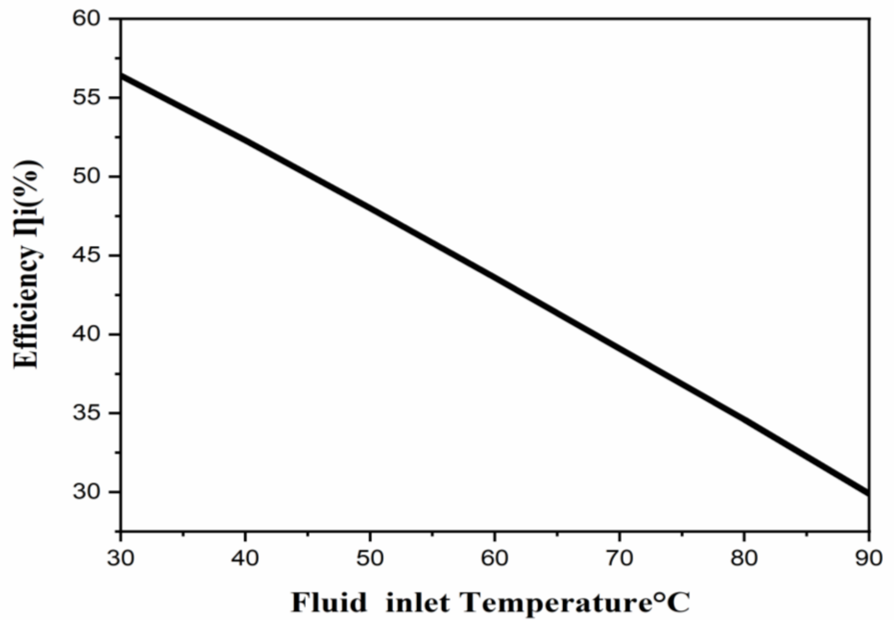
- Nu_L = 1 conduction region with the minimum occurring at a spacing corresponding to $Ra_L\cos\beta$ =1708
- Spacing of f 4- 8 cm is suggested by Buchberg et al.
- For large spacing (5 cm) collector area requirements can be reduced by 2 to 8%.
- h varies with temperature difference and tilt.

Effect of inlet temperature

✓ **Fluid inlet temperature strongly influences the performance of a FPC**

T_{fi}(°C)	30	40	50	60	70	80	90
T_{pm}(K)	326.5	334.8	343.0	351.2	359.3	367.5	375.5
U_l(W/m²-K)	3.78	3.90	4.02	4.12	4.22	4.31	4.39
q_u(W)	1149.0	1065.0	977.4	888.3	796.6	703.4	608.9
T_{fo}(K)	317.3	326.3	335.2	344.1	353.0	361.9	370.7
η_i(%)	56.4	52.3	48.0	43.6	39.1	34.6	29.9

- ✓ Decrease in efficiency is because of the higher temperature level at which the collector as a whole operates when the fluid inlet temperature increases.
- ✓ As a result top loss coefficient as well as the temperature difference with the surroundings increases **(heat lost increases and the useful heat gain decreases)**



Variation of efficiency of collector with fluid inlet temperature

Effect of cover transmissivity on performance of the collector

- ✓ Transmissivity of the cover affects the performance of the collector significantly
- ✓ Higher transmissivity means lower extinction coefficient of the cover material.

Efficiency increases from 43.6 % to 47.4% as the extinction coefficient decreases from 19 m^{-1} to 4 m^{-1}

	Selective surface	
	α= 0.94, ε_p=0.14	α= 0.95, ε_p=0.085
$(\alpha\tau)_b$	0.8554	0.8631
$(\alpha\tau)_d$	0.7836	0.7907
T_{pm}(K)	352.8	353.5
U_T(W/m^2-K)	4.14	3.86
T_{fo}(K)	345.1	345.5
q_u(W)	964.7	1001.6
η_i(%)	47.4	49.2

- Higher the transmissivity, the better is the performance of the collector

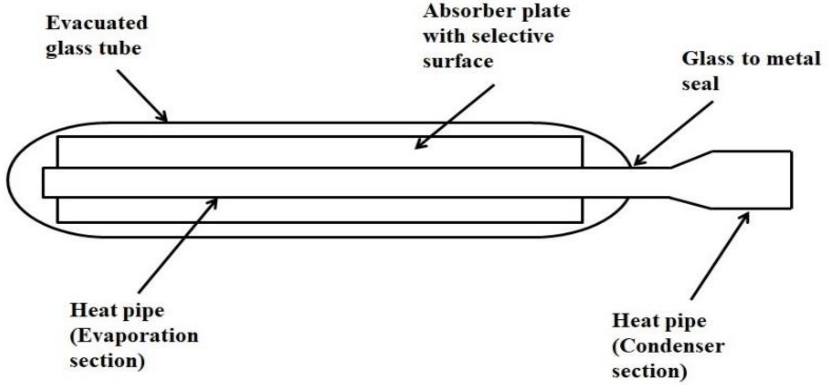
Dust on top cover

- When a collector is deployed in a practical system, dust gets accumulated over it, reducing the transmitted flux through the cover.
- Cleaning is generally done in a few days.

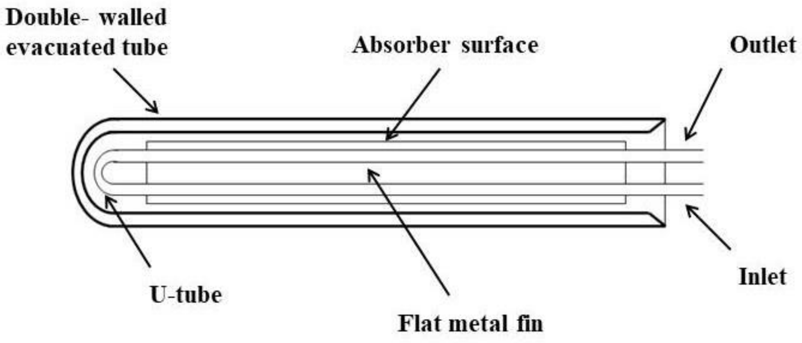
- ✓ Why incidence flux is multiplied by a correction factor?
- ✓ Correction factor: ratio of normal transmissivity to a dust-laden cover to the normal transmissivity.
- ✓ In general a correction factor of 0.92-0.99 is considered.

Depends on the material of the cover (glass or plastic), tilt of the collector and frequency of cleaning.

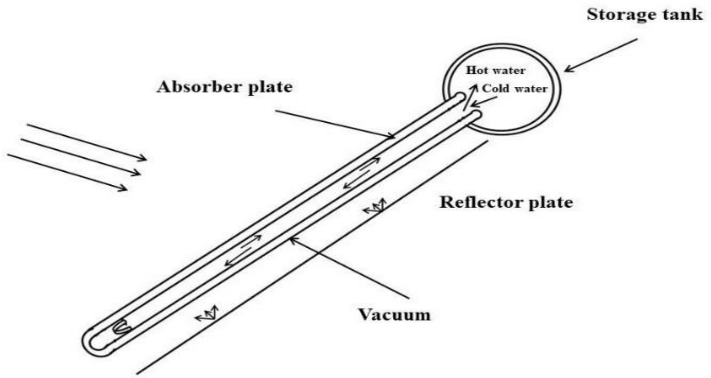
Evacuated tube collectors



Flat plate type with heat pipe



Double walled evacuated tube



Water in Glass Type

Objectives for development of alternatives:

- To improvement of efficiency
- To reduce cost
- To increase the operating temperature
- To reduce the weight of the collector

How? By reducing the heat lost by convection from the top cover

Evacuated tube collector

- Consists of a number of rows of parallel transparent glass tubes connected to a header pipe.
- Glass tubes are cylindrical in shape. Therefore, the angle of the sunlight is always perpendicular to the heat absorbing tubes which enables these collectors to perform well even when sunlight is low.
- Evacuated tube collectors are particularly useful in areas with cold, cloudy weathers.

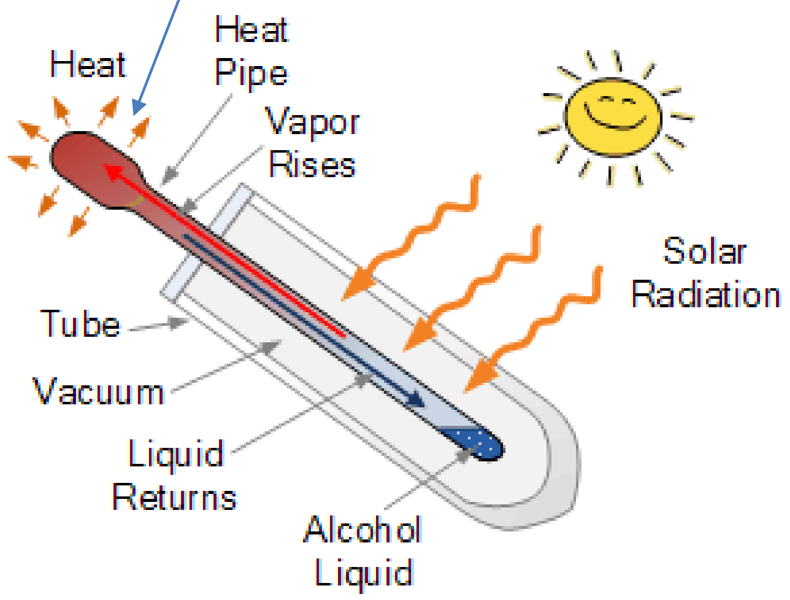
- ✓ Dia: 25 mm to 75 mm, and length: 1500 mm to 2400 mm.
- ✓ Each tube consists of a thick glass outer tube and a thinner glass inner tube, which is covered with a special coating that absorbs solar energy but inhibits heat loss.
- ✓ The tubes are made of borosilicate or soda lime glass, - strong, resistant to high temperatures and has a high transmittance for solar irradiation.

- ❖ Unlike flat panel collectors, evacuated tube collectors do not heat the water directly within the tubes. Instead, air is removed or evacuated from the space between the two tubes, forming a vacuum. This vacuum acts as an insulator reducing any heat loss to the surrounding atmosphere.
- ❖ With the assistance of this vacuum, evacuated tube collectors generally produce higher fluid temperature.

Heat Pipe evacuated tube collector

A **heat pipe** combines the principles of both thermal conductivity and phase transition to effectively transfer heat between two solid interfaces

releasing the latent heat

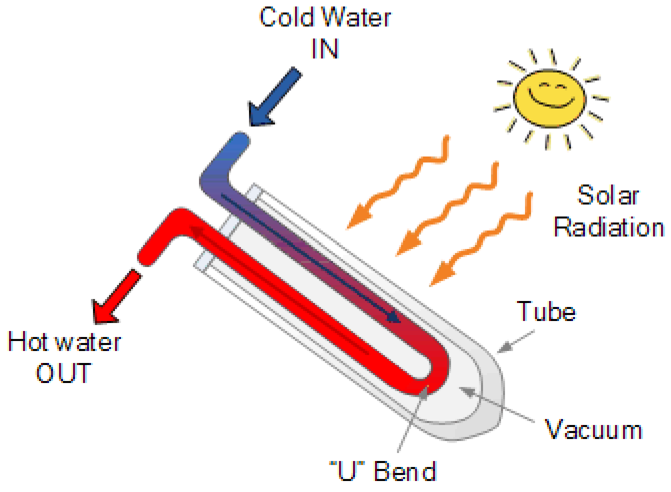


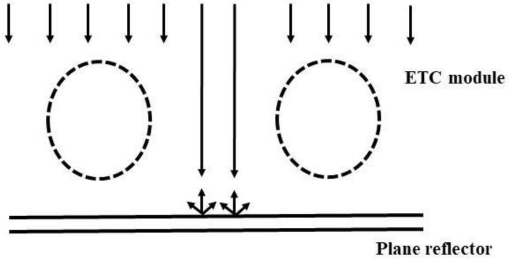
Gravity, Capillary action

- ✓ In heat pipe evacuated tube collectors, a sealed heat pipe, usually made of copper to increase the collectors efficiency in cold temperatures, is attached to a heat absorbing reflector plate within the vacuum sealed tube.
- ✓ The main advantage of **Heat Pipe Evacuated Tube Collectors** is that there is a “dry” connection between the absorber plate and the manifold.

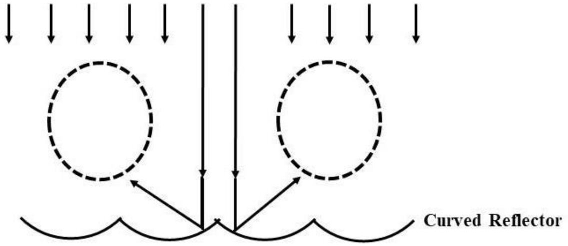
Direct Flow Evacuated Tube Collector

- ✓ Two heat pipes running through the center of the tube.
- ✓ The absorber plate and the heat transfer tube are also vacuum sealed inside a glass tube providing exceptional insulation properties.





- ➢ Direct flow evacuated tubes can collect both direct and diffuse radiation and do not require solar tracking.



Other collectors

- The BNL collector
- The polymer solar collector
- The concrete collector

Summary

- Factors influencing the performance of a FPC
  - Selective surface
  - Number of covers
  - Spacing
  - Collector tilt
  - Dust on the top cover
- Evacuated tube collector

Thank you

Heat Pipe

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- At the hot interface of a heat pipe a liquid in contact with a thermally conductive solid surface turns into a vapor by absorbing heat from that surface.
- The vapor then travels along the heat pipe to the cold interface and condenses back into a liquid – releasing the latent heat.
- The liquid then returns to the hot interface through either capillary action, centrifugal force, or gravity, and the cycle repeats.
- Due to the very high heat transfer coefficients for boiling and condensation, heat pipes are highly effective thermal conductors.
- The effective thermal conductivity varies with heat pipe length, and can approach 100 kW/(m·K) for long heat pipes, in comparison with approximately 0.4 kW/(m·K) for copper

Need of R and D efforts

- UV stable plastics
- Cheaper techniques for making selective absorbers
- Better forming (roll bonding) techniques for absorber manufacture
- Toughened glass
- Light weight high performance, insulation
- Effective sealants, including providing ease in assembly
- Conducting non-metals, which may replace dependence on copper or Aluminium solving the problem of corrosion concurrently