CHAPTER 5

Long Term Analysis

The Chapter aimed to estimate the unit cost of the distilled water production from the system of the solar thermal desalination of seawater by bubble pump technique under the Chiang Mai climatic condition.

5.1 System Simulation of Daily Performance in each Month

5.1.1 Operating Conditions and Constants for Simulation

Conditions for the system simulation were shown in Table 5.1. The modeling of Solar Desalination with the Bubble Pump that had been developed and proven in previous chapters was used in this simulation.

Table 5.1 Simulating conditions for operating system.

Solar thermal collector	$F_R(\tau\alpha)_e$ = 0.776, $F_R U_L$ = 2.16 W/m^2.K, Area = 2.8 m^2
Feed salt water temperature, T_f	25 °C
Daily operating time	10 hours, From 7:00 am to 5:00 pm

The initial salinity of the solution selected (X_f) for this simulation were 3, 3.5 and 4% of water by weight. The driving heat of the bubble pump selected were 270, 216 and 162 mm or 100, 80 and 60% of the evaporator's height, respectively.

5.1.2 Weather Data for the Simulation

5.1.2.1 Calculation of Solar Radiation on Sloped Surfaces

There are two types of time indicating the sun's position in the sky: solar time and mean solar time or local clock time. In most studies, standard time is converted to solar time based on location of the observer's meridian and the earth's rate of rotation. The equation of conversion is

$$Solar\ time - Standard\ time = 4(L_{st} - L_{loc}) + E. \tag{5.1}$$

where, L_{st} : Standard meridian for the local time zone, [degree].

L_{loc} : Longitude of the location, [degree west]

The parameter E is the difference in minutes between solar time and standard time, which is from Spencer (1971).

$$E = 9.87 sin2B - 7.53 cosB - 1.5 sinB. \quad (5.2)$$

where B is a parameter in a function of the certain day of the year (n), given by

$$B = \frac{360(n-81)}{365}. \quad (5.3)$$

The daily extraterrestrial solar radiation on a horizontal surface on a whole day H_0 could be calculated from

$$H_0 = \frac{24\times3600}{\pi} G_{sc} \left[1 + 0.033 \cos\left(\frac{360n}{365}\right)\right] \left[cos\phi cos\delta sin\omega_s + \frac{2\pi\omega_s}{360} sin\phi sin\delta\right]. \quad (5.4)$$

$$\omega_s = \cos^{-1}\left(\frac{sin\phi sin\delta}{cos\phi con\delta}\right) = \cos^{-1}(-tan\phi tan\delta). \quad (5.5)$$

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right). \quad (5.6)$$

where ω_s : Sunset hour angle, [degree].

δ : Angular position of the sun, $-23.45° \leq \delta \leq 23.45°$.

ϕ : Local latitude, [degree].

Table 5.2 Average days for months and values of n and H_0 by months [19].

Month	Date	Day of the year	Hourly radiation per month(MJ/m^2hr)
January	17	17	17.25
February	16	47	19.28
March	16	75	21.04
April	15	105	20.62
May	15	135	19.08
June	11	162	16.35
July	17	198	15.79
August	16	228	17.33
September	15	258	17.78
October	15	288	16.14
November	14	318	15.71
December	10	344	18.02

According to Pratinthong [19], the correclation between the daily diffuse solar radiation (H_d), the daily global solar radiation (H) and H_0 is given

$$\frac{H_d}{H_0} = -4.6408 + 26.5495\left(\frac{H}{H_0}\right) - 28.3422\left(\frac{H}{H_0}\right) - 31.4546\left(\frac{H}{H_0}\right)^3 + 46.4421\left(\frac{H}{H_0}\right)^{4\ 2}. \quad (5.7)$$

The equation of the solar radiation on horizontal plane (I) is

$$I = H \times \frac{\pi}{24}(a + bcos\omega)\frac{cos\omega - cos\omega_s}{sin\omega_s - \left(\frac{2\pi\omega_s}{360}\right)cos\omega_s}. \quad (5.8)$$

Where $a = a_1 + a_2 \sin(\omega_s - 60)$
$b = b_1 + b_2 \sin(\omega_s - 60)$
$\omega = 15t$, ω is the hourly angle

The coefficients a_1, a_2, b_1 and b_2 for Thailand was given by Pratintong [19].

The diffuse solar radiation on horizontal plane (I_d) is

$$I_d = H_d \times \frac{\pi}{24}\frac{cos\omega - cos\omega_s}{sin\omega_s - \left(\frac{2\pi\omega_s}{360}\right)cos\omega_s}. \quad (5.9)$$

$$I_b = I - I_d. \quad (5.10)$$

There is an effect of the ground albedo,

$$I_T = I_bR_b + I_d\left(\frac{1 + cos\beta}{2}\right) + (I_b + I_d)\left(\frac{1 - cos\beta}{2}\right)\rho. \quad (5.11)$$

And R_b is calculated from

$$R_b = \frac{cos\theta}{cos\theta_z}. \quad (5.12)$$

$$cos\theta_z = cos\varphi cos\delta cos\omega + sin\varphi sin\delta. \quad (5.13)$$

$$cos\theta = sin\delta sin\varphi cos\beta - sin\delta cos\varphi sin\beta cos\gamma + cos\delta cos\varphi cos\beta cos\omega + cos\delta sin\varphi sin\beta cos\gamma cos\omega + cos\delta sin\varphi sin\beta sin\gamma sin\omega. \quad (5.14)$$

where
β : Inclination angle of surface from horizontal plane, [degree].
γ : Surface azimuth angle, [degree].
δ : Declination angle, [degree].
θ : Incidence angle [degree].
θ_z : Zenith angle, [degree].

The calculation steps to evaluate the solar radiation on the sloped surfaces in Chiang Mai was shown in Figure 5.1.

Table 5.3 Coefficients a_1, a_2, b_1 and b_2 for main stations in Thailand [19].

Station	Coefficients			
	a_1	a_2	b_1	b_2
Chiang Mai	0.514	0.228	0.512	0.083
Ubon Ratchathani	0.760	-0.031	0.207	0.238
Hat Yai	0.607	-0.124	0.417	0.007
Bangkok	0.792	-0.250	0.189	0.471

5.1.2.2 Calculation of Ambient Temperature

The ambient temperature was determined from Chaichana et al. [20], which was

$$T_a = \frac{1}{2}\left[(T_{max} + T_{min}) + (T_{max} + T_{min})\mathrm{Sin}\left(\frac{2\pi}{24}(t-9)\right)\right]. \qquad (5.15)$$

where T_{max} : Maximum ambient temperature, [°C].

T_{min} : Minimum ambient temperature, [°C].

Table 5.4 The average max-minimum temperature in Chiang Mai province [20].

Temp	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max}	31.4	34.1	33.6	37.6	35.2	33.3	32.9	32.9	32.5	32.7	31.4	30.2
T_{min}	13.2	15.3	17.8	22.0	22.4	23.5	23.2	23.1	22.8	21.4	17.3	14.0

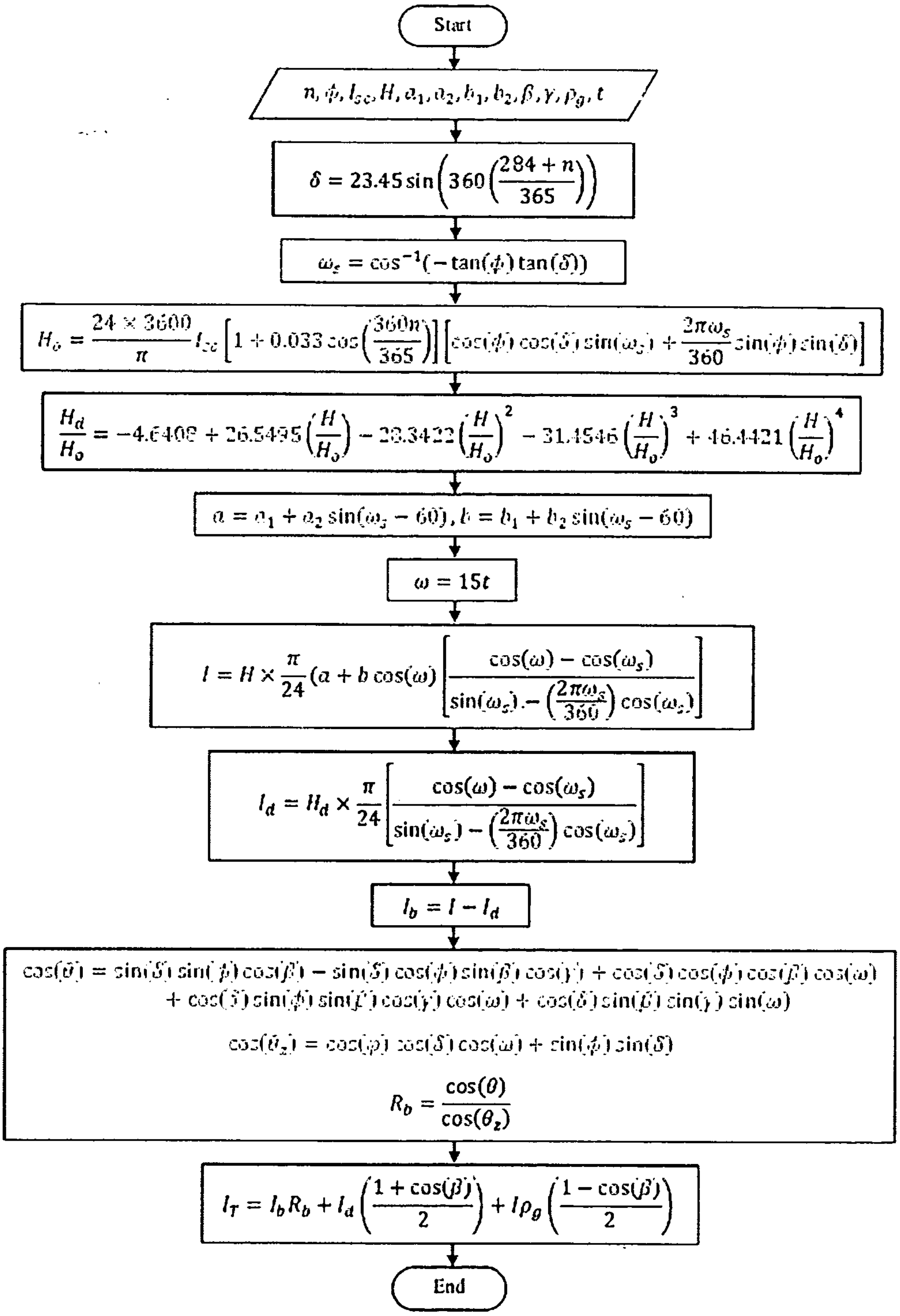

Figure 5.1 Flow chart for evaluating the solar radiation on tilting plane.

5.1.3 Simulation Results

The results from the calculation were illustrated in 3 graphs. These graphs showed the amount of distilled water produced per day in each month of the year. Two variable factors were involved. The first factor was driving head or reservoir level in the bubble pump. The second factor was percentage of initial salt content in the solution.

5.1.3.1 Initial salinity of 3%

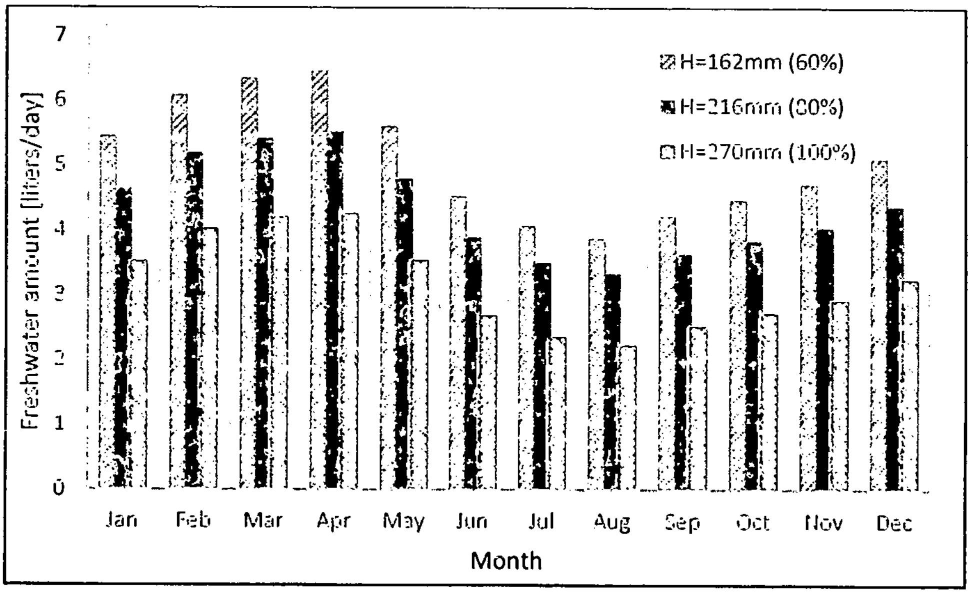

Figure 5.2 Monthly distilled water yield at the initial salinity of 3%.

Reservoir level of 100% capacity was represented by blue bar, 80% by red bar and 60% by gray bar. Figure 5.2 showed the production yield of distilled water (in liters) in each month, produced from the salt water with the initial salinity of 3% in 3 different reservoir level of the bubble pump which were 100%, 80% and 60%.

The fluctuation of daily production was correspondent to the quantity of solar radiation and the ambient temperature available in each month (as shown Table 5.2 and Table 5.4). 60% reservoir level was proven to the most efficient.

5.1.3.2 Initial salinity of 3.5%

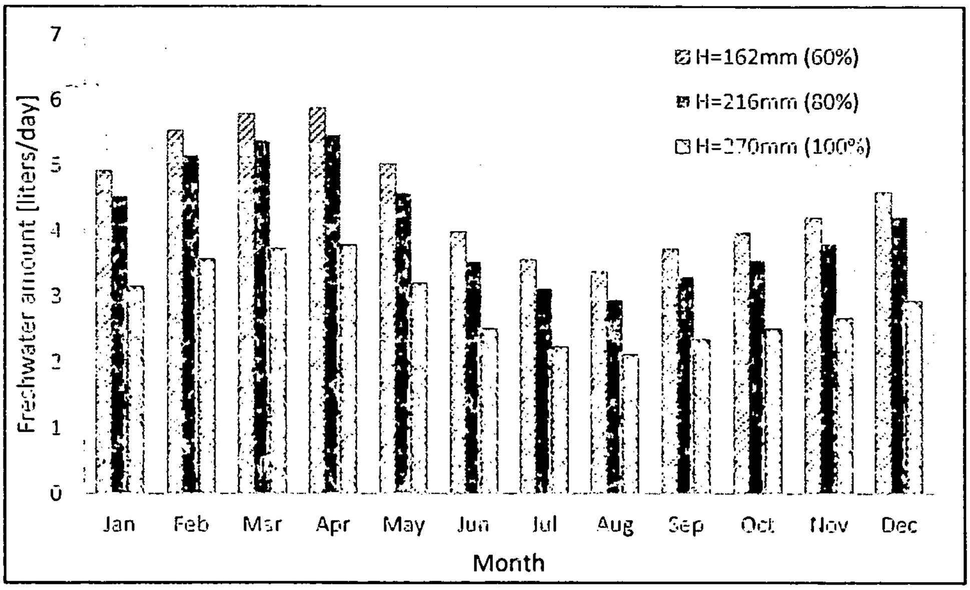

Figure 5.3 Monthly distilled water yield at the initial salinity of 3.5%.

5.1.3.3 Initial salinity of 4%

Distilled water yield at 60% of reservoir level capacity was shown only.

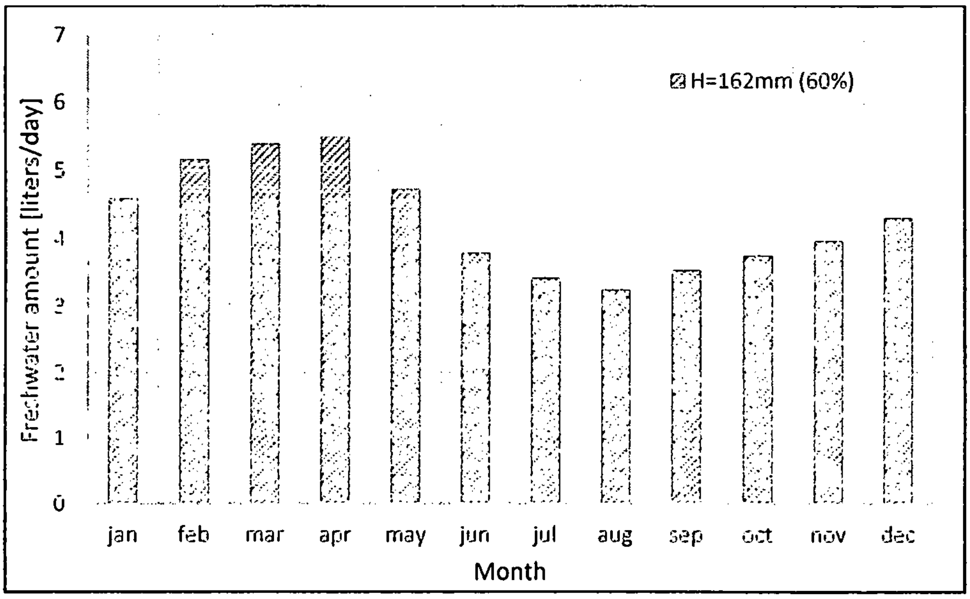

Figure 5.4 Monthly distilled water yield at the initial salinity of 4%.

In general, the average daily amount of the distilled water product produced by the solar desalination with bubble pump technique were different in each months. This was because of the level of solar radiation changed from month to month. The high quantity were produced from December to May as the sky were mostly clear. In other 5 months, the sky were mostly cloudy and raining resulted to the low productions.

5.2 Economic Analysis

5.2.1 Conditions and Constants for Economic Analysis

Table 5.5 Operating Conditions of Economic Analysis.

Monthly operating time	28 days a month (equals 336 days a year)
Yearly maintenance cost	2% of the initial investment
System service life	15 years
Interest rate	i = 8%
Electricity cost	4 baht per kWh

Table 5.6 Expenses on the testing material.

List of testing material	Expenses
Evacuated tube collector	23,200 baht
Evaporator	4,300 baht
Condenser	4,100 baht
Electrical pump	4,500 baht
Cooling tower	12,000 baht
Others	1,500 baht
Total expenses	49,600 baht

5.2.2 Unit Cost Calculation

The present value is the worth of a predictable income stream determined as of the date of valuation. The present value must equal to or less than the future value because of interest-earning potential, a characteristic bring up to as the time value of money. The present expenses of the system come from initial investment, yearly operation and maintenance cost minus the salvage value of the system at the present worth.

$$C = C_{inv} + C_{o\&m} - C_{sv}. \tag{5.16}$$

where,
C : Total cost at the present worth [baht].
C_{inv} : Initial investment cost at the present worth [baht].
$C_{o\&m}$: Operation and maintenance cost at the present worth [baht].
C_{sv} : Income from the salvage value at the present worth [baht].

The annual expense of the system come from the conversion of present value to the annual expenses.

$$C_{annual} = C \times \frac{i(1+i)^n}{[(1+i)^n - 1]}. \qquad (5.17)$$

where, C_{annual}: Total annual expense [baht/year].

i : Discount rate [%].

n : Service life of the system.

The unit cost of distilled water can be calculated by

$$C_{product} = \frac{\text{annual expenses}}{\text{annual product amount}}. \qquad (5.18)$$

Yearly operation and maintenance cost at the present worth could be calculated by

$$C_{o\&m} = R\frac{[(1+i)^n - 1]}{i(1+i)^n}. \qquad (5.19)$$

The salvage value of the plant was assumed to be 10% of the initial investment, calculated from the equation as:

$$C_{sv} = \frac{0.1 \times C_{inv}}{(1+i)^n}. \qquad (5.20)$$

5.2.3 Results and Discussion

Table 5.7 shows the cost estimation of the distilled water produced by the system in each cases was done under the conditions. The unit cost per liter depends on the amount of distilled water produced per year. As discussed previously, 60% reservoir level was proven to the most efficient. The factor of the initial salinity was also proven to influence the productivity yield. In fact, the less the initial salinity, the more amount of distilled water was produced by the system.

Table 5.7 The yield and cost of distilled water production.

Reservoir level [%]	Initial salinity [%]	Yearly product amount [liters]	Unit cost [bahts/liter]
60	3	1704.92	4.32
	3.5	1528.83	4.82
	4	1437.06	5.13
80	3	1460.92	5.04
	3.5	1389.39	5.30
100	3	1071.58	6.88
	3.5	974.54	7.56

The system could produce the most distilled water in the case of 3% initial salinity with 60% reservoir level as shown in Table 5.7. The unit cost in this case was 4.32 baht per liter. The main cost of the system was in the initial investment (see Table 5.6). However, the maintenance cost was relatively cheap as the system doesn't have any mechanical parts and the electrical energy consumption was as little as 71.7 W which was dramatically different from that of Reverse Osmosis and Multiple stage flash distillation, which generally consume more than 5 kW [2]. The energy supply is "free" because the heat energy from the sun is completely no cost.

5.2.4 Sensitivity Analysis

A main determinant of the initial cost of the unit is the price of the solar collector. This section would examine factors affecting the unit cost of distilled water produced by the system. The first factor was the price of the solar collector which was a main determinant of the initial investment. The second factor was the discount rate.

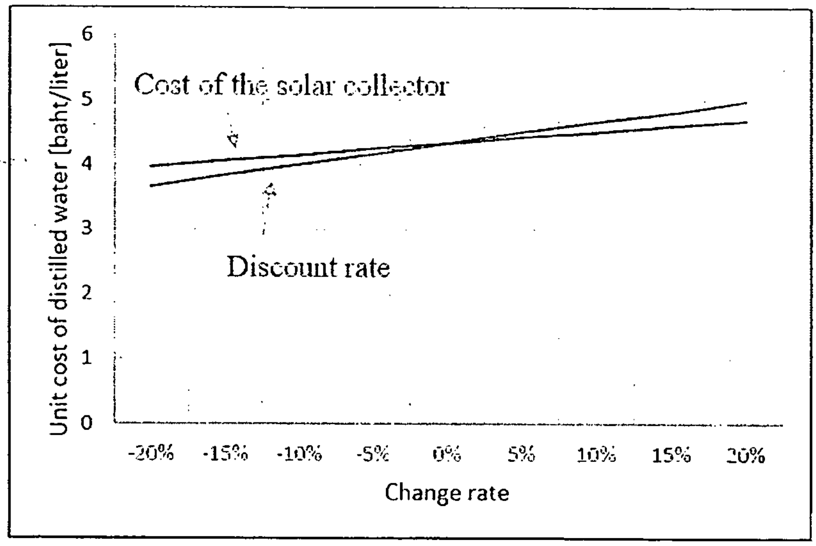

Figure 5.5 The solar collector cost and the discount rate affecting the production cost.

The effect of the cost of the solar collector and the discount rate on the distilled water production cost is shown in Figure 5.5. The vertical one represented the unit cost of the production. While the horizontal axis represented the change of the solar collector cost and the discount rate in percentage from the reference values of 23,200 bahts and 8%, respectively. The results show that the discount rate had more effect on the unit cost of distilled water than the cost of the solar collector.