Investigation and Mathematical Modeling of Solar-Thermal Desalination with Bubble Pump Technique

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ABSTRACT

The objective of this study was to investigate performance of a solar seawater desalination with bubble pump technique. A model was also developed to simulate the system behavior and ultimately to estimate the unit cost of distilled water. The sample of salt solution of 3% was tested in various levels of the bubble pump at 162, 216 and 270 mm or 60, 80 and 100% relatively to height of the bubble pump column, respectively. The experiment was done at a laboratory scale under Chiang Mai climatic condition. The bubble pump model was mathematically developed as a correlation between the distilled water rate, brine water rate, the initial salinity of the salt solution, the outlet temperature of the working fluid from the solar collector, and the liquid level in the bubble pump column. The correlation with the uncertainty of $\pm 7.02\%$ was as given by

$$M_d = (-353.83100 + 2.75650H - 0.0065452H^2) \\ + (3.61750 - 0.0269416H + 0.00006298H^2)T_o.$$

The results from the calculation could be fitted with 91.66% of the experimental data with $\pm 10\%$ deviation. It was evident from the results that the system with the liquid level at the bubble pump of 60% was the most efficient case. The system could produce distilled water from 3.87 to 6.46 liters per day depending on hours of direct sunshine. The study showed that the lower the reservoir level of the bubble pump, the higher rate of distilled water the system could be produced. The cheapest cost of the production from the solar thermal desalination of seawater by bubble pump technique was 4.32 baht per liter.

Keywords: bubble pump technique, evacuated tube solar collector, desalination, evaporator.

1. INTRODUCTION

Three fourth of the entire earth's surface is covered in water but less than one percent is accessible freshwater. The majority of all water sources is not desirable for human consumption because it contains too much salt and many harmful organisms. Due to growing concerns about water shortages and disputes over water resources, a tremendous amount of effort has been devoted to developing seawater desalination technology. Desalination can be considered a way to overcome natural limitations on high quality freshwater.

While substantial progress has been made in recent years, desalination remains to be an insignificant source of water in all, but the wealthiest, water scarce regions. Desalination remains to be an expensive option to be a primary source of fresh water and presents important social, environmental, and technological obstacles that must be overcome. The reason being that current plants were developed for large-scale demands which require a large amount of energy to function [1].

There are many methods of desalination and current plants which are based mostly on large-scale demands. In choosing a process, one must consider geographic conditions, salt content of the water, economic feasibility, quality of water required and engineering experience and skills of the local population. The goal of this research project is to increase the number of options available for small scale potable water production.

In order to solve the problem of high energy consumption, this study considered the use of solar energy as a heat source. An example of using solar energy for desalination is solar stills.

The drawbacks of solar energy are a relatively low productivity rate and low thermal efficiency [2]. However, solar collectors which are commonly used for hot water production in residential and commercial buildings have been proven to be more efficient. The two main components in an active solar collector system are a solar collector and a storage tank as shown in Figure 1.

Medium solar collectors such as the evacuated tube solar collector could generate temperature over 120°C [3] which is adequate to boil sea water. The current study used an evacuated tube solar collector as a heat source, designed with a small storage tank so that the temperature of the fluid in the system can increase faster.

A bubble pump technique was also used in the system. The bubble pump is basically a fluid filled tube. When it is heated until vapor bubbles are created, the bubbles rise up and carry some of the liquid into an upper reservoir. Based on literature reviews, the bubble pump technique has been used mostly for ethanol distillation [5-8].
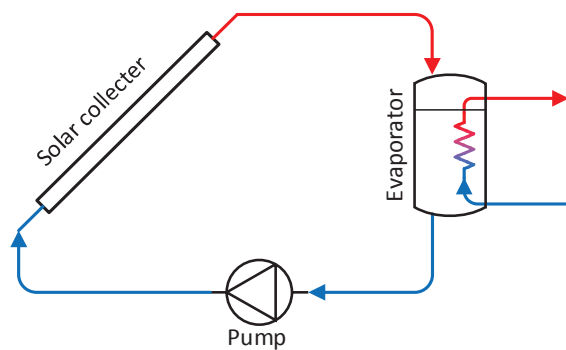

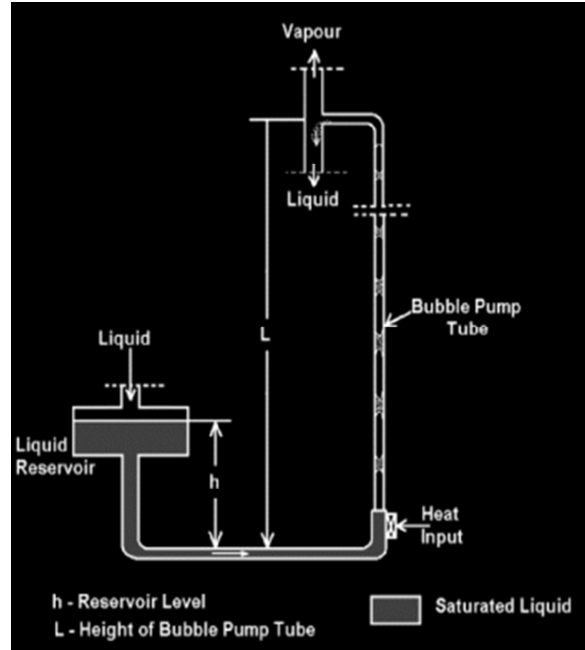**Figure 1** One of the solar thermal collector design.

Figure 2 Bubble pump concept [4].

2. METHODOLOGY
2.1System operation

Figure 3 shows a schematic diagram for the desalination system running on solar energy with the bubble pump technique.

In the solar collector, 40% of propylene glycol was added to the water in the solar collection system to extend the boiling point of water to about 103.5°C [9]. The intake seawater (M_f) at a temperature (T_f) and a salt concentration (X_f) was fed into the evaporator through a coil tube in a counter-current mode, where the heat of hot water from solar collector (Q_{coll}) was transferred. After receiving the heat from the evaporator, the temperature (T_f) of the fed saline water was increased. When it reached the boiling temperature (T_b), the vapor formed at a rate of (M_d). The mixture of saline water and steam were separated in the separator tank by their densities. The vapor went through a pipe into the condenser which was cooled by cool water at a temperature (T_{cw}) and with a mass flow rate of (M_{cw}), thus the distillate could be obtained with a flow rate of (M_d). While the brine water (M_b) would go through another pipe to a receiver.
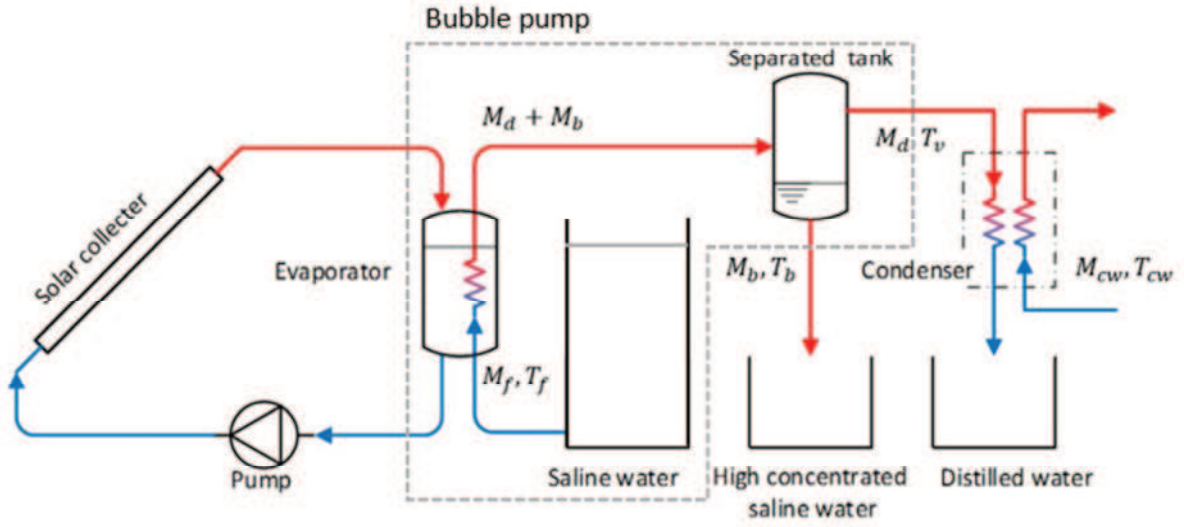
Figure 3 Solar desalination by bubble pump technique.

2.2 Bubble pump model

The yield rate of distilled water (M_d) were formed as a function of three factors which were; initial salinity of the solution (X_f), height level of the solution (H) and outlet temperature working fluid from solar collector (T_o) in the form of

$$M_d = f(H, T_o, X_f). \tag{1}$$

The model was used for the system simulation to calculate distilled water rate (M_d), brine water rate (M_b) and its salinity (X_b) and verified by the measured data.

2.3 Calculation of Distilled Water Rate

This amount of heat Q_{coll} with the outlet temperature T_o from the solar collector which could be expressed in an equation as:

$$Q_{coll} = A_c[F_R(\tau\alpha)_e I_T - F_R U_L(T_i - T_a)], \tag{2}$$

$$\text{and} \quad T_o = T_i + \frac{Q_{coll}}{(mC_P)_w}. \tag{3}$$

From time to time, the hot water from the collector increased the evaporator temperature T_w as well as the saline water solution with heat transfer coefficient UA as

$$Q_{coll} = \frac{(mC_P)_w(T_w^+ - T_w)}{\Delta t} + UA(T_w - T_f), \tag{4}$$

$$\text{or} \quad T_w^+ = \left(Q_{coll} - UA(T_w - T_f)\right) \times \frac{\Delta t}{(mC_P)_w} + T_w. \tag{5}$$

At the non-boiling state, the temperature of saline water sensibly increased and could be determined by:

$$UA(T_w - T_f) = \frac{(mC_p)_s(T_f^+ - T_f)}{\Delta t}, \tag{6}$$

$$\text{or} \quad T_f^+ = UA(T_w - T_f) \times \frac{\Delta t}{(mC_P)_s} + T_f. \tag{7}$$

At the boiling stage, distilled water was produced from the Eq. 1 while its temperature was assumed to be stable at the boiling point.

The calculation process was shown in the Figure 4.

During the boiling stage, all amount of thermal energy from the solar collector was assumed to be transferred to the saline water since the capacity of evaporator was very small. The overall mass and salt balances at the evaporator could be given by

$$M_f = M_b + M_d. \tag{8}$$

$$M_f X_f = M_b X_b. \tag{9}$$

By assuming the steady state condition during boiling and neglecting heat loss from the evaporator to the ambient, the energy balance at the evaporator could be expressed as:

$$Q_{coll} = M_d h_d + M_b h_b - M_f h_f, \qquad or \qquad (10)$$

$$Q_{coll} = M_d h_d + M_b h_b - (M_b + M_d) h_f \qquad (11)$$

From the above equation, a relation between M_b and M_f could be written as:

$$M_b = \frac{Q_{coll} - M_d(h_d - h_b)}{h_b - h_f}. \qquad (12)$$

The specific enthalpy of salt water can be calculated from IAPWS [10].

2.3 Experimental Setup

The artificial salt solution was used as a sample for this laboratory instead of the sea water. The salt content of the water by weight in this sample was 3% which was closed to the natural sea water [11].
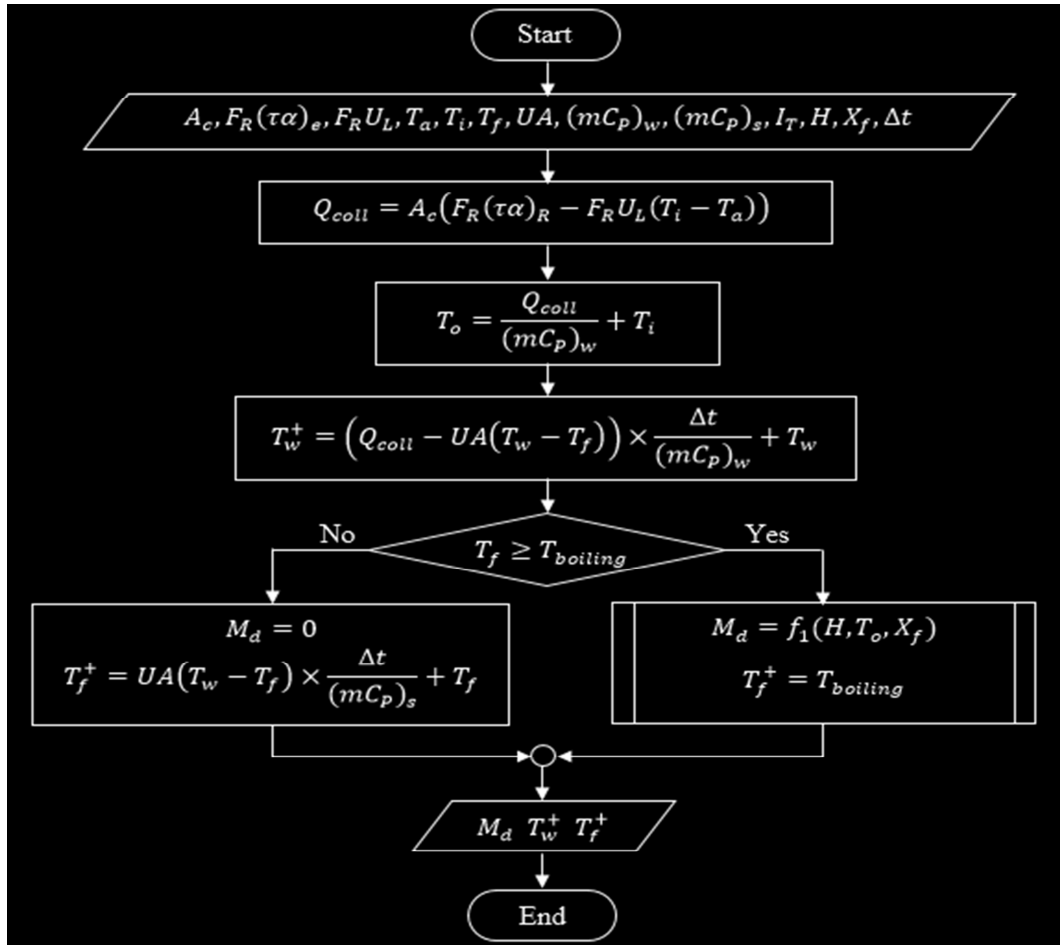

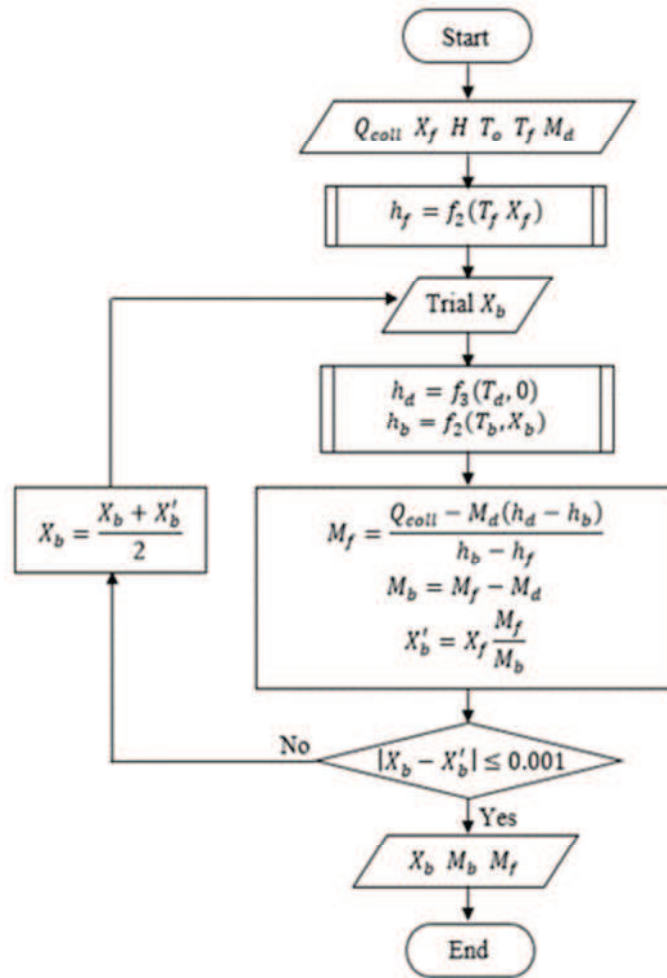**Figure 4** Calculation of distilled water rate.

Figure 5 Calculation of the brine water rate and its salinity.

The bubble pump unit in this laboratory was made of a spiral tube enclosed in a cylindrical shaped tube as shown in Figure 6. The cylindrical tube was filled with working fluid from the solar collector which was near boiling temperature. The salt water traveling through the spiral tube exits at boiling temperature. The cylindrical tube had an internal capacity of approximately 1.4 liters.
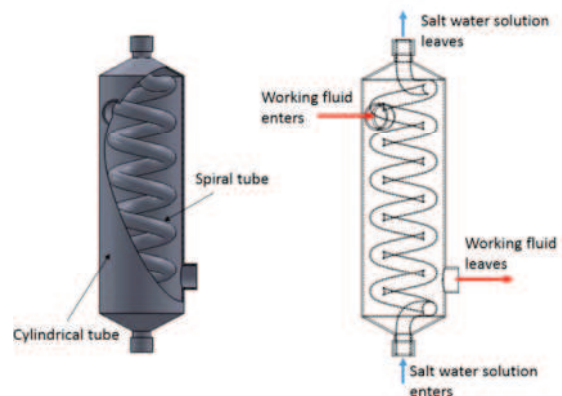

Figure 6 The bubble pump design.

The main system unit consisted of an evacuated-tube solar collector, electrical pump, evaporator, saline water reservoir, separator and a condenser. The characteristics of the solar collector, $F_R(\tau\alpha)_e$ was 0.51 and $F_R U_L$ was $3.42 \, W/m^2 K$, with an aperture area of $2.8 \, m^2$. 71.7W of electrical power was consumed to run a pump in the solar collector system and a pump at the cooling tower.

The solar radiation was measured by a pyranometer with an accuracy of ±0.5%. Temperatures was recorded with a data logger with an accuracy of ±0.5%. Salinity of the solution was measured by a salinity measurement (Atago 2313 Master Series Hand-Held Brix Refractometer with Metal Sample Stage) with as accuracy of ±0.1%. The amount of distilled water and brine water were manually measured by lab glasses with an accuracy of ±10ml.

3. RESULTS AND DISCUSSION
3.1 Overall Heat Transfer Coefficient
The total overall heat transfer coefficient of the bubble pump was $45 \, W/m^2$ and the boiling point of the solution with the initial salinity of 3% by weight was 94^oC (from the experiment). The specific heat capacity of the solution was $4025.3 \, W/m^2.K$ [12].

3.2 Bubble Pump Model
The measured data of the distilled water yielded in milliliters per minute was illustrated in the function of the outlet temperature and the absolute reservoir level (H) (but relative value in percentage was shown instead) in Figure 7.
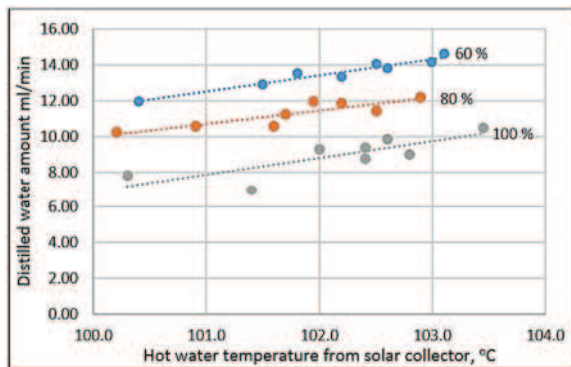

Figure 7 The distilled water yield rate from the experiment.

60% reservoir level of the bottom of the evaporator was proven to the most efficient. In fact, the lower the reservoir level and the higher amount of the distilled water was produced. The data from Figure 7 can be formulated in Eq. 13. The reservoir level ranges from 162 (60%) to 270 mm (100%) and the outlet temperature ranges from 95 to 103^oC with the uncertainty of ±7.02%.

$$M_d = (-353.83100 + 2.75650H \qquad (13) \\ - 0.0065452H^2) + \\ (3.61750 - 0.0269416H + 0.00006298H^2)T_o.$$

Comparison of the production rate of distilled water by varying the reservoir level from the experiment with the Eq. 13 could be shown in Figure 8.
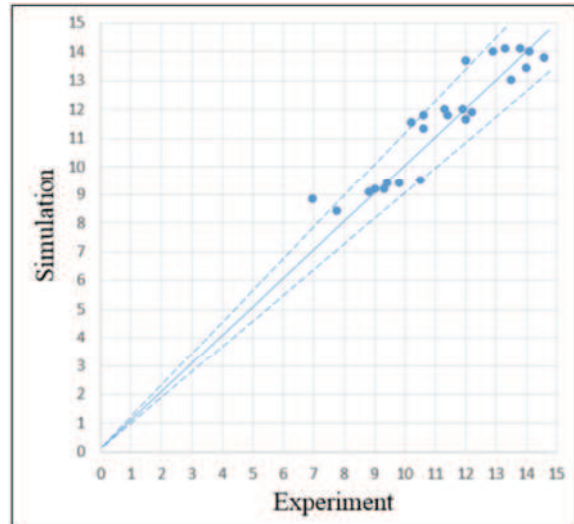

Figure 8 Verifying the model with experimental data.

Figure 8 shows that 91.66% of the experimental data was consistent with the simulation data within ±10%.

3.3 Model verification
The simulation data was validated by the experimental data throughout the day with various reservoir levels of 162 mm (60%), 216 mm (80%) and 270 mm (100%). The desired data from the experiment were the mass flow rate of the distilled water (M_d) as well as the mass flow rate of the brine water (M_b) and the brine water salinity (X_b).
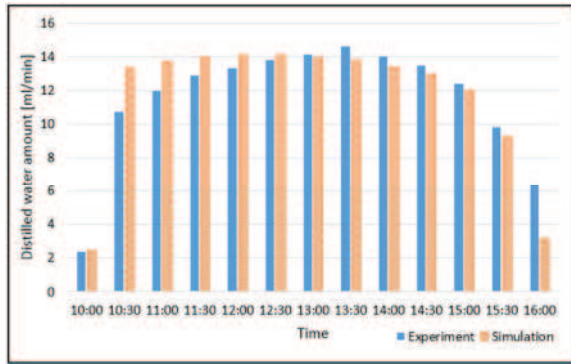
Figure 9 Simulation and experimental data of the system with the reservoir of 162 mm (60%).
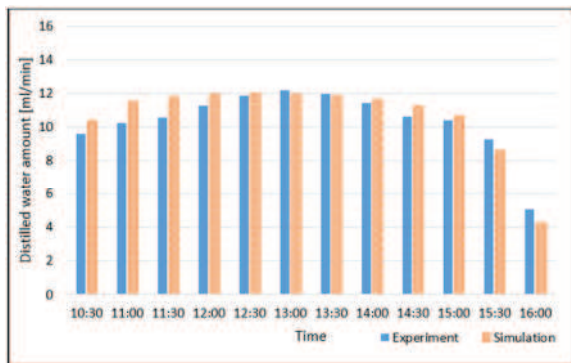

Figure 10 Simulation and experimental data of the system with the reservoir of 216 mm (80%).
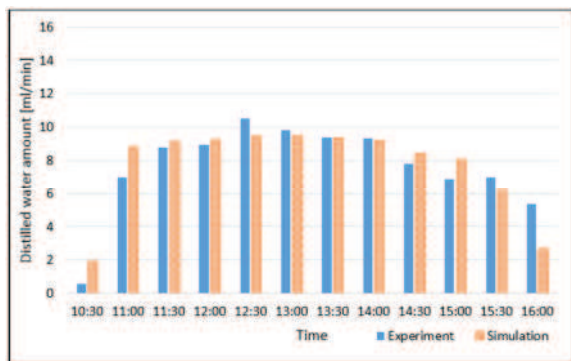

Figure 11 Simulation and experimental data of the system with the reservoir of 270 mm (100%).

The total yield of distilled water data from the simulations and the experiments from Figure 9, 10 and 11 are summarized in Table 1.

Table 1 Simulation and experiment results of the distilled water yield.

H(relatively) [%]	Sim [cc]	Exp [cc]	Dif [%]
60	4506.4	4454	1.16
80	3832.5	3750	2.15
100	2853.4	2694	5.59

In general, the data of the distilled water yield from the experiment was less than that from the simulation with a maximum difference of 5.6% due to some liquid remains in the system piping.

Table 2 Simulation and experiment results of the average brine water rate.

H(relatively) [%]	Sim [cc/min]	Exp [cc/min]	Dif [%]
60	124.1967	108.0667	12.99
80	124.9067	104.8333	16.07
100	123.39	125.6233	1.78

Table 2 compares the simulation data to the experimental data of the brine water rate in average. The data was selected from 11:00 am to 2:30 pm when there was boiling of liquid water in all cases. The differences were quite high, about 13% in most cases.

Table 3 Simulation and experiment results of the brine water salinity.

H(relatively) [%]	Sim [%]	Exp [%]	Dif [%]
60	3.58	3.6	0.56
80	3.49	3.3	5.44
100	3.33	3.2	3.90

Table 3 shows the verification to the simulation data of salinity of brine water in average in all cases by the experimental data. The comparison shows that the data of brine water salinity from the computer simulation and from the experiment was less than 5.5% different.

3.4 Long Term Analysis

The simulation was done under Chiang Mai climatic condition which the solar radiation data were taken from Pratinthong [12] and ambient temperature data were taken from Chaichana et al [14]. The bubble pump model was used in the system simulation with conditions as described in Table 4:

Table 4 Simulating conditions for operating system.

Solar thermal collector	$F_R(\tau\alpha)_e = 0.51$, $F_R U_L = 3.42$ W/m^2.K Area = 2.8 m^2
Feed salt water temperature, T_f	25 ^{o}C
Boiling point of the salt solution	94 ^{o}C
Overall heat transfer of the bubble pump	45 W/m^2 the average value of the experimental data with the uncertainty of 10%
Specific heat capacity of the salt solution	$4025.3\ W/m^2.K$
Daily operating time	10 hours, From 7:00 am to 5:00 pm

Figure 12 shows the production yield of distilled water (in liters) in each month with 3 different reservoir level of the bubble pump which were 100%, 80% and 60%. In general, the system with the reservoir of 162 mm (60%) was the most efficient. The system could produce distilled water from 3.87 to 6.46 liters per day. The fluctuation of daily production was correspondent to the quantity of solar radiation and the ambient temperature available in each month. The high quantity were produced from December to May as the skies were mostly clear. In other 5 months, the sky were mostly cloudy and raining which resulted in low productions.
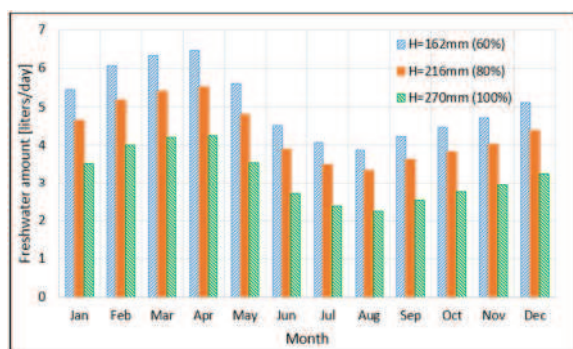
Figure 12 Average calculated daily production of distilled water in each month.

The cost of the distilled water produced by the system in each cases was done under the conditions as shown in Table 5.

Table 5 The yield and cost of distilled water production.

H(relatively) [%]	Yearly product yield [liters]	Unit cost [bahts/liter]
60	1704.92	4.32
80	1460.92	5.04
100	1071.58	6.88

The unit cost per liter depends on the amount of distilled water produced per year. 60% reservoir level was proven to the most efficient with the unit cost of 4.32 bahts per liter.

Two factors that affecting the unit cost of distilled water production were examined. 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 which is interest rate used in discounted cash flow analysis to define the present value of future cash flows.
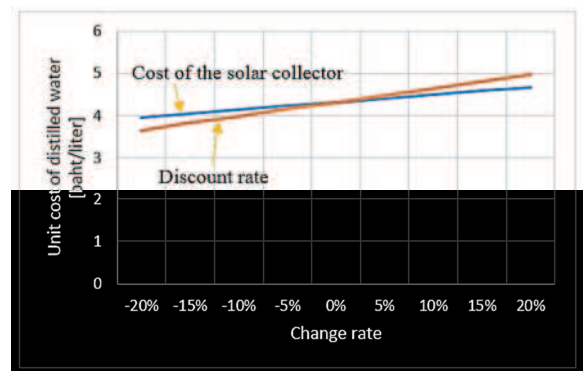

Figure 13 The solar collector cost and the discount rate affecting the production cost.

Figure 13 shows the effect of the cost of the solar collector and the discount rate on the distilled water production cost. The horizontal axis represents the change of the solar collector cost and the discount rate in percentage from the reference values of 23,200 bahts and 8%, respectively. While the vertical axis represents the unit cost of the production. The results show that the discount rate had more effect on the unit cost of distilled water than the cost of the solar collector.

4. CONCLUSION

The mathematical model of the distilled water rate was formed in function of the initial salinity of the salt solution of 3%, the outlet temperature of the working fluid from the solar

collector ranges from 95 to 103°C, and the reservoir level ranging 162, 216 and 270 mm or 60, 80 and 100% relatively to the bottom of the evaporator, respectively.

$$M_d = (-353.83100 + 2.75650H - 0.0065452H^2) + (3.61750 - 0.0269416H + 0.00006298H^2)T_o.$$

The correlation has the uncertainty of $\pm 7\%$ and the experimental data was consistent by 91.66% with the simulation data within $\pm 10\%$.

It was evident from the results that the system with the reservoir level of 60% was the most efficient case. The system could produce distilled water from 3.87 to 6.46 liters per day depending on hours of direct sunshine. The lower the reservoir level of the bubble pump, the high rate of distilled water the system could produce.

The lowest cost of the production from the solar thermal desalination of seawater by bubble pump technique was 4.32 baht per liter. The initial investment and the discount rate were the main factors of the system. The discount rate had more effect on the unit cost of distilled water than the cost of the solar collector. So the production cost was relied on the market rate of interest.

5. ACKNOWLEDGEMENT

6. NOMENCLATURES

A_c	Aperture area of solar collector, m^2
$F_R U_L$	Overall heat loss coefficient of the collector, $W/m^2°C$
$F_R(\tau\alpha)_e$	Transmittance-absorptance product of the collector
Q_{coll}	Heat gain from solar collector, W
h_b	Specific heat capacity of brine water, $J/°C$
h_d	Specific heat capacity of distilled water at vapor state, $J/°C$
h_f	Specific heat capacity of fed salt solution, $J/°C$
I_T	Solar radiation, W/m^2
$(mC_P)_s$	Heat capacity of salt solution during non-boiling state, $J/°C$
$(mC_P)_w$	Heat capacity of working fluid in the solar collector, $J/°C$
M_b	Mass flow rate of brine water during boiling state, kg/s
M_d	Mass flow rate of distilled water during boiling state, kg/s
M_f	Mass flow rate of fed salt solution during boiling state, kg/s
T_a	Ambient temperature of working fluid entering the collector, $°C$
T_f	Temperature of salt solution in the storage tank during non-boiling state, $°C$
T_f^+	Temperature of salt solution in the storage tank during non-boiling state at the next time step, $°C$
T_i	Inlet temperature of working fluid entering the collector, $°C$
T_o	outlet temperature of working fluid leaving the collector, $°C$
T_w	Temperature of working fluid in the storage tank, $°C$
T_w^+	Temperature of working fluid in the storage tank at the next time step $°C$
UA	Overall heat transfer of the evaporator, $W/°C$
X_b	Salinity of brine water, $\%$
X_d	Salinity of distilled water, $\%$
X_f	Salinity of fed salt solution, $\%$
Δt	Time step

REFERENCES

[1] Cooley, Heather and Gleick, Peter H and Wolff, Gary, Desalination: with a Grain of Salt, Pacific Institute, Oakland, California, 2006.

[2] H. M. a. B. F. Qiblawey, "Solar thermal desalination technologies," *Desalination,* vol. 220, pp. 633-644, 2008.

[3] "Solar thermal collector," Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Solar_thermal_collector. [Accessed 16 June 2015].

[4] A. Sathe, "Experimental and theoretical studies on a bubble pump for a diffusion absorption refrigeration system," *India Institute of Technology, Madras, India,* 2001.

[5] J. Sornpherk, "Ethanol Distillation with Bubble Pump Techique," 2003.

[6] P. Jittayasothon, "Performance Analysis of Ethanol Distillation in Bubble Pump distiller," 2008.

[7] A. Rakhom, "Effect of Ethanol Concentrations from Distillation with Bubble pump technique by using Precusors of Agricultural product," 2011.

[8] N. Malawonno, "Performance Analysis of a Direct Boiling Solar Ethanol Distillation," 2008.

[9] "The engineering toolbox," [Online]. Available: http://www.engineeringtoolbox.com/propylene-glycol-d_363.html. [Accessed 14 June 2015].

[10] Jamieson, DT and Tudhope, JS and Morris, R and Cartwright, G, "Physical properties of sea water solutions: heat capacity," vol. 7, pp. 23-30, 1969.

[11] "UCSB ScienceLine," [Online]. Available: http://scienceline.ucsb.edu/getkey.php?key=621. [Accessed 4 june 2015].

[12] M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair, Desalination, vol. 16, 2010, pp. 354-380.

[13] N. Pratinthong, Long Term Simulation of Concrete Solar Collector, King Mongkut's Institute of Technology Thonburi, Bangkok, Thailand, 1996.

[14] Chaichana, Chatchawan and Kiatsiriroat, Tanongkiat and Nuntaphan, Atipoang, "Comparison of conventional flat-plate solar collector and solar boosted heat pump using unglazed collector for hot water production in small slaughterhouse," *Heat Transfer Engineering,* vol. 31, pp. 419-429, 2010.

APPENDIX

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.

$$C = C_{inv} + C_{o\&m} - C_{sv}. \tag{14}$$

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

$$C_{annual} = C \times \frac{i(1 + i)^n}{[(1 + i)^n - 1]}. \tag{15}$$

The unit cost of distilled water can be calculated by

$$C_{product} = \frac{\text{annual expenses}}{\text{annual product amount}}. \tag{16}$$

The initial investment cost was shown in detail in the Table 2.

Table 1 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

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

$$C_{o\&m} = R \frac{[(1 + i)^n - 1]}{i(1 + i)^n}. \tag{17}$$

Table 2 Annual expenses on the system.

Operation and maintenance cost	Expenses
Annual operation cost by electricity consumption (71.7 W)	771 baht/year
Annual maintenance cost (0.02% of the initial investment)	992 baht/year
Total annual cost at the present worth	15089.59 baht

The salvage value of the plant was assumed to be 10% of the initial investment. The present worth of the salvage value equals 1564 baht, calculated from the equation as:

$$C_{sv} = \frac{0.1 \times C_{inv}}{(1 + i)^n}. \tag{18}$$