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# Parameters Analysis and Potential of Energy Storage Case Study : Solar collector for diurnal water heating and nocturnal water cooling.

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**Abstract**

This research used computer program to calculate the parameters analysis and potential of systems of energy storage by solar collector for diurnal water heating and nocturnal water cooling. Solar collector has surface area of 1.67 $m^2$ with capacity of water storage tank of 60 litres/day and the average solar radiation incident on surface area of 400 $W/m^2$.The compound parameters such as; air temperature transmittance, absorbtance, heat transfer coefficient, collector heat removal factor were simulated by mathematic equations.During diurnal period, solar collector stored thermal energy and make temperature of water in the system increase.During the nocturnal period, solar collector releases thermal energy into sky radiation which influences solar collector as well as water in the system are cooled down. Computer simulation program approved the maximum temperature of solar collector heating system is 74.77 °C and efficiency of solar collector system were observed 56% followed by 53%and 51% respectively at slope of 15 °followed by 5 °and 30 °. Minimum temperature of water cooling system by sky radiation, is 0.04 °C and the efficiencies of solar collector system were found 60% followed by 57% and 53% at slope of 5 ° followed by 15 ° and 30 ° significantly.

## 1. Introduction

Nowadays solar-powered heating systems are greatly developed e.g. water heating system by flat plate solar collector, air heating for dryer purpose and water distillation. In the water heating system, the solar collector which use sunlight radiation will operate only at day time when sunlight radiate the heating to the world. The investment expense is rather high compared with other equipment using another kinds of energy. But if adding cooling system by cooling water in night time will increase utility factor of the system. In daytime the sun will approximately radiate the heating at wavelength 0.3-3 micrometers. These heating is absorbed by the atmosphere and earth and at the same time it will radiate the heating between the earth and atmosphere in the heating range and radiate the heating from the atmosphere to the air. During the night -time, there is no sunlight radiation, the object on earth will radiate the heating from itself to the atmosphere at wavelength about 5-50 micrometers. It results in decreasing of the temperature of the earth. From this basis, it can be applied to cool the air by using natural circulation of Thermosyphon. No energy from other sources is needed. The cost will be cheaper and there is no pollution. It is also easy for production and maintenance. Otherwise, it is difficult to measure the temperature of fluid. Thus the computer program is set to calculate temperature, energy and efficiency of the system with solar collector simulations at different degrees.

## 2. Assumption of mathematics simulation equation

1. Sky temperature ($T_k$) and air temperature ($T_a$) are stable at a period of time. The sky temperature varied according to air temperature, but air temperature will not much change at the short time.
2. Water flow system is laminar because the system is natural flow.
3. Flow rate is steady, both the water cooling system and the water heating system.
4. The change of temperature in solar collector and water tank is laminar.
5. Heat conducted in tube of solar collector that radiate heating at night time and energy collected at day time are constant because of linear flow.
6. Negligible the heat loss from the friction of joints in the system .
7. The air inside close sheet and solar collector is not moving so there is neglected on heat loss from heat conduction

## 3. Theory of the water heating system and water cooling system

3.1 Water heating system by flat plate solar collector

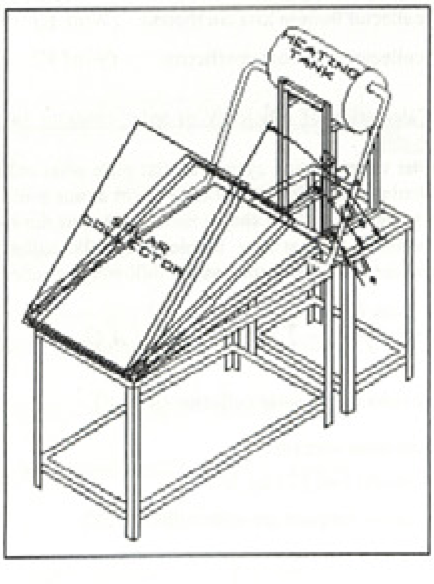


Figure 1 Water heating system design

In water heating system, flat plate solar collector and heating tank are mainly used. The system works on natural circulation or Thermosyphon. Fluid is water as a heat conduction from solar collector. Solar radiation can be calculated from equation [1]

$$I_T = I_b R_b + I_d \quad (1)$$

$I_T$ = total incident radiation (W / m$^2$)

$I_b$ = beam radiation (W / m$^2$)

$I_d$ = diffuse radiation (W / m$^2$)

$R_b$ = ratio of beam radiation on the tilted surface to that on horizontal surface.

Flat Plate Solar Collector will be placed in the position that can receive the sunlight radiation all day long in north-south direction so the equation of Hottel and Woertz [1] will be:

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \quad (2)$$

$\phi$ = latitude angle of solar collector

β = slope of solar collector

$\delta$ = declination sun solar noon

$\omega$ = hour angle

Set noon-time as zero and each hour is equal to 15$^0$ Longitude. The morning time give surplus value and afternoon time give minus, for example $\omega$ = +15$^0$ means 11.00 a.m. and $\omega$ = -37.5$^0$ means 14.30 p.m.

$\delta$ (declination) can calculate from Cooper's equation[1]:

$$\delta = 23.45 \sin\left[360(284+n)/365\right] \quad (3)$$

heat transfer coefficient of 3 sides can be calculated from equation (4) as follows:

$$U_T = U_t + U_b + U_s \quad (4)$$

$U_T$ = overall loss coefficient (W/m$^2$ K)

$U_t$ = collector top loss coefficient (W/m$^2$ K)

$U_b$ = collector bottom loss coefficient (W/m$^2$ K)

$U_s$ = collector edge loss coefficient (W/m$^2$ K)

### 3.2 Calculation of efficiency of solar collector in water heating system

In the water heating system by flat plate solar collector, it can calculate the efficiency of the system at one point from solar collector [1] which shows its efficiency as the ratio of energy available for that time to energy of solar radiation on solar collector at the same time as the following equation:

$$\eta_{hc} = mc_p\left(T_O - T_i\right) / A_c G_T = Q_u / A_c G_T \quad (5)$$

$G_T$ = irradiance on solar collector $(W/m^2)$

$A_C$ = collector area (m$^2$)

$C_P$ = specific heat (J / kg K)

$T_o$ = outlet temperature solar collector (K)

$T_i$ = inlet temperature solar collector (K)

$Q_u$ = energy available for one unit of time (W)

$\eta_{hc}$ = efficiency of solar collector in water heating system

From equation of balance energy of flat plate solar collector at steady working condition, it can calculate the equation of energy available from Hottel-Whillier-Bliss Equation [1] as follow:

$$Q_u = A_c F_R\left[G_T(\tau\alpha)_s - U_L\left(T_i - T_a\right)\right] \quad (6)$$

From equation (5) substitute $Q_u$ to equation (6) the efficiency of solar collector.

$$\eta_{hc} = \left[F_R(\tau\alpha)_s - F_R U_L\left(T_i - T_a\right)\right] / G_T \quad (7)$$

$F_R$ = collector heat removal factor

$(\tau\alpha)_s$ = coefficient of transmittance and absorbtance at angle of incidence of solar collector.

$T_a$ = ambient temperature (K)

$U_L$ = collector overall heat loss coefficient $(W/m^2K)$

### 3.3 Calculation of efficiency of water heating system

$$M_T C_p dT_S / dt = F_R A_C\left[G_T(\tau\alpha)_S - U_L\left[\left(T_i - T_a\right)\right] - U_C A_S\left(T_S - T_a\right)\right] \quad (8)$$

In equation (8) is similar to the equation of Close, D.J.[1] when heating system is a closed system and the flow of fluid is natural circulation or Thermosyphon, the equation is :

$$M_T C_p dT_S / dt = F_R A_C\left[G_T(\tau\alpha)_S - U_L\left[\left(T_O - T_i\right)/2 - T_a\right] - U_c A_S\left(T_S - T_a\right)\right]$$

$$= F_R A_C\left[G_T(\tau\alpha)_S - U_L\left(T_m - T_a\right)\right] - U_c A_S\left(T_S - T_a\right) \quad (9)$$

$G_T$ = irradiance on tilted plane $(W/m^2)$

$A_S$ = surface area of heating tank and tube system (m$^2$)

$U_C$ = heat transfer coefficient of tank and tube $(W/m^2K)$

$C_P$ = specific heat (J/kg K)

$A_C$ = collector area (m$^2$)

$T_S$ = surface temperature of black body (K)

$\eta_{hs}$ = efficiency of water heating system

$F_R$ = collector heat removal factor

$T_a$ = ambient temperature (K)

$M_T$ = total mass of water (kg)

$T_m$ is average temperature of water in solar collector which is equal to average temperature of water in the whole system ($T_S$) that is $T_S$ = $T_m$ as in equation (9)

$$M_T C_p dT_m = F_R A_C G_T(\tau\alpha)_S dt - A_C F_R U_L\left(T_m - T_a\right)dt - U_C A_S\left(T_m - T_a\right)dt \quad (10)$$

calculate equation (10) at time t = 0 to t = n will be as follow:

$$\int_0^n M_T C_p dT_m = \int_0^n F' A_C G_T(\tau\alpha)_s dt - \int_0^n A_C' U_L(T_m - t_a)dt - \int_0^n U_C U_s(T_m - T_a$$

$$M_T C_p(T_m^n - T_m^o) = A_C F_R(\tau\alpha)_s \sum_{t=0}^{n} G_T^t \Delta t - A_C F_R U_L \sum_{t=0}^{n} (T_m^t - T_a^t)\Delta t$$

$$-U_C A_s \sum_{t=0}^{n}\left(T_m^t - T_a^t\right)\Delta t \qquad (11)$$

The efficiency of the system is heating energy accumulated in the system to sunlight radiation energy on solar collector

$$\eta_{hs} = M_T C_p\left(T_m^n - T_a^o\right) / \left(A_C \sum_{t=0}^{n} G_T^t \Delta t\right)$$

when $A_C \sum_{t=0}^{n} G_T^t \Delta t$ divide equation ( 11 ) the result is

$$\frac{M_T C_p\left(T_m^n - T_m^o\right)}{A_C \sum_{t=0}^{n} G_T^t \Delta t} = F_R(\tau\alpha)_s - \left(F_R U_L + U_C\right)\frac{\sum_{t=0}^{n} \left(T_m^t - T_a^t\right)\Delta t}{\sum_{t=0}^{n} G_T^t \Delta t}$$

new equation as follow:

$$\eta_{hs} = F_R(\tau\alpha)_s - U_T \frac{\sum_{t=0}^{n} \left(T_m^t - T_a^t\right)\Delta t}{\sum_{t=0}^{n} G_T^t \Delta t}$$

$$\eta_{hs} = F_R(\tau\alpha)_S - U_T\left(\overline{T}_m - \overline{T}_a\right) / \overline{G_T} \qquad (12)$$

$\overline{T_m}$ = average temperature of the system from time t = 0 to t = n

$\overline{T_a}$ = average ambient temperature from time t = 0 to t = n

$\overline{G_T}$ = average irradiance on solar collector from time

$U_T$ = Overall heat transfer coefficient in the system ($F_R U_L + U_S$)

3.4 theory of water cooling system by sky radiation

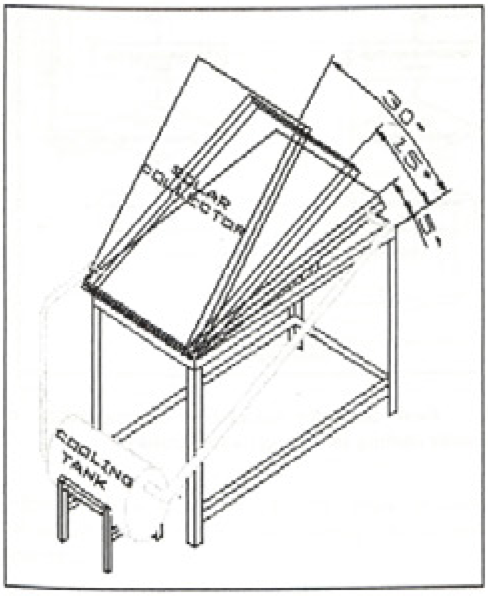


Figure 2 water cooling system design

Water cooling system by flat plate solar collector using thermal radiation between the earth and the atmosphere is always occurred. During diurnal period, sunlight radiate thermal energy to the atmosphere and the earth and make them warm up.During noctural period, there is no sunlight radiation and the atmosphere as well as the earth are still warm thus thermal energy are radiated to the sky.

3.5 Heating radiation of body

Thermal energy released from the object surface are considered depending on the absolute temperature and object surface characteristics.The object that can radiate overall thermal energy is called "Black body".It radiated thermal energy follow Stefan-Boltzmann 's Law.

$$E_b = \int_0^\infty E_{b\lambda} d\lambda = \sigma T^4 \qquad (13)$$

$\lambda$ = wave length ( μm )

$E_{b\lambda}$ = black body radiate the heating radiation energy at any wave length ( W/m )

$\sigma$ = Stefan-Boltzmann constance $5.67 \cdot 10^{-8}$ W/m$^2$ k$^4$

3.6 Calculation of efficiency of water cooling system by sky radiation

Calculation of efficiency of water cooling system by sky radiation is in contrast to water heating system by theory of sky radiation. From balance energy equation, it will be:

$$\sum Q_s = \sum Q_{in} - \sum Q_{LS} \qquad (14)$$

$Q_S$ is energy storage = $M_T C_p dT_m / dT$

$Q_{in}$ is energy input = $-Q_{out} = \dot{m} C_p\left(T_i - T_O\right)$

$Q_{LS}$ is energy loss to surrounding = $U_S\left(T_m - T_a\right)$

in equation ( 14 ) calculation of average water temperature $\overline{T}_m$ by Forward Finite Difference Method, that is

$$T_m^{t+\Delta t} = T_m^t + (\Delta t / M_T c_p)\left[Q_{in} - U_s\left(T_m{}' - T_a\right)\right] \qquad (15)$$

from equation ( 14 ) $Q_{in}$ = - $Q_{out}$ can be rewritten as follow:

$$-M_T C_p dT_m / dt = Q_{out} - U_S\left(T_a - T_m\right) \qquad (16)$$

$Q_{out}$ = net energy that solar collector radiate heating = $Q_O - Q_{LC}$

$Q_O$ = energy that solar collector radiate

$Q_{LC}$ = heat transfer of energy from solar collector radiate to surrounding = $U_L\left(T_a - T_m\right)$

to substitute $Q_{out}$ in equation ( 16 ) and solar collector has space in sky radiation as $A_C$ the result is

$$-M_T C_p dT_m / dt = A_C Q_O - A_C U_T\left(T_a - T_m\right) \qquad (17)$$

= heat transfer coefficient of the system

= ( W / m$^2$ K)

to integrate equation ( 17 ) from time t = 0 to time t = n, the equation is as follows:

$$\int_{o}^{n} -M_T C_P dT_m / dt = A_C \int_{o}^{n} Q_o dt - A_C U_T \int_{o}^{n} (T_a - T_m) dt$$

$$M_T C_P \left(T_m^o - T_m^n\right) = A_C \sum_{t=o}^{n} Q_o^t \Delta t - A_C U_T \sum_{t=o}^{n} \left(T_a^t - T_m^t\right) \Delta t \quad (18)$$

If only thermal radiation of solar collector is considered at any time without the interference of another energy system,the efficiency of nocturnal water cooling system ($\eta_{cs}$) is equal to overall thermal energy in the system/ radiation energy in the system.

$$\eta_{cs} = M_T C_P \left(T_m^0 - T_m^n\right) / A_C \sum_{t=o}^{n} Q_{\max}^t \Delta t$$

equation ( 18 ) divided by $A_C \sum_{t=o}^{n} Q_{\max}^t \Delta t$ to obtain the equation of system efficiency as follows:

$$\frac{M_T C_P \left(T_m^o - T_M^N\right)}{A_C \sum_{t=o}^{n} Q_{\max}^t \Delta t} = \frac{\sum_{t=o}^{n} Q_o^t \Delta t}{\sum_{t=o}^{n} Q_{\max}^t \Delta t} - U_T \frac{\sum_{t=o}^{n} \left(T_a^t - T_m^t\right) \Delta t}{\sum_{t=o}^{n} Q_{\max}^t \Delta t}$$

new formation $\eta_{cs} = \eta_{co} - U_T \dfrac{\sum_{t=0}^{n} (T_a{}' - T_m{}') \Delta t}{\sum_{t=0}^{n} Q'_{\max} \Delta t}$

$$= \eta_{co} - \frac{U_T(\overline{T}_a - \overline{T}_m)}{\overline{Q}_{\max}} \quad (19)$$

$\overline{T}_m$ = average temperature of system from time range t = 0 to t = n

$\overline{T}_a$ = average air temperature from time range t = 0 to t = n

$M_T$ = total mass of water cooling system

$\overline{Q}_{\max}$ = average $Q_{\max}^t$ from time range t = 0 to t = n

$\eta_{CS}$ = efficiency of water cooling system

$U_T$ = overall heat transfer coefficient in the system

**4. Flow chart to calculate temperature and efficiency of solar collector**

1. Select the environment option time period: by hour or day
2. Select the operation calculated process: diurnal calculated process or nocturnal calculated process
3. Calculation by forward finite difference equation
4. Calculate the efficiency of process
5. Increase time and repeat step 3,4
6. Display the results reported on screen

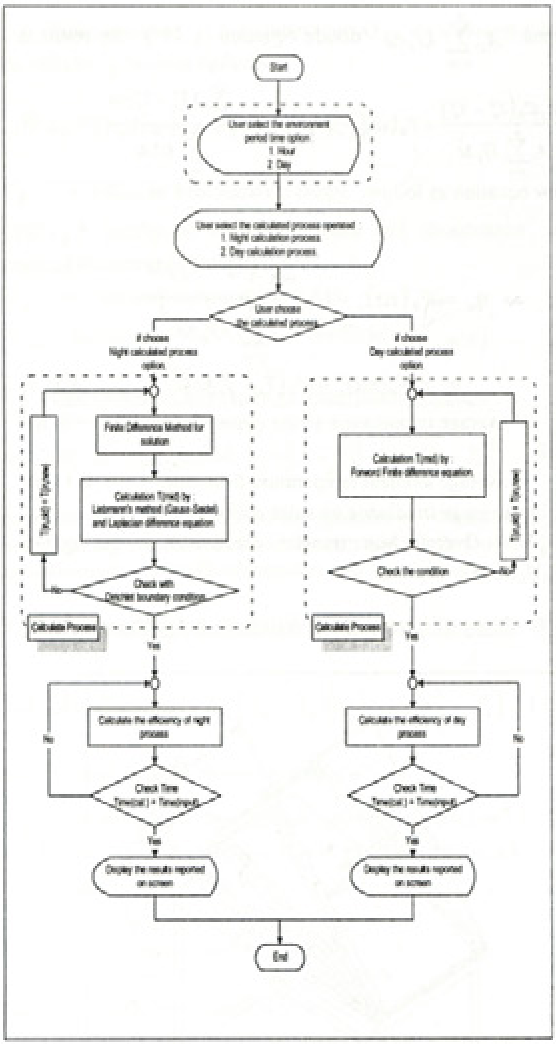


Figure 3 Flow chart for calculation of temperature of nocturnal water cooling and diurnal water heating.

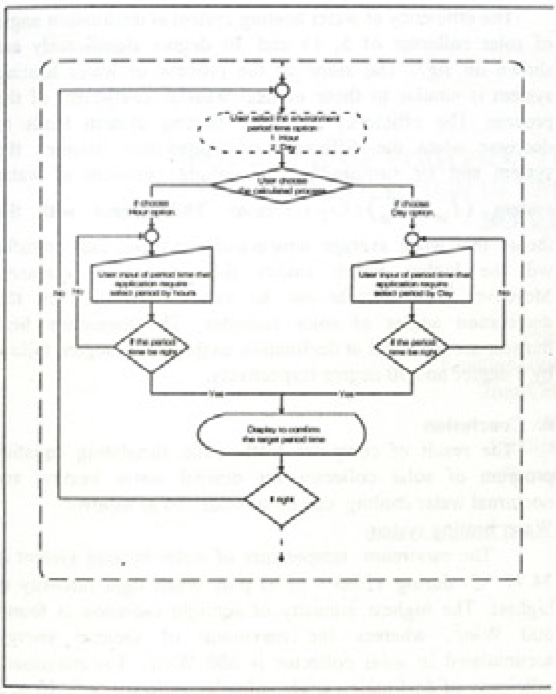

Figure 4 Flow chart for the user to select the environment period time options per hour of day

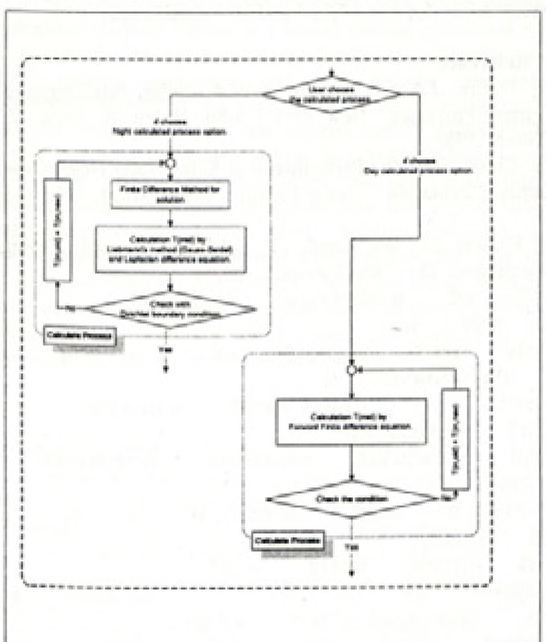

Figure 5 Flow chart showing the steps of temperature calculation of nocturnal water cooling and diurnal water heating.

**5. The results from simulation of water heating and water cooling system**

5.1 Water cooling system , The minimum temperature of water cooling system is 0.04 °C at declination angle of solar collector of 5, 15 and 30 degree respectively (table1)

Table 1 Minimum temperature at different declination angles simulated by mathematic equation from computer program.

| Air temperature °C | Minimum average temperature of process °C | | | Difference of air temperature and minimum average temperature of process °C | | |
|---|---|---|---|---|---|---|
| | Declination angle 5 degree | Declination angle 15 degree | Declination angle 30 degree | Declination angle 5 degree | Declination angle 15 degree | Declination angle 30 degree |
| 40 | 35.56 | 35.64 | 36.06 | 4.44 | 4.36 | 3.94 |
| 30 | 23.27 | 23.41 | 23.74 | 6.73 | 6.59 | 6.26 |
| 20 | 11.45 | 11.46 | 12.05 | 8.55 | 8.54 | 7.95 |
| 10 | 0.04 | 0.16 | 0.45 | 9.96 | 9.84 | 9.55 |

From table 1, the minimum temperature of process will decrease when declination angle of solar collector decrease. Otherwise, The geometric factors formed of solar collector and sky and the efficiency of the process increase.The best results are found at 5 , 15 and 30 degree respectively.

In the case of declination angle of solar collector is stable whereas air temperature increases,the minimum temperature of water cooling process will also increase.This is because the sky temperature is reduced much more than air temperature about 1.5 power $\left(T_k = 0.0552T_a^{1.5}\right)$. In addition, sky radiation of solar collector will increase.

The relation between $\eta_{cs}$ and $\left(\overline{T}_s - \overline{T}_a\right)/\overline{Q}_{max}$ in equation (19) will be the straight line equation with the slope of $-U_T$ and intercept $\eta_{cs}$ will be at $\eta_{co}$. This interception is the efficiency of thermal radiation from solar collector, without heat transfer calculated from the formation of mathematic simulation equation (19) which have the process of water cooling at declination angle 5, 15 and 30 degree as shown in figure 6.

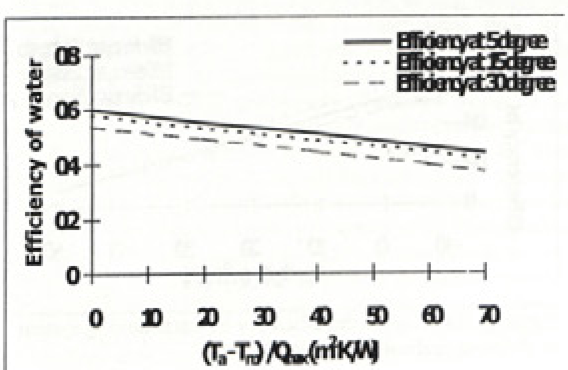


Figure 6 The efficiency of water cooling system at different declination angles of solar collector

The slope in fig.6 is as heat transfer coefficient of the process.The efficiency of water cooling system tends to decrease when the difference of temperatures between system and air surrounding reach to net energy of thermal radiation and $(\overline{T}_c - \overline{T}_a)/\overline{Q}_{max}$ will increase.This agrees with the theory, when average temperature increase, heat transfer occurs in higher rate, and make the efficiency decrease.Moreover, heat transfer is varied depending on the declination angles of solar collector.The slope of the process in table2 shows maximum heat transfer at declination angle of 5,15 and 30 degrees significantly.

5.2 Water heating system

The process simulation calculated with computer indicated that, the maximum temperature occurs during 12:00 – 14:00 p.m.,the time when the sunlight intensity is highest. The maximum of water heating system is 74.77 °C at declination angle of solar collector of 5, 15 and 30 degree respectively (Table2)

Table 2 Maximum average temperature of the process from computer program and mathematic simulate equations of simulation at different declination angles.

| Air temperature °C | Maximum average temperature of process °C | | | Difference of air temperature and maximum average temperature of process | | |
|---|---|---|---|---|---|---|
| | Declination angle 5 degree | Declination angle 15 degree | Declination angle 30 degree | Declination angle 5 degree | Declination angle 15 degree | Declination angle 30 deg |
| 10 | 65.06 | 72.94 | 57.79 | 55.06 | 62.94 | 47.79 |
| 20 | 71.90 | 72.51 | 64.63 | 51.90 | 52.51 | 44.63 |
| 30 | 78.74 | 82.38 | 74.50 | 48.74 | 52.38 | 44.50 |
| 40 | 84.97 | 87.40 | 84.37 | 44.97 | 47.40 | 44.37 |

From equation (12) the relation between $\eta_{hs}$ and $(\overline{T}_m - \overline{T}_a)/\overline{G}_T$ will be the linear equation with slope of $-U_T$ and intercept $\eta_{cs}$ at $F_R(\tau\alpha)$ This interception is the efficiency of solar collector, without heat transfer to surrounding.

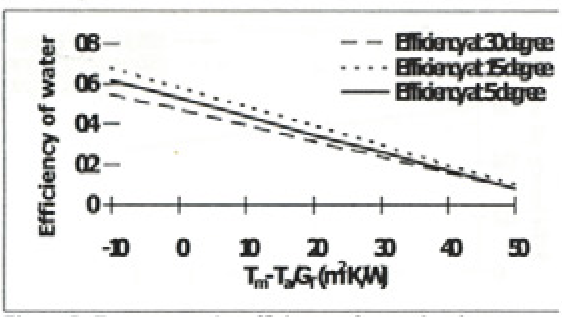


Figure 7 To compare the efficiency of water heating system at different declination of solar collector

The efficiency of water heating system at declination angle of solar collector of 5, 15 and 30 degree significantly are shown on fig7. The slope of the process of water heating system is similar to these of heat transfer coefficient of the process. The efficiency of water heating system tends to decrease when the difference of temperature between the system and air surrounding in sunlight radiation of water system $(\overline{T}_m - \overline{T}_a)/\overline{G}_T$ increases. This agrees with the theory that when average temperature increase, heat transfer will be higher which makes the efficiency decreases. Moreover, heat transfer can be varied depending on the declination angles of solar collector. The maximum heat transfer are observed at declination angles of 15 degree follow by 5 degree and 30 degree respectively.

## 6. Conclusion

The result of computer mathematic simulating equation program of solar collector for diurnal water heating and nocturnal water cooling can be summarized as follows:

Water heating system

The maximum temperature of water heating system is 74.77 °C during 12.00 - 14.00 p.m. when light intensity is highest. The highest intensity of sunlight radiation is found 800 W/m², whereas the maximum of thermal energy accumulated in solar collector is 600 W/m². The maximum efficiency of declination angles of solar collector at 5, 15 and 30 degree are 53 %, 56 % and 51 % respectively.

Water cooling system.

Minimum temperature of water cooling system by sky radiation is 0.04 °C and the efficiencies of solar collector system are at slope of 5 °,15 ° and 30 ° significantly.

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