ALMUSTAQBAL UNIVERSITY COLLEGE
Iraq - Babylon

RENEWABLE ENERGY TECHNOLOGY

Sustainable Path For a Carbon Free Future

Refrigeration and Air conditioning Techniques
Engineering Department

Subject : Renewable Energy
Grade: 4th Class

Lecture : 9

Performance of Flat Plate Collectors

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Performance of Flat Plate Collectors

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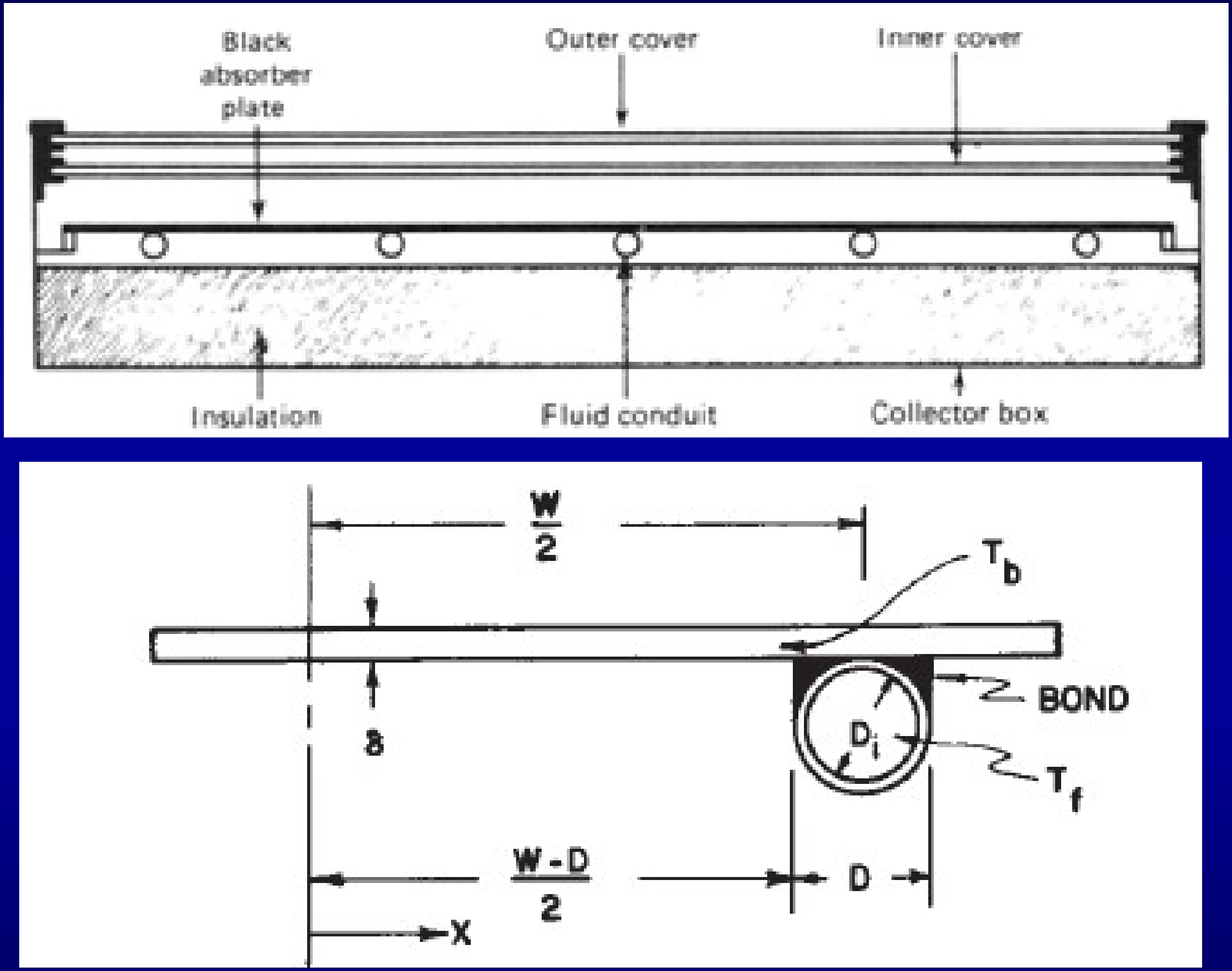
Description of Flat Plate Collectors



Sketch of a conventional flat plate collector

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- The thermal performance of a collector can be calculated from a first-law energy balance. According to the first law of thermodynamics, for a simple flat-plate collector an instantaneous steady-state energy balance is :

Useful energy = energy absorbed – heat loss to
gain (Q_u) by the collector surroundings

And,

- Absorbed energy = $A_c\, F_R\, S$
- Lost energy = $A_C\, F_R\, U_L\, (T_f - T_a)$

where ;

A_c = Collector area, m^2
F_R = Heat removal factor, unitless
S = $I_T\, (\tau\alpha)$ = Absorbed solar radiation, J/m^2
I_T – solar radiation
$\tau\alpha$ - transmittance-absorptance
U_L = Heat transfer loss coefficient, $J/m^2{}^\circ C$
T_f = The temperature of fluid enters the collector, °C
Ta = The ambient temperature, °C.

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- Therefore;

$$Q_U = A_C F_R S - A_C F_R U_L (T_f - T_a)$$

$$Q_U = A_C F_R [S - U_L (T_f - T_a)]$$

$$Q_U = A_C F_R [I_T (\tau\alpha) - U_L (T_f - T_a)]$$

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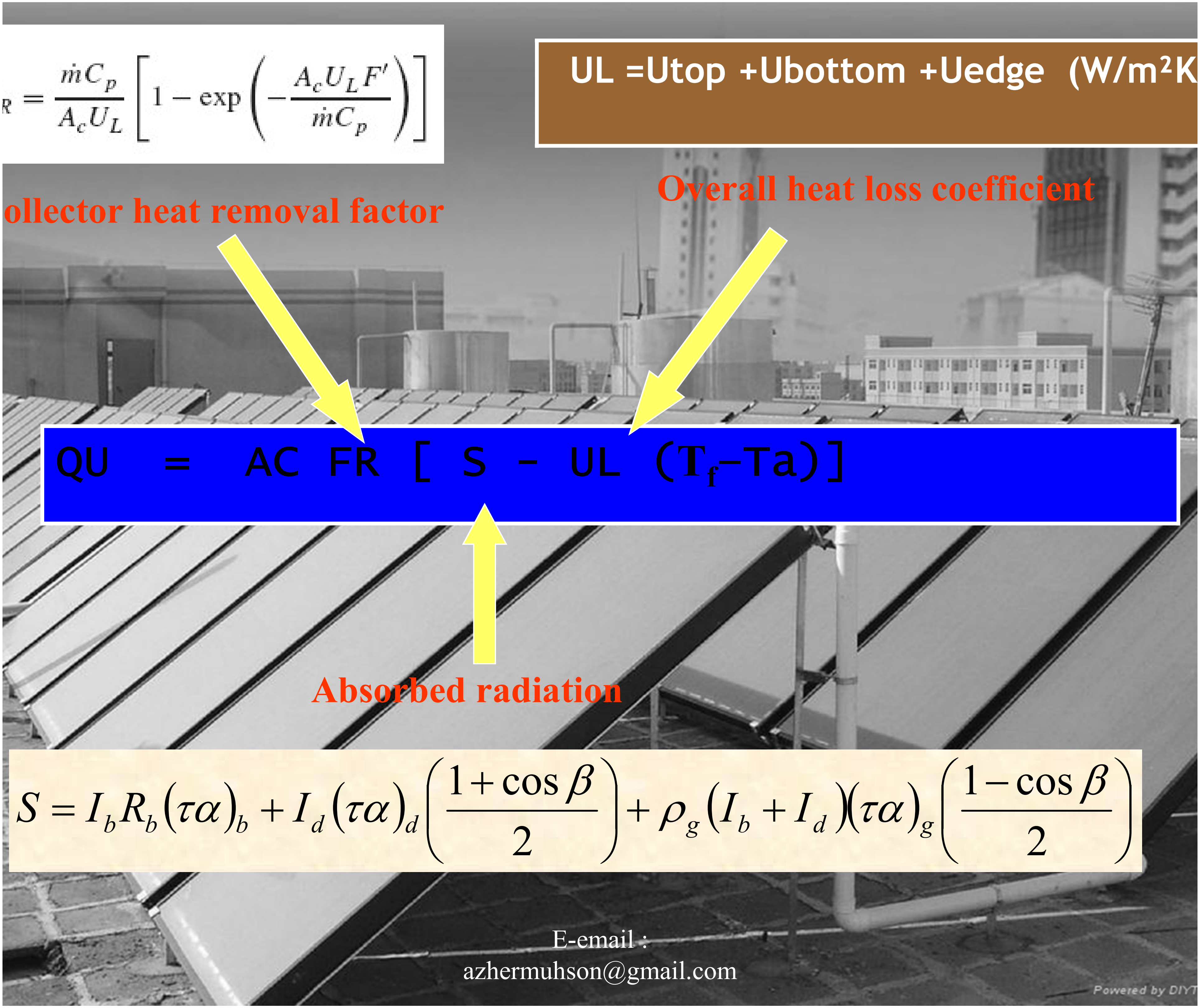

$$R = \frac{\dot{m} C_p}{A_c U_L}\left[1 - \exp\left(-\frac{A_c U_L F'}{\dot{m} C_p}\right)\right]$$

UL =Utop +Ubottom +Uedge (W/m^2K

Overall heat loss coefficient

ollector heat removal factor

QU = AC FR [S - UL (T_f–Ta)]

Absorbed radiation

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g (I_b + I_d)(\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right)$$

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Absorbed radiation

In equation, S is absorbed radiation and it is equal to:

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g (I_b + I_d)(\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right)$$

In equation; $(1+\cos\beta/2),(1-\cos\beta/2)$ are the view factors from the collector to the sky and from the collector to the ground, respectively.

The subscripts *b*,*d*, and *g* represent beam, diffuse, and ground , respectively. $(\tau\alpha)$ is transmittance and absorptance product. R_b is the ratio of beam radiation on the tilted surface to that on a horizantal surface at any time.

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Collector Heat Removal and Flow Factor

In equation, FR is collector heat removal factor; a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surfaces were at the fluid inlet temperature.

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

Where;

ṁ = Fluid mass flow rate, kg/s

Cp = Fluid specific heat, J/kg °C

F′ =collector efficiency factor

The quantitiy FR is equavialent to the effectiveness of a conventional heat exchange, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. The maximum possible useful energy gain (heat transfer) in a solar collector occurs when the all whole collector is at the inlet fluid temperature; heat losses to the surroudings are than at a minimum.

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The collector efficiency factor *F′ is given as*

$$F' = \frac{1/U_L}{W\left[\dfrac{1}{U_L\,[D + (W - D)\,F]} + \dfrac{1}{C_b} + \dfrac{1}{\pi D_i h_{fi}}\right]}$$

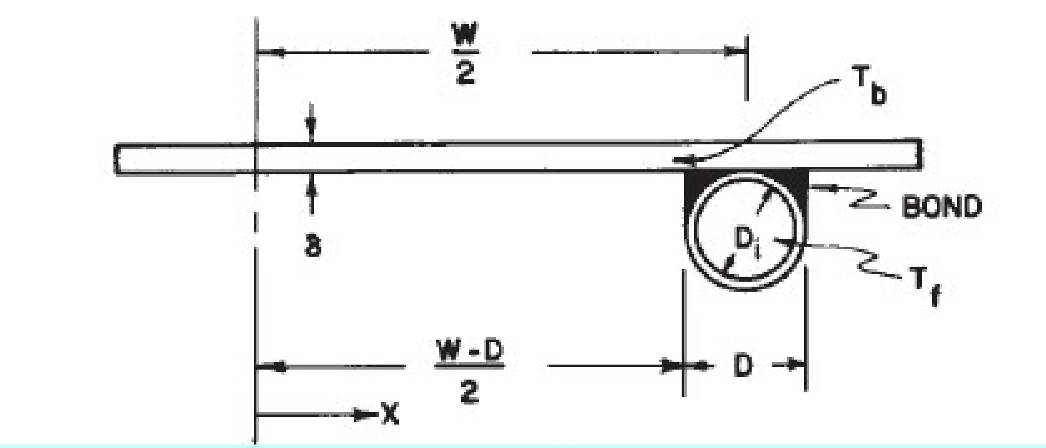
Outside Tube diameter

Tube spacing

fin efficiency factor

Bond conductance

Heat transfer coefficient inside tubes



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- And the function F is the fin efficiency factor :

$$F = \frac{\tanh[m(W-D)/2]}{m(W-D)/2}$$

$$m = \sqrt{\frac{U_L}{k\delta}}$$

Plate Thermal conductively

Plate thickness

The bond conductance can be estimated from:

$$C_b = \frac{k_b b}{\gamma}$$

Where

bond thermal conductivity k_b, the average bond thickness γ, and the bond width b. On a per-unit-length basis,

- The collector flow factor F'' as the ratio of FR to F'

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

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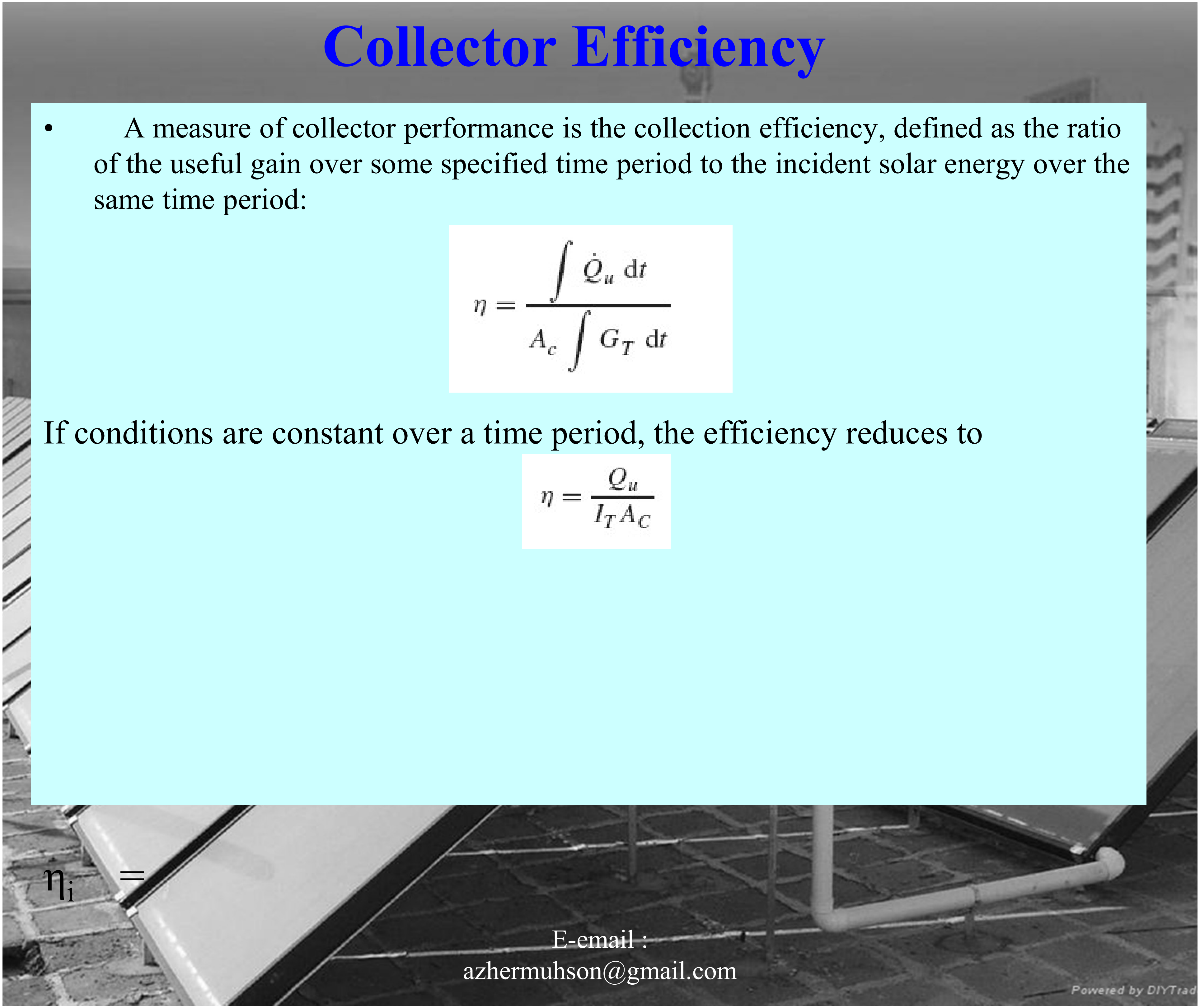
Collector Efficiency



- A measure of collector performance is the collection efficiency, defined as the ratio of the useful gain over some specified time period to the incident solar energy over the same time period:

$$\eta = \frac{\int \dot{Q}_u \, dt}{A_c \int G_T \, dt}$$

If conditions are constant over a time period, the efficiency reduces to

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

$\eta_i \quad =$

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MEAN FLUID AND PLATE TEMPERATUR

When a collector is producing useful energy, the mean plate temperature will always be greater than the mean fluid temperature due to the heat transfer resistance between the absorbing surface and the fluid. This temperature difference is usually small for liquid heating collectors but may be significant for air collectors. The mean fluid temperature can be found by integrating this Equation :

$$T_{fm} = \frac{1}{L} \int_0^L T_f(y)\, dy$$

Performing this integration and substituting *FR and Qu ,* the mean fluid temperature was shown by Klein et al. (1974) to be

$$T_{fm} = T_{fi} + \frac{Q_u / A_c}{F_R U_L} (1 - F'')$$

and the mean plate temperature, we have

$$T_{pm} = T_{fi} + \frac{Q_u / A_c}{F_R U_L} (1 - F_R)$$

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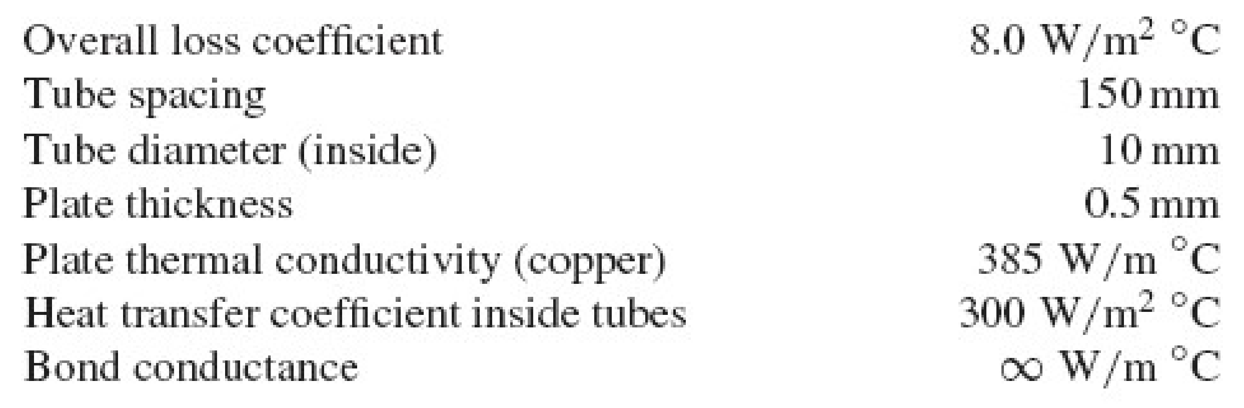
Question 2

Calculate the daily useful gain and efficiency of an array of 10 solar collector modules installed in parallel at a slope of 60◦ and a surface azimuth of 0◦. The hourly radiation on the plane of the collector *IT , the hourly radiation absorbed by the* absorber plate *S, and the hourly ambient temperature Ta are given in the table 1*. For a copper plate 1mm thick, *kδ = 0.4 W/◦C; for a steel plate 0.1mm thick, kδ = 0.005 W/◦C. Thus,* the probable range of *kδ is from 0.005 to 0.4. The bond conductance was assumed to be* very large (i.e., 1/*Cb = 0) and the outside tube diameter was selected as 0.012 m.* Calculate the collector efficiency factor for the following specifications:



Overall loss coefficient	8.0 W/m^2 °C
Tube spacing	150 mm
Tube diameter (inside)	10 mm
Plate thickness	0.5 mm
Plate thermal conductivity (copper)	385 W/m °C
Heat transfer coefficient inside tubes	300 W/m^2 °C
Bond conductance	∞ W/m °C

The water flow rate through each 1 × 2-m collector panel is 0.03 kg/s and the inlet water temperature remains constant at 40◦C. Assume a controller turns off the water flow whenever the outlet temperature is less than the inlet temperature. Find the mean fluid and plate temperatures for the hour 11 to 12 .

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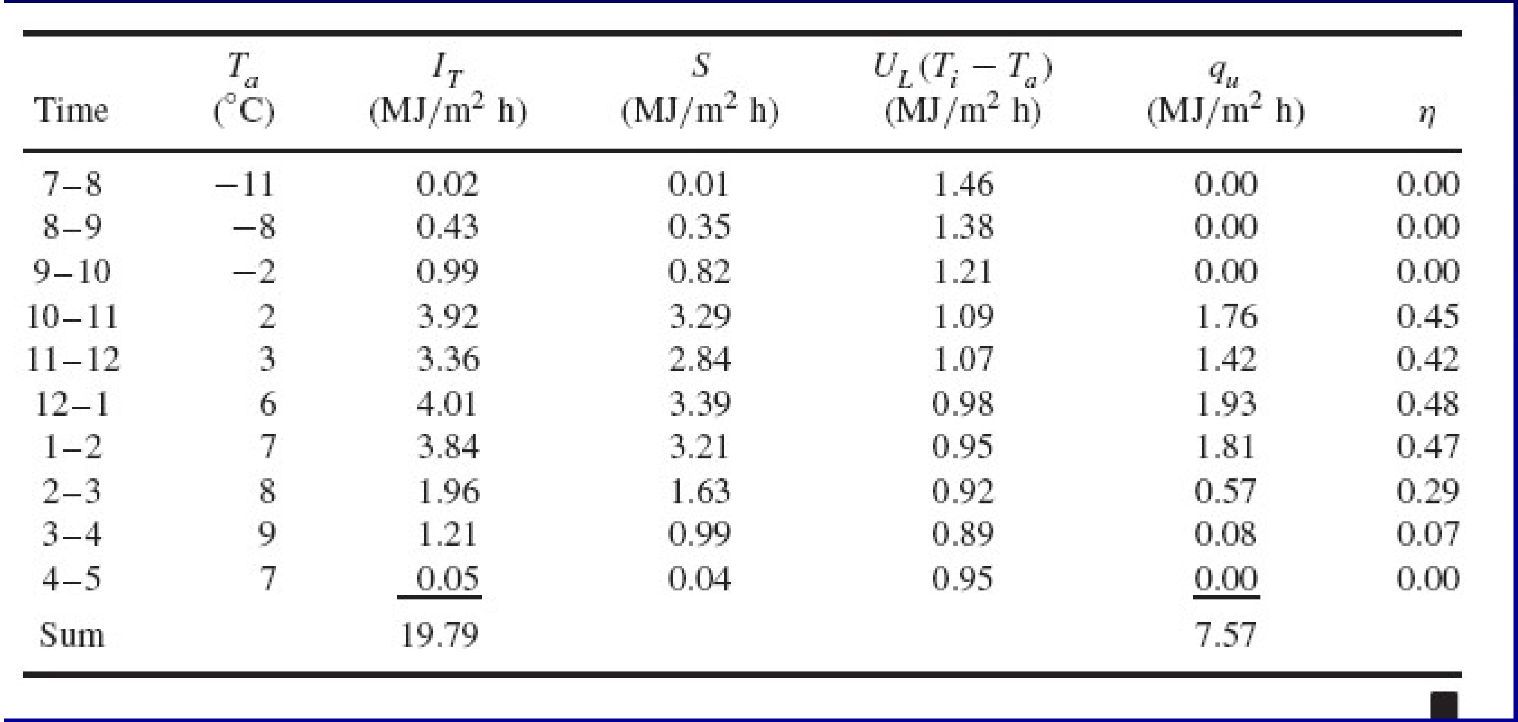
Table 1 Illustrate the hourly radiation S, and the hourly ambient temperature Ta with daily useful gain and efficiency of the array .



Time	T_a (°C)	I_T (MJ/m^2 h)	S (MJ/m^2 h)	$U_L(T_i - T_a)$ (MJ/m^2 h)	q_u (MJ/m^2 h)	η
7–8	−11	0.02	0.01	1.46	0.00	0.00
8–9	−8	0.43	0.35	1.38	0.00	0.00
9–10	−2	0.99	0.82	1.21	0.00	0.00
10–11	2	3.92	3.29	1.09	1.76	0.45
11–12	3	3.36	2.84	1.07	1.42	0.42
12–1	6	4.01	3.39	0.98	1.93	0.48
1–2	7	3.84	3.21	0.95	1.81	0.47
2–3	8	1.96	1.63	0.92	0.57	0.29
3–4	9	1.21	0.99	0.89	0.08	0.07
4–5	7	0.05	0.04	0.95	0.00	0.00
Sum		19.79			7.57	

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Solution :

To calculate the daily useful gain :

$$Q_U = A_C F_R [I_T (\tau\alpha) - U_L (T_f - T_a)]$$

First calculate the heat removal factor :

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

Then , The collector efficiency factor F′

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

The fin efficiency factor *F*

$$F = \frac{\tanh[m(W - D)/2]}{m(W - D)/2}$$

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Solution :

The fin efficiency factor F,

$$F = \frac{\tanh[m(W - D)/2]}{m(W - D)/2}$$

$$m = \sqrt{\frac{U_L}{k\delta}}$$

$$m = \left(\frac{8}{385 \times 5 \times 10^{-4}}\right)^{1/2} = 6.45 \ [1/\mathrm{m}]$$

$$= \left(\frac{\tanh[6.45(0.15-0.012)/2]}{6.45(0.15-0.012)/2}\right) = 0.925$$

The collector efficiency factor F'

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

$$= \left(\frac{1/8}{0.15\left[\dfrac{1}{8[0.012+(0.15-0.012)0.925} + \dfrac{1}{\infty} + \dfrac{1}{\pi \times 0.01 \times 300}\right]}\right) = 0.841$$

The dimensionless collector mass flow rate is

$$\frac{\dot{m}C_p}{A_c U_L F'} = \frac{0.03 \times 4190}{2 \times 8 \times 0.841} = 9.35$$

so that the collector flow factor,

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

$$F'' = 9.35\left[1 - \exp\left(-\frac{1}{9.35}\right)\right] = 0.948$$

the heat removal factor is

$$F_R = F'F'' = 0.841 \times 0.948 = 0.797$$

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The useful energy gain is

$$Q_U = A_C F_R [S - U_L (T_i - T_a)]$$

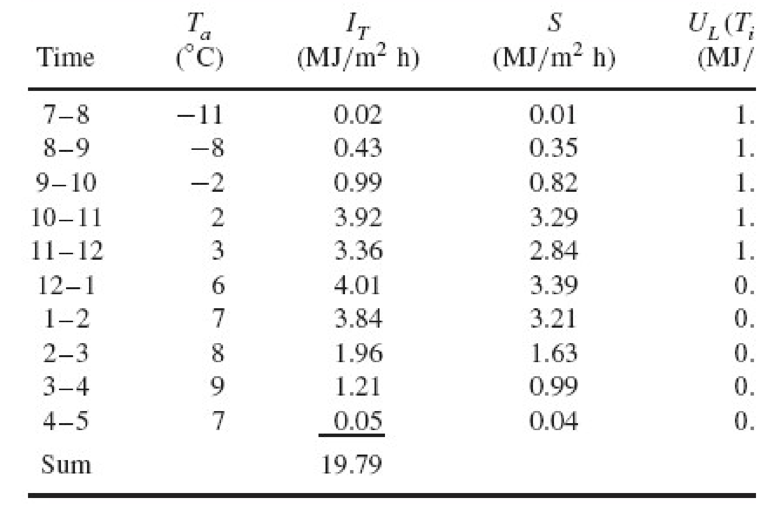
Table 1

he average loss rate for the hour 10 to 11, based on an inlet mperature of 40◦C, is

$$U_L(T_i - T_a) = 8(40 - 2) \times 3600 = 1.09 \text{ MJ/m}^2 \text{ h}$$

SO, the average useful energy gain per unit of collector area is

$$q_u = \frac{Q_u}{A_c} = 0.797(3.29 - 1.09) \times 10^6 = 1.7$$



Time	T_a (°C)	I_T (MJ/m² h)	S (MJ/m² h)	$U_L(T_i$ (MJ/
7–8	−11	0.02	0.01	1.
8–9	−8	0.43	0.35	1.
9–10	−2	0.99	0.82	1.
10–11	2	3.92	3.29	1.
11–12	3	3.36	2.84	1.
12–1	6	4.01	3.39	0.
1–2	7	3.84	3.21	0.
2–3	8	1.96	1.63	0.
3–4	9	1.21	0.99	0.
4–5	7	0.05	0.04	0.
Sum		19.79		

The collector efficiency for this hour

$$\eta = \frac{Q_u}{I_T A_c} = \frac{q_u}{I_T} = \frac{1.76}{3.92} = 0.45$$

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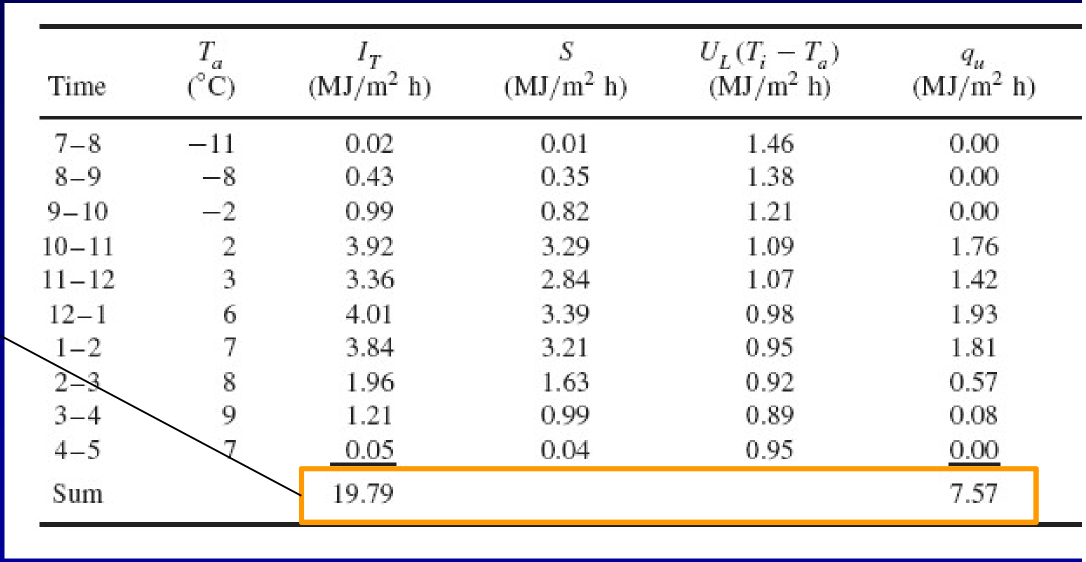
nd the day-long collector efficiency is

$$\eta_{\text{day}} = \frac{\sum q_u}{\sum I_T} = \frac{7.57}{19.79} = 0.38$$



Time	T_a (°C)	I_T (MJ/m^2 h)	S (MJ/m^2 h)	$U_L(T_i - T_a)$ (MJ/m^2 h)	q_u (MJ/m^2 h)
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2–3	8	1.96	1.63	0.92	0.57
3–4	9	1.21	0.99	0.89	0.08
4–5	7	0.05	0.04	0.95	0.00
Sum		19.79			7.57

The daily useful energy gain of the 10 collector modules in the array is

$$\sum Q_u = 10 \times 2 \times 7.57 \times 10^6 = 150 \text{ MJ}$$

array of solar collector

Area of the collector

Daily average useful energy gain

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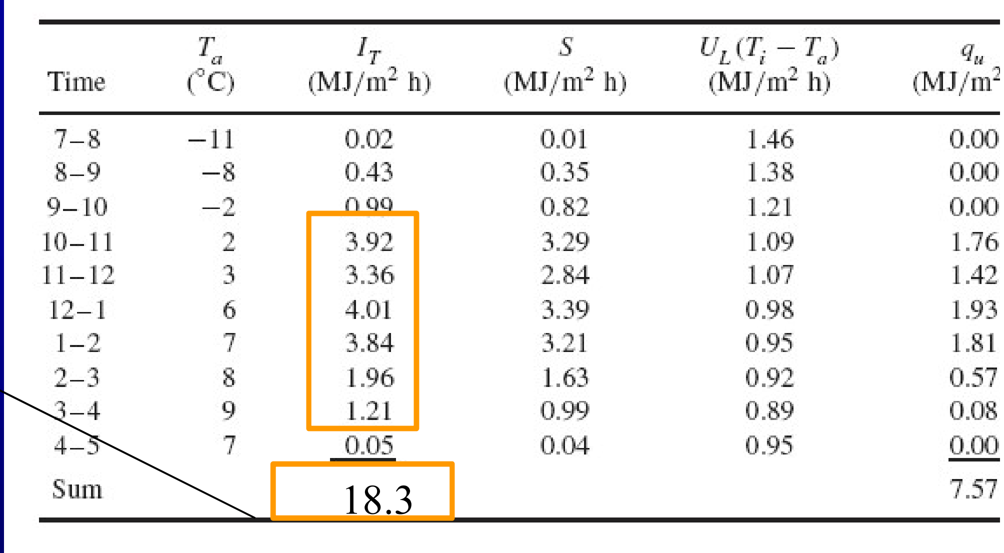
The losses are both thermal and optical, and during the early morning and late afternoon the radiation level was not sufficient to overcome the losses. The collector should not be operated during hese periods. Daily efficiency may also be based on the period while the collector is operating.

So the collector efficiency during this hours is :

$$\eta_{\text{day}} = \frac{\sum q_u}{\sum I_T} \quad \frac{7.57}{18..3} \quad = \mathbf{0.41}$$



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3–4	9	1.21	0.99	0.89	0.08
4–5	7	0.05	0.04	0.95	0.00
Sum		18.3			7.57

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The mean fluid and plate temperatures for the hour 11
o 12 are calculate from this equ:

From table 1 , (qu)

$$T_{fm} = T_{fi} + \frac{Q_u/A_c}{F_R U_L}(1 - F'')$$

$$T_{fm} = 40 + \frac{1.42 \times 10^6/3600}{8 \times 0.797}(1 - 0.948) = 43^\circ\mathrm{C}$$

FR=0.797

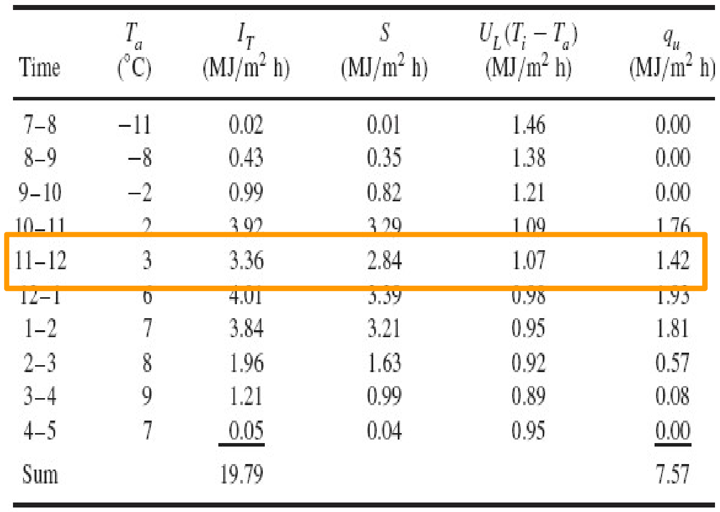
F″=0.948

UL= 8 W/m2 ◦C,

The mean plate temperature is

$$T_{pm} = T_{fi} + \frac{Q_u/A_c}{F_R U_L}(1 - F_R)$$

$$T_{pm} = 40 + \frac{1.42 \times 10^6/3600}{8 \times 0.797}(1 - 0.797) = 53^\circ\mathrm{C}$$



Time	T_a (°C)	I_T (MJ/m^2 h)	S (MJ/m^2 h)	$U_L(T_i - T_a)$ (MJ/m^2 h)	q_u (MJ/m^2 h)
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Sum		19.79			7.57

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THANK YOU

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