EN671: Solar Energy Conversion Technology

Thermal Energy Storage

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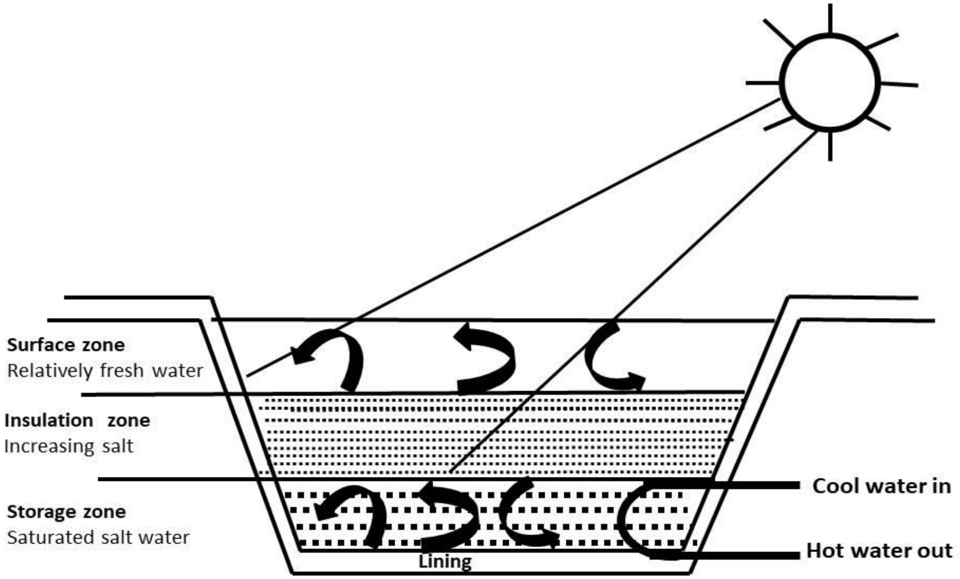
Solar Pond – Salt Gradient Solar Pond

- ✓ **Economical way of colleting and storing of solar energy requiring low temperature process (70-80^{o}C)**

Solar Pond

- ✓ A **solar pond** is a pool of saltwater which collects and stores solar thermal energy.
- ✓ The saltwater naturally forms a vertical salinity gradient, in which low-salinity water floats on top of high-salinity water.
- ✓ The layers of salt solutions increase in concentration (and therefore density) with depth.
- ✓ Below a certain depth, the solution has a uniformly high salt concentration.



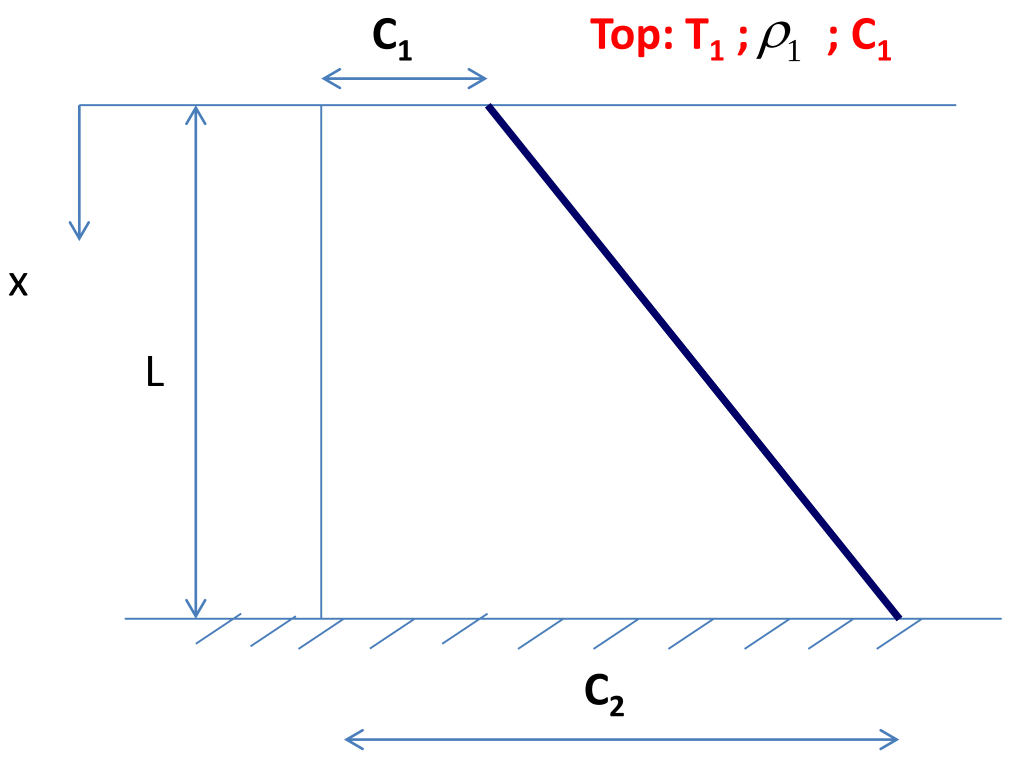
Some facts related to Solar Pond

- First solar ponds were constructed in Israel in the early sixties by Tabor and his co- workers.
- A maximum temperature of 100°C were obtained at the bottom, many practical difficulties were encountered and the work was abandoned.
- Number of solar ponds have been built all around the world to utilize the stored heat for providing process heat and generating power.
- Largest solar pond: Installed at Beit Ha'aravah in Israel (area -250000 m^2). Heat is used to generate electricity using an ORC.

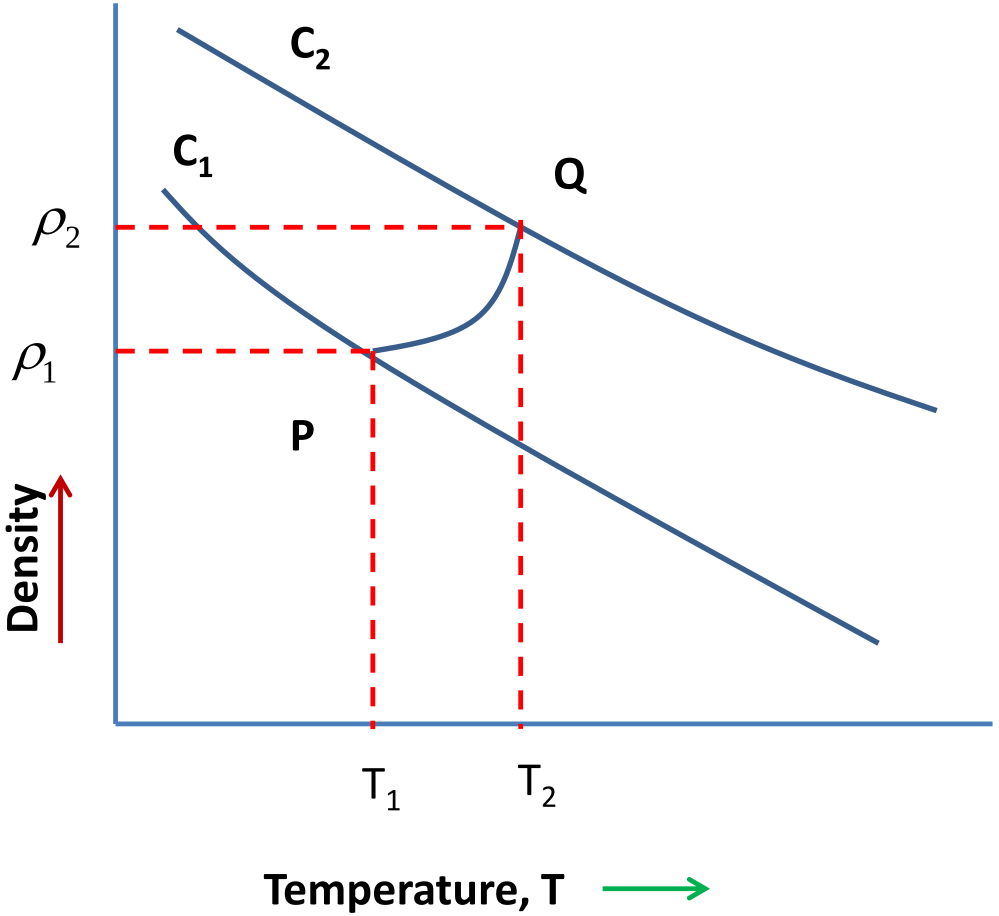
- Applications: **Desalination and brine management**
  - ✓ Australia: used to supply heat in salt production process (Pyramid Hill)

  India: Largest pond about 6000 m^2 built at Bhuj, Gujarat (used to supply process heat to a dairy farm)

Principle of working of Solar Pond



Bottom : T_2 ; ρ_2 ; C_2



✓ No convection will occur so long as the slope of the curve **PQ** is positive

Stability criteria

$$\frac{d\rho}{dx} > 0 \qquad (1)$$

$$\because \rho = \rho(C,T)$$

Hence,

$$d\rho = \left(\frac{\partial\rho}{\partial C}\right)_T dC + \left(\frac{\partial\rho}{\partial T}\right)_C dT \qquad (2)$$

Dividing the above expression by dx

$$\frac{d\rho}{dx} = \left(\frac{\partial\rho}{\partial C}\right)_T \frac{dC}{dx} + \left(\frac{\partial\rho}{\partial T}\right)_C \frac{dT}{dx} \qquad (3)$$

Using eqn.(1),

$$\frac{d\rho}{dx} = \left(\frac{\partial\rho}{\partial C}\right)_T \frac{dC}{dx} + \left(\frac{\partial\rho}{\partial T}\right)_C \frac{dT}{dx} > 0$$

$$\Rightarrow \frac{dC}{dx} > -\frac{\left(\frac{\partial\rho}{\partial T}\right)_C \frac{dT}{dx}}{\left(\frac{\partial\rho}{\partial C}\right)_T}$$

$$\frac{dC}{dx} > -\left\{\frac{\upsilon+\alpha}{\upsilon+D}\right\}\left\{\frac{\left(\frac{\partial\rho}{\partial T}\right)_C \frac{dT}{dx}}{\left(\frac{\partial\rho}{\partial C}\right)_T}\right\}$$

Minimum concentration gradient required for maintaining a given concentration gradient at a particular level in a solar pond.

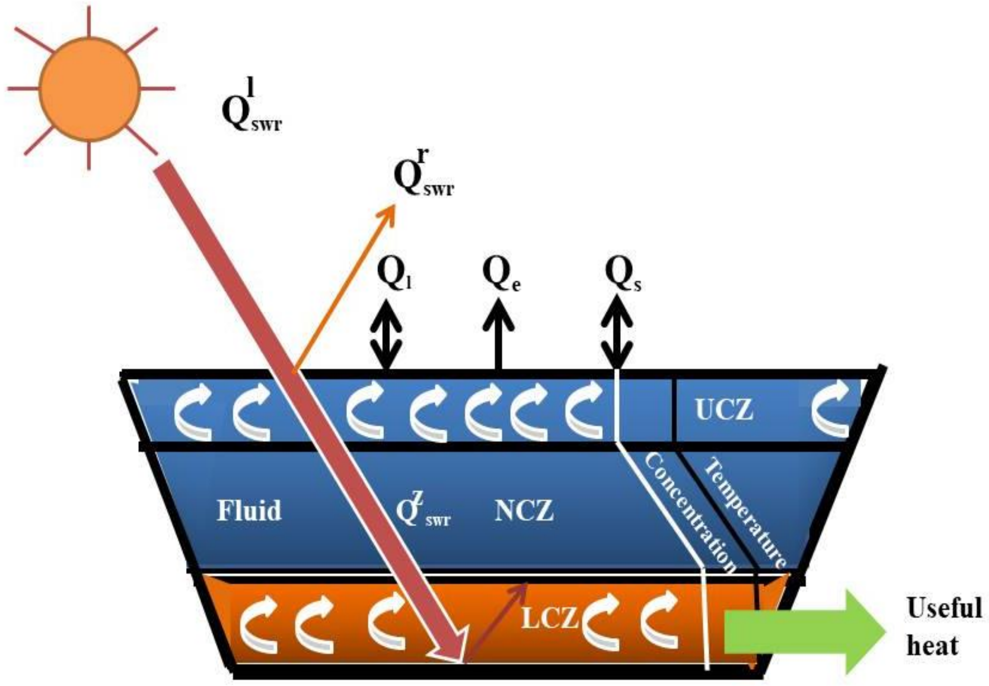
Ex.1: Sodium chloride is used as the salt in a solar pond. Estimate the minimum concentration (kg of salt per kg of water) required at the bottom if the concentration at the top is 0.02 and a temperature difference of 65 ^oC is to be maintained. Assume that the concentration and temperature profiles are straight lines and take the average values of $(\partial\rho/\partial T)$ and $(\partial\rho/\partial C)$ to be -0.5kg/m^3-^oC and 650 kg/m^3 respectively.

$$\Rightarrow \frac{dC}{dx} > -\frac{\left(\frac{\partial\rho}{\partial T}\right)_C \frac{dT}{dx}}{\left(\frac{\partial\rho}{\partial C}\right)_T} = -\frac{(-0.5)\times\frac{dT}{dx}}{650} \Rightarrow dC = \frac{0.5}{650}\times dT \Rightarrow C_2 - C_1 = \frac{0.5}{650}\times 65 = 0.05$$

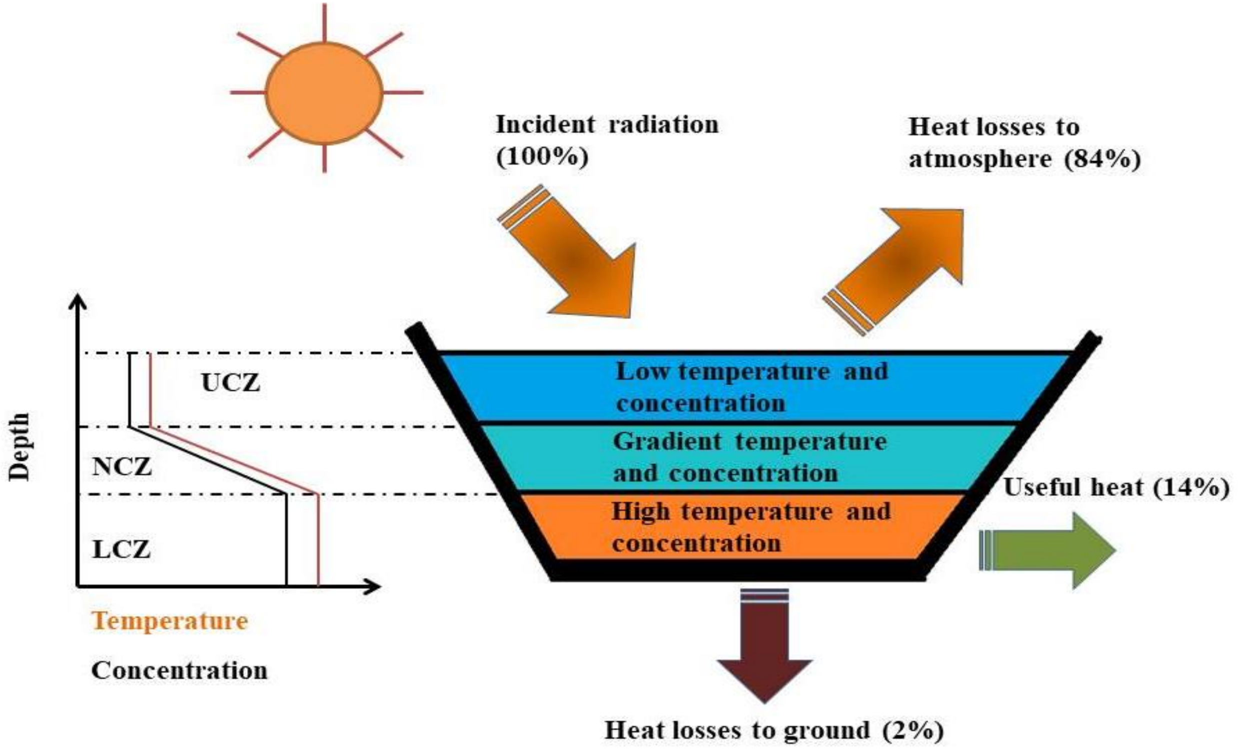
$$\Rightarrow C_2 = 0.07 \text{ kg of salt/kg of water}$$

Working principle

- ✓ Surface convective zone, SCZ
  - 10-20 cm thickness
  - Uniform concentration
  - Uniform temperature
- ✓ Concentration gradient zone (Non convective zone-NCZ)
  - Half of the depth of the pond
  - Temperature and concentration increase with depth
  - Act as insulating layer, reduces heat losses in the upward direction
- ✓ Lower convective zone, LCZ
  - Temperature and concentration constant
  - Serves as the main heat collection as well as thermal storage medium



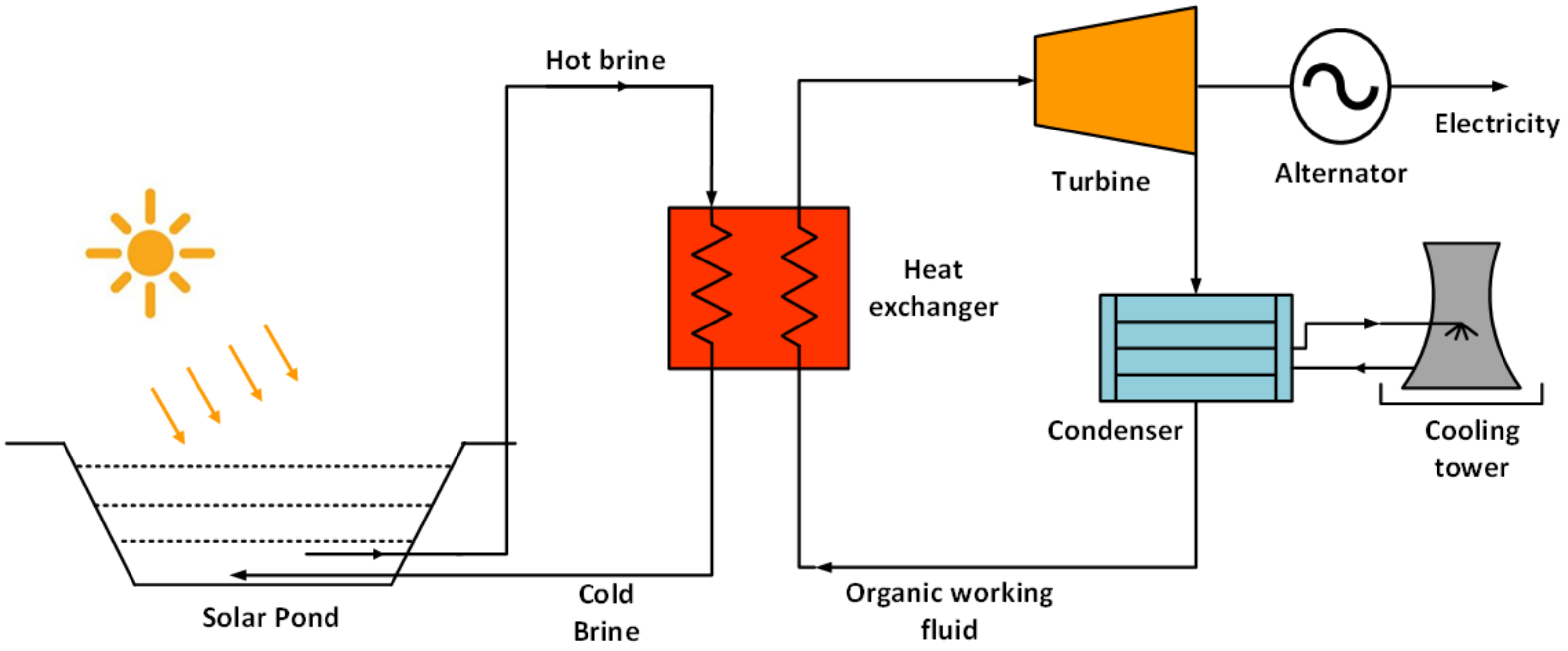
Working principle



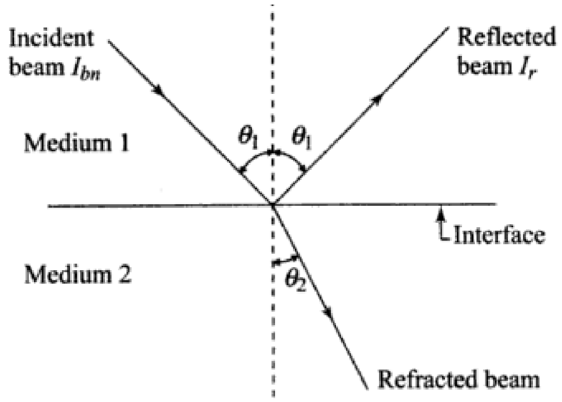
- ✓ Typically 2-3 m deep
- ✓ Thick durable liner (low density polyethylene-LDPE, High density polyethylene-HDPE, Woven polysestern yarn) at the bottom.
- ✓ Slats: magnesium chloride, sodium chlorise
- ✓ Concentration varies from – 20-30% at the bottom to zero at the top
- ✓ the temperature of the lower layer may rise to as much as 95°C

- **Salt required is about 50 g/m^2-day**
- **The annual collection efficiency varies between 15 -25 % which is less than flat-plate collector**
- **Cost per square meter is much less that that for a LFPC**

Solar Pond Power Generation



Transmissivity based on reflection and refraction at the air-water interface of a solar pond



Angle of incidence Θ_1 (degree)	Angle of refraction Θ_2(degree)	ρ_1	ρ_{II}	$\rho = ½(\rho_1 + \rho_{II})$	$\tau_r = (1—p)$
0	0	0.020	0.020	0.020	0.980
15	11.32	0.022	0.018	0.020	0.980
30	22.08	0.030	0.012	0.021	0.979
45	32.12	0.052	0.003	0.027	0.973
60	40.63	0.114	0.004	0.059	0.941
75	46.57	0.312	0.111	0.211	0.789
90	48.75	1	1	1	0

Snell's Law:
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

$$\rho_I = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)}$$

$$\rho = \frac{1}{2}(\rho_I + \rho_{II})$$

$$\rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)}$$

$$\tau_r = \frac{1}{2}(\tau_{rI} + \tau_{rII})$$

- For angle of incidence from 0 to 60° the loss due to reflection is small i.e. 2-6%
- For large angles, the loss is large (not intersected because these are associated with low values of radiation)

Trasmisivity based on Absorption

Bouger's law:

$$dI = -KIdx$$

$$\frac{I_l}{I_{bn}} = \tau_a = e^{-K\delta_c}$$

- ✓ Extinction coefficient is a strong function of wavelength
- ✓ Rebl and Nielsen: $$\tau_a = \sum_{j=1}^{4} A_j e^{-K_j x}$$

x = depth of water

- ❑ 77.6 % of radiation is accounted (corresponding to wavelength 02-1.2 μm)
- ❑ Balance 22.4 % corresponding to the radiation wavelengths grater than 1.2 μm – absorbed near the surface (1-2 cm)

$A_1 = 0.237$,	$K_1 = 0.032\ m^{-1}$	for	$0.2 < \lambda < 0.6$ μm
$A_2 = 0.193$,	$K_2 = 0.45\ m^{-1}$	for	$0.6 < \lambda < 0.75$ μm
$A_3 = 0.167$,	$K_3 = 3\ m^{-1}$	for	$0.75 < \lambda < 0.9$ μm
$A_4 = 0.179$,	$K_4 = 35\ m^{-1}$	for	$0.9 < \lambda < 1.2$ μm

- ✓ Bryant and Colbeck: $$\tau_a = 0.36 - 0.08 \ln x$$

x = depth of water in meter, valid for x >0.01 m

If the radiation is not incident normally,

$$\tau_a = 0.36 - 0.08 \ln \frac{x}{\cos\theta_2}$$

Example-2: A 2 m deep solar pond is built in Guwahati (26°8'). The values of global and diffuse radiation measured on a horizontal surface on 15th May at 1300 hr (LAT) are 900 W/m^2 and 200 W/m^2 respectively. Calculate (1) flux reflected from the water surface, (2) Flux entering the water and (3) solar flux at a depth of , 0.01 m, 0.5 m, 1 m and 2 m.

On May 15, n = 135

$$\phi = 26 + \frac{8}{60} = 26.13^o$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+135)\right] = 18.79^o$$

$$\cos\theta_1 = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$
$$\Rightarrow \cos\theta_1 = \sin 26.13^o \sin 18.79^o + \cos 26.13^o \cos 18.79^o \cos(-15^o)$$
$$\Rightarrow \cos\theta_1 = 0.9628$$
$$\Rightarrow \theta_1 = 15.667^o$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\mu_2}{\mu_1} = 1.33 \Rightarrow \theta_2 = \sin^{-1}\left(\frac{\sin\theta_1}{1.33}\right) = 11.715^o$$

$$\rho_b = 0.02;\ \text{for beam radiation}$$

$$\text{For beam radiation: } \theta_1 = 60^o, \theta_2 = 40.63^o, \rho_d = 0.059$$

Angle of incidence Θ_1 (degree)	Angle of refraction Θ_2(degree)	ρ_1	ρ_{II}	$\rho = ½(\rho_1 + \rho_{II})$	$\tau_r = (1—\rho)$
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- Flux reflected from the water surface: $\boxed{I_b\rho_b + I_d\rho_d = 700\times 0.02 + 200\times 0.059 = 25.8 \text{ W/m}^2}$
- Flux entering the water : 900 – 25.8 = 874.2 W/m^2
- Transmissivity based on the absorption:

If the radiation is not incident normally,

$$\boxed{\tau_a = 0.36 - 0.08\ln\frac{x}{\cos\theta_2}}$$

Transmissivity	At x = 0.01 m	X = 0.5	X = 1	X = 2
For beam, τ_{ab} $(\theta_2 = 11.715^o)$	**0.7267**	**0.4137**	**0.3583**	**0.3028**
For diffuse, τ_{ad} $(\theta_2 = 40.63^o)$	**0.7063**	**0.3933**	**0.3379**	**0.2824**

Solar flux at various depth =

$$\boxed{I_b \times \tau_{rb} \times \tau_{ab} + I_d \times \tau_{rd} \times \tau_{ad} \ \ (\text{W/m}^2)}$$

Depth (m)	Solar Flux (W/m^2)
0.01	**631.44**
0.5	**357.81**
1	**309.38**
2	**260.86**

Reflection and absorption of a solar radiation in a solar pond

- **SCZ: 10 cm, radiation absorbed in the wavelengths: 1- 2 μm.**
- **269 W/m^2 ~30% of the incident energy is absorbed in SCZ.**
- **This energy is almost entirely lost to the surroundings – reason for low collection efficiency.**

- **Flux penetrating to the bottom of the pond is ~261 W/m^2 ~ 31% of the incident energy.**

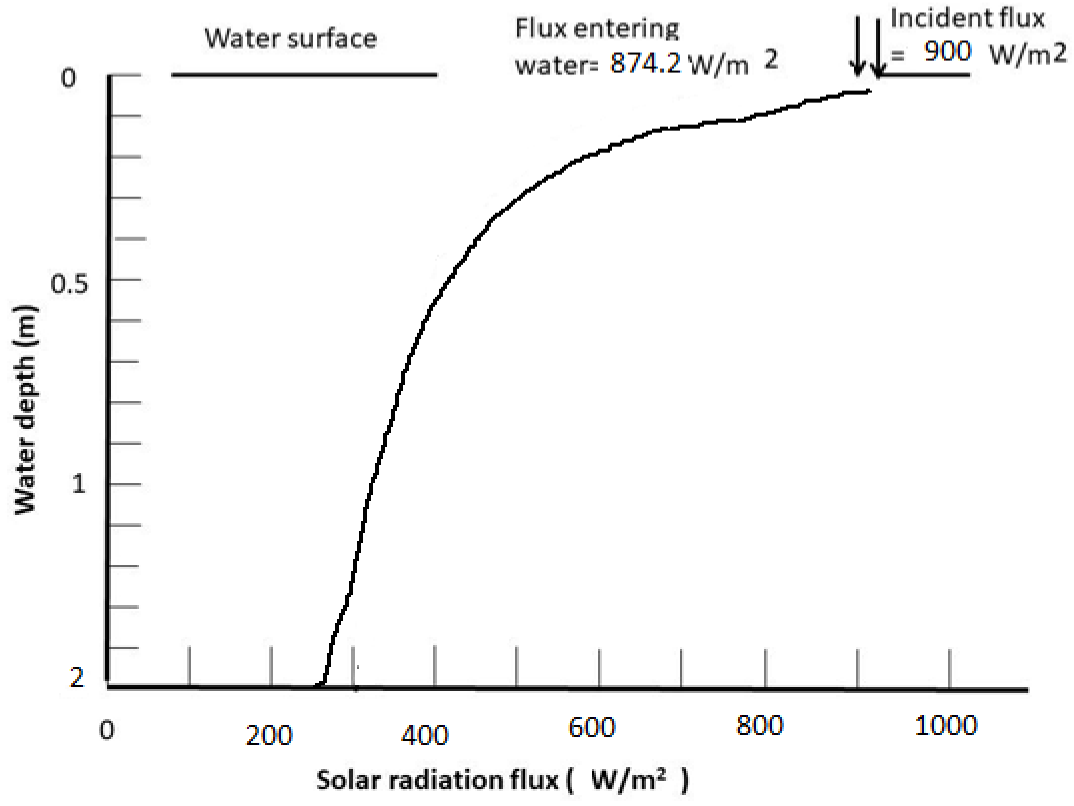
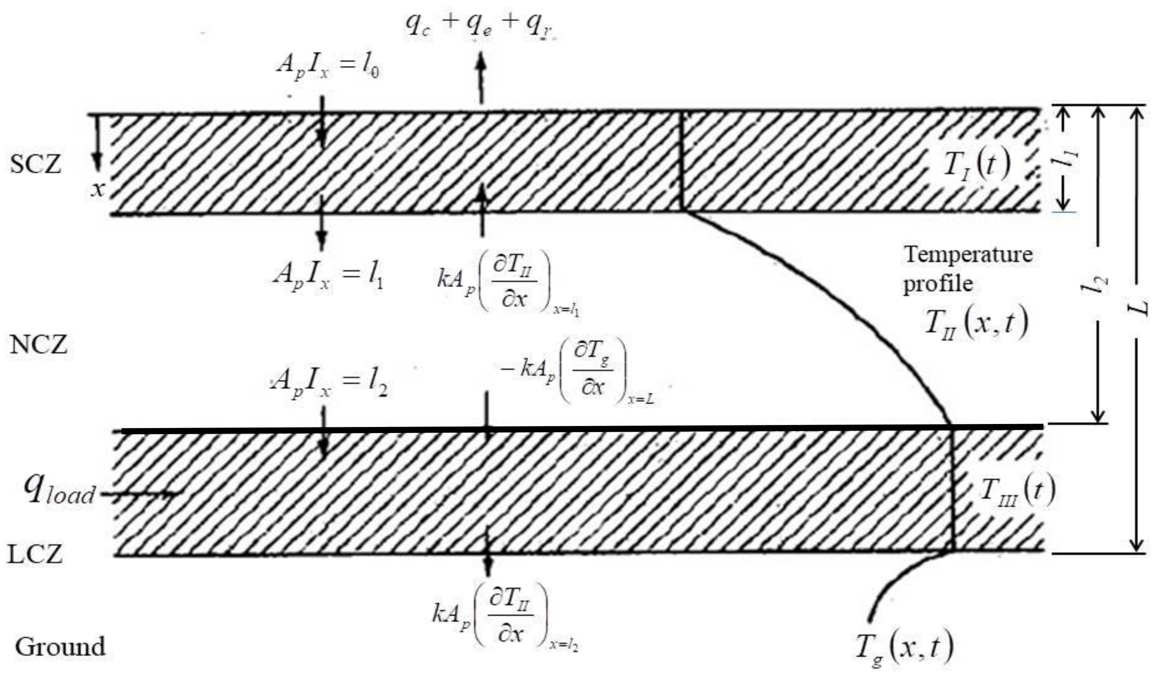


Fig. Variation of solar radiation flux with depth

Temperature distribution and collection efficiency



Energy flow diagram

- For an exact solution, one has to solve the appropriate differential equation for each zone.
- Matching condition has to be used at the interfaces between the zones and satisfy the boundary conditions at the top and bottom surfaces of the pond.
- Assumption: (a) the upper convective zone and the lower convective zone are assumed to be perfectly-mixed layers at uniform temperatures which change only with time, (b) lateral dimensions of the pond are large compared to its depth *L (temperature varies only in the vertical direction), properties are constant.*

Differential equation for the non-convective zone is the heat conduction equation of the form:

$$\rho C_p \frac{\partial T_{II}}{\partial t} = k \frac{\partial^2 T_{II}}{\partial x^2} - \frac{dI}{dx}$$

Solar radiation absorbed in the pond

$$I = I_b \tau_{rb} \tau_{ab} + I_d \tau_{rd} \tau_{ad}$$

Energy Balance

For the surface Convective Zone:

$$\rho l_1 C_p \left(\frac{dT_1}{dt} \right)_{x=l_1} = k \left(\frac{\partial T_{II}}{\partial x} \right)_{x=l_1} + \left[(I)_{x=0} - (I)_{x=l_1} \right] - \frac{1}{A_p} \left(q_c + q_e + q_r \right)$$

Rate of change of energy contained in the surface convective zone of thickness, l_1

Rate at which heat is conducted in from the non-convective zone

Solar radiation absorbed in the thickness, l_1

Rate at which heat is lost from the top surface by convection, evaporation and radiation

For the Lower Convective Zone:

$$\rho (L - l_2) C_p \left(\frac{dT_{III}}{dt} \right)_{x=l_2} = k \left(\frac{\partial T_{II}}{\partial x} \right)_{x=l_2} + (I)_{x=l_2} - \left[+ k_g \left(\frac{\partial T_g}{\partial x} \right)_{x=L} \right] - \frac{q_{\text{load}}}{A_p}$$

Rate at useful heat extraction

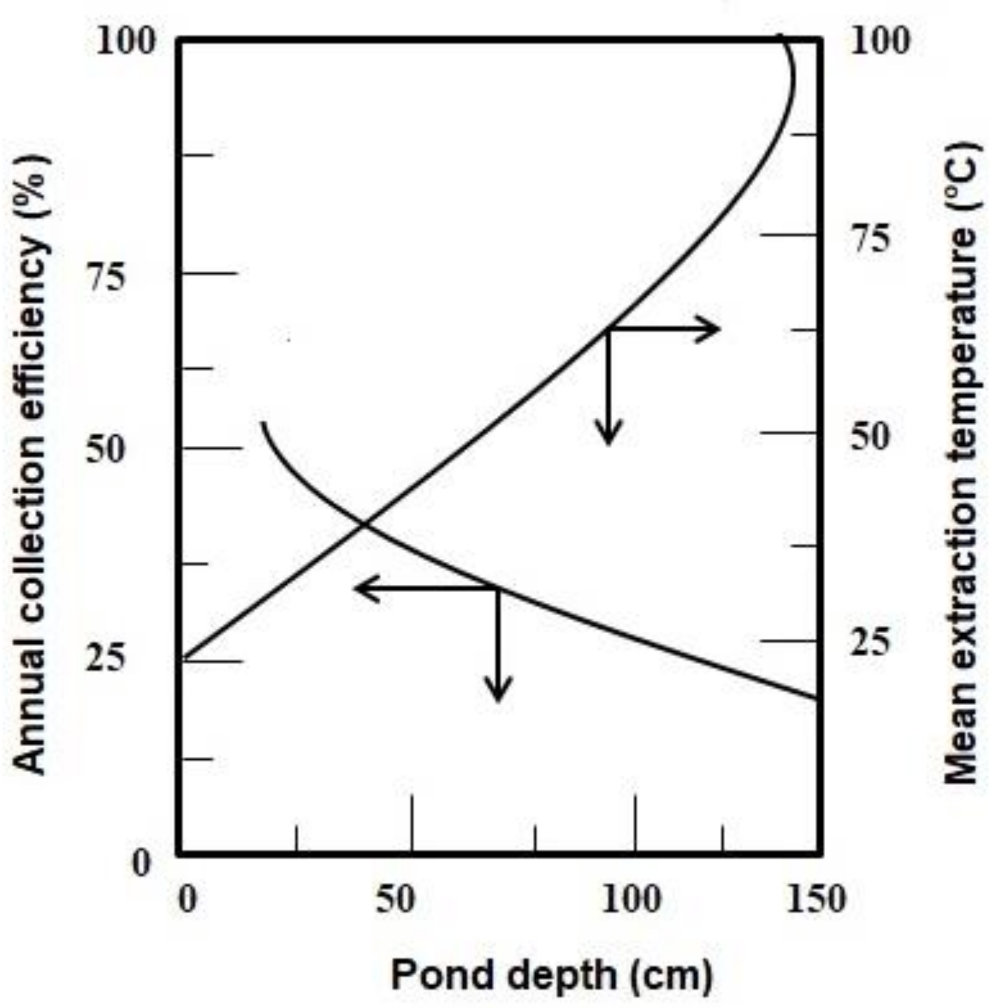
Rate of change of energy contained in the lower convective zone of thickness, $(L - l_2)$

Rate at which heat is conducted in from the non-convective zone

Solar radiation absorbed in the thickness, l_2

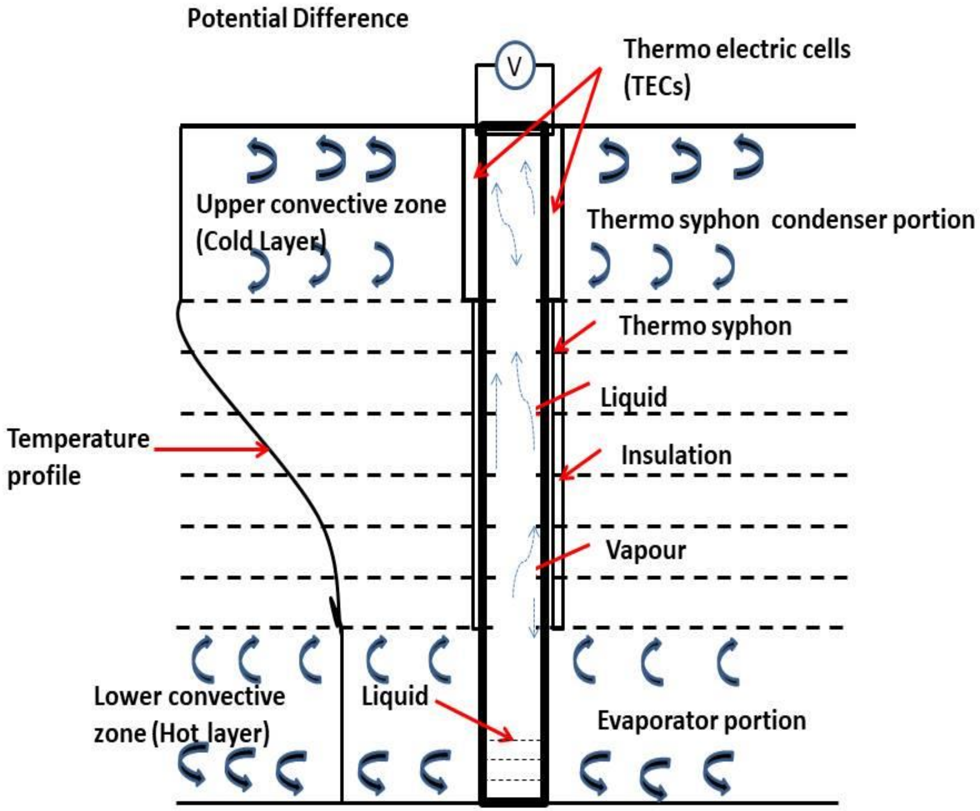
Rate at which heat conducted out to the ground underneath

Annual collection efficiency and extraction temperature as a function of pond depth

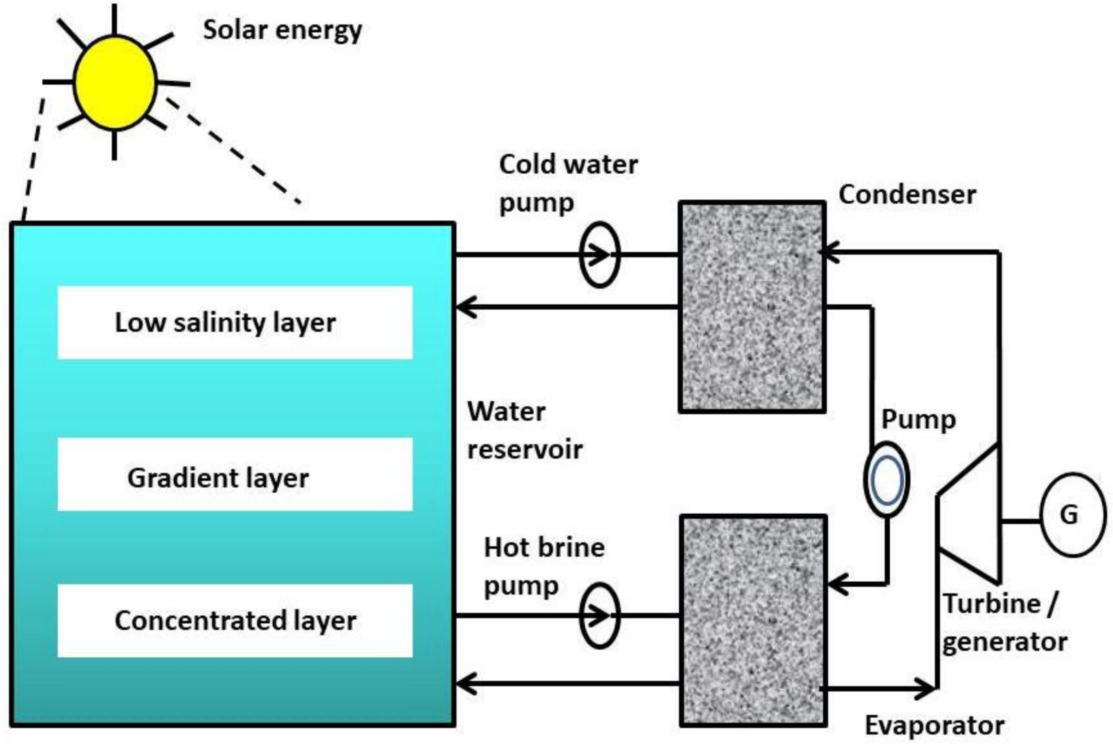


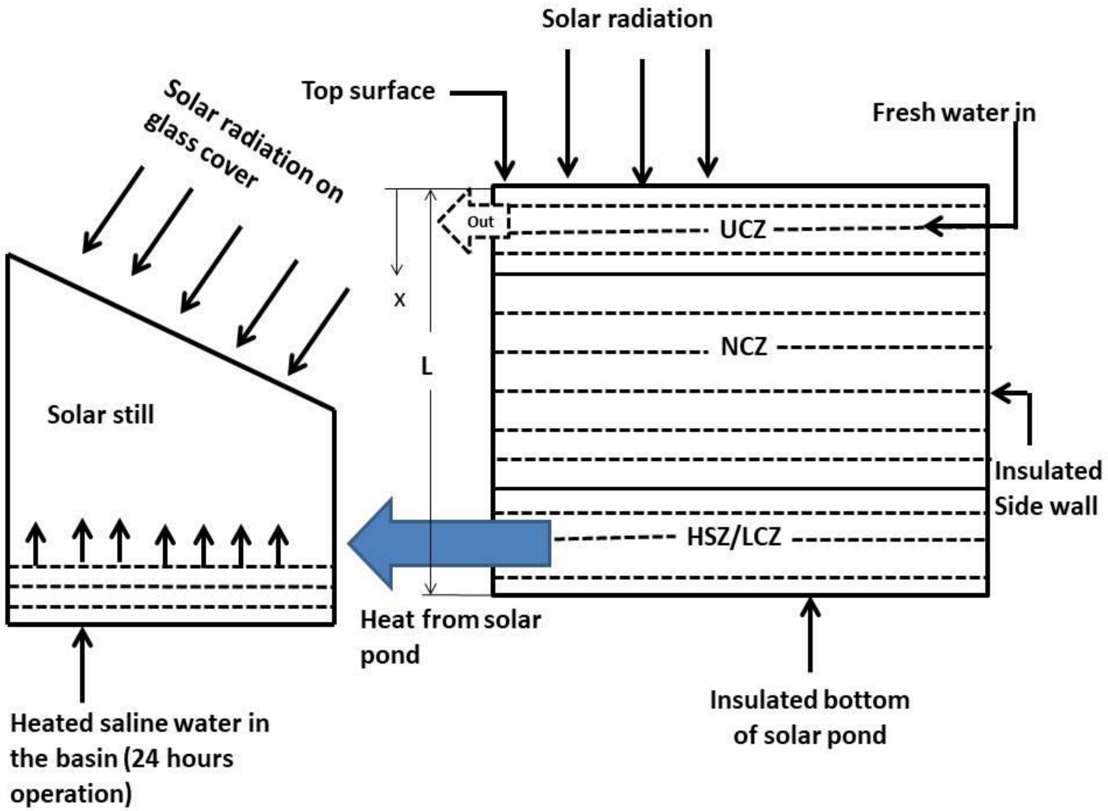
Applications of Solar ponds

Combined system of thermosiphon and thermoelectric modules to generate electricity from solar ponds.



Electric power generation from solar pond using Organic Rankine cycle





Active solar distillation systems integrated with solar ponds.

Operational shortcomings of Solar Pond

- Wind-induced waves
- Effect of rain
- Biological Growth
- Fouling due to dirt and leaves
- Effect of bottom reflectivity

Solar Gel Pond

- A thick layer of a polymer gel floats on the lower convection zone and act as non-convective zone. Gel (98.3% water and 1.7 % polyacrylamid) has good optical and thermal insulating properties.
- Project demonstration at New Mexico: Surface area: 400 m^2, and 5 m deep. Small concentration is necessary to float gel on top of LCZ.
- Gel was kept in thin transparent plastic bags made from Tedlar and floated on the salt solution. Thickness of the gel: 0.6 m, Designed to supply a minimum of 1 GJ per day at 70 $^{\circ}$C .

  - Evaporation loss from the surface are eliminated.
  - Maintenance requirement reduces.
  - The environment hazards associated with handling salt are eliminated.

Solar ponds across the globe

Israel's 150kw Solar Pond

Solar Pond in Gujarat India

ORC operated Solar Pond of Alice springs in Australia

Summary

- Fundamentals and working principle of solar ponds
- Temperature profiles and energy balance
- Max temperature during Summer and winter are reported to be 95^{o}C and 60^{o}C respectively
- Operational shortcomings
- Types of solar pond
- Applications