CHAPTER 2

Theory

A new distillation system for desalination was presented. This chapter involved in the design concept of freshwater production from seawater by solar desalination under bubble pump technique in detail. Furthermore, this involved analyzing the parameters affecting the productivity rate of distilled water and modeling the performance of the whole system for long term analysis.

2.1 Introduction to the New Desalination Technique Concept

It is worth spending time to examine the basic principles of distillation, solar thermal collection and the bubble pump technique in order to better understand the new technology in this study.

2.1.1 Basic Concepts of Distillation

Distillation is a process of separating the main components of substances from a liquid mixture by selective evaporation and condensation. The process follows the principle that water and salts do not separate naturally but require some external energy to force the separation to happen.

Figure 2.1 illustrates the basic of how the distillation of salt water works. First, the salt water solution is heated by external thermal energy until it reaches the water boiling point. During the boiling stage, only water vapor rises from the distillation flask and enters a cooling column called the condenser. All of the vapor condenses and goes into a receiving container.

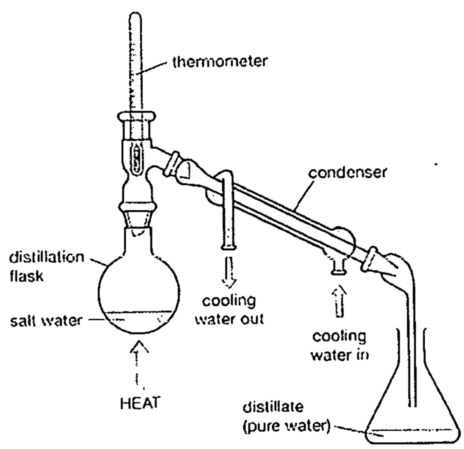

Figure 2.1 Basic process of distillation [13].

2.1.2 Solar Thermal Concepts Overview

One of the most cost-effective applications is heating water by solar thermal energy. There are many uses for hot water in residential and commercial buildings. The most common are hot water for indoor uses and swimming pools. One of the most common system designs is shown in Figure 2.2. In this system design, the solar collector and the heat storage tank are the two main components. Heat from the sun is collected by the solar collector and transferred to the hot water storage tank through a working fluid. The tank can function as either a heat exchanger or a hot water source, depending on the end uses.

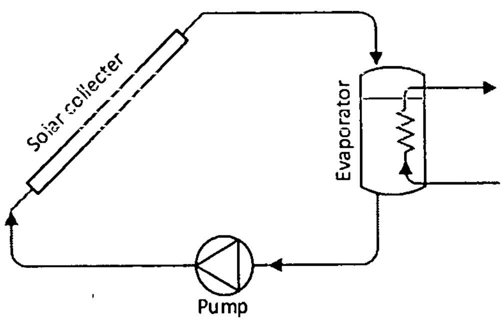

Figure 2.2 One of the solar thermal collector design.

2.1.3 Principle of Bubble Pump Technique

The bubble pump is simply a liquid 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. Since the bubble pump is a fluid pump that functioned by thermal energy, the system is just a small circular cross-section of vertical tube.

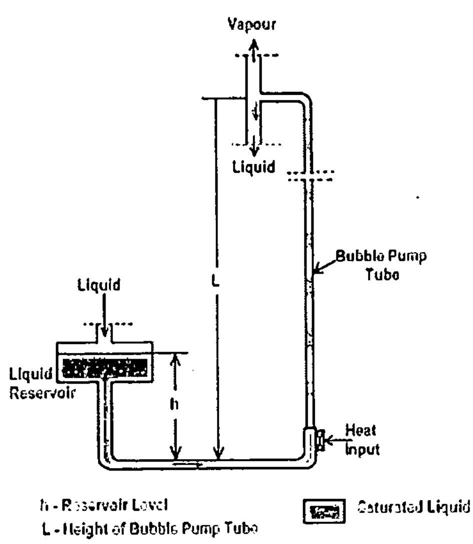

Figure 2.3 Bubble pump concept [14].

Figure 2.3 illustrates the basic concept of the operating process of the bubble pump. The liquid in the liquid reservoir initially fills the tube to the same level (h). The bottom of the tube is heated at a rate appropriate to evaporate a portion of the liquid in the tube. The result is vapor bubbles rising in the tube to pump lift (L). Because of the small diameter of the pump tube, the vapor bubbles occupy the complete cross-section of the tube and are separated by small liquid slugs. Each bubble acts as a gas piston and lifts the corresponding liquid slug to the top of the pump tube. The bulk density of the liquid and vapor mixture in the pump tube is reduced relative to the liquid in the liquid reservoir, thereby creating an overall buoyancy lift.

The energy sources normally used are electric heat and flame heat. In the latter case, the entire length of the bubble pump is heated to increase the heat transfer area.

2.1.4 Solar Desalination Design in the Study

Medium solar collectors such as the evacuated tube solar collector could produce temperatures over 120 °C which is an enough level to boil sea water. The solar heat is then supplied to the fluid in a storage tank which also functions as a heat exchanger for generating heat to a salt water solution stream. The solution is contained in a small diameter tube and absorbs heat until it reaches the boiling point, and some of the bubbles could be generated then two phase fluid, vapor and liquid slugs and moving up and go to the separator. The water vapor condenses in a condenser and the high salinity goes into a receiver. Figure 2.4 shows a concept of solar desalination with a bubble pump technique.

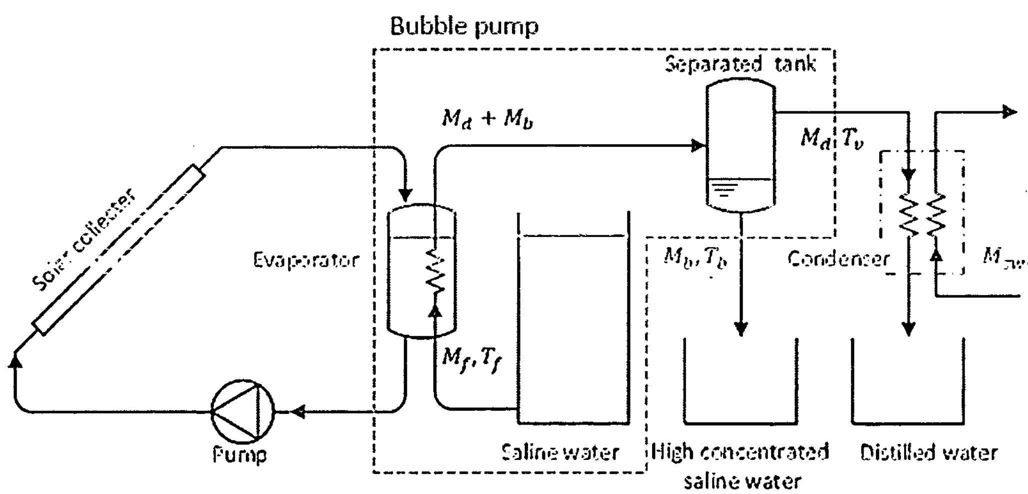

Figure 2.4 Solar desalination by bubble pump technique.

2.2 Modeling of Solar Desalination with the Bubble Pump

2.2.1 Calculation Step of Distilled Water Rate

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

$$Q_{coll} = A_c[F_R(\tau\alpha)_e I_T - F_R U_L(T_i - T_a)], \tag{2.1}$$

$$and \quad T_o = T_i + \frac{Q_{coll}}{(\dot{m}C_P)_w}. \tag{2.2}$$

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

$$Q_{coll} = \frac{(\dot{m}C_P)_w(T_w^+ - T_w)}{\Delta t} + UA(T_w - T_f), \tag{2.3}$$

$$or \quad T_w^+ = \left(Q_{coll} - UA(T_w - T_f)\right) \times \frac{\Delta t}{(\dot{m}C_P)_w} + T_w. \tag{2.4}$$

where, $\dot{m}$: mass flow rate $[kg/s]$.

C_p : Specific heat of water $[kJ/kg°C]$.

A_c : Aperture area of the solar collector $[m^2]$.

$F_R(\tau\alpha)_e$: Transmittance-absorptance product of the solar collector.

$F_R U_L$: Overall heat loss coefficinet of the solar collector $[W/m^2.°C]$.

I_T : Solar irradiation $[W/m^2]$.

Δt : Time step $[s]$.

UA : Heat transfer coefficient of the evaporator $[W/°C]$.

Sub w : Indicates the properties of water.

T_a : The ambient temperature [°C].

T_i : Temperature of water entering the collector [°C].

T_o : Temperature of water leaving the collector [°C].

T_f : Temperature of the saline water [°C].

T_w : Water temperature in the evaporator [°C].

T_w^+ : Water temperature in the evaporator at the next time step [°C].

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

$$UA(T_w - T_f) = \frac{(mC_p)_s(T_f^+ - T_f)}{\Delta t} \tag{2.5}$$

$$or\ T_f^+ = UA(T_w - T_f) \times \frac{\Delta t}{(mC_P)_s} + T_f. \tag{2.6}$$

where, Sub. s : Indicates the properties of saline water.

T_f^+ : Temperature of the saline water at the next time step.

At the boiling stage, distilled water was produced while its temperature was assumed to be stable at the boiling point. The yield rate of distilled water (M_d) depended on three factors which were; initial salinity of the solution (X_f), reservoir level of the solution (H) and outlet temperature working fluid from solar collector (T_o) in the form of

$$M_d = f(H, T_o, X_f).$$

The diagram showing the calculation for evaluating the amount of distilled water was presented in Figure 2.5.

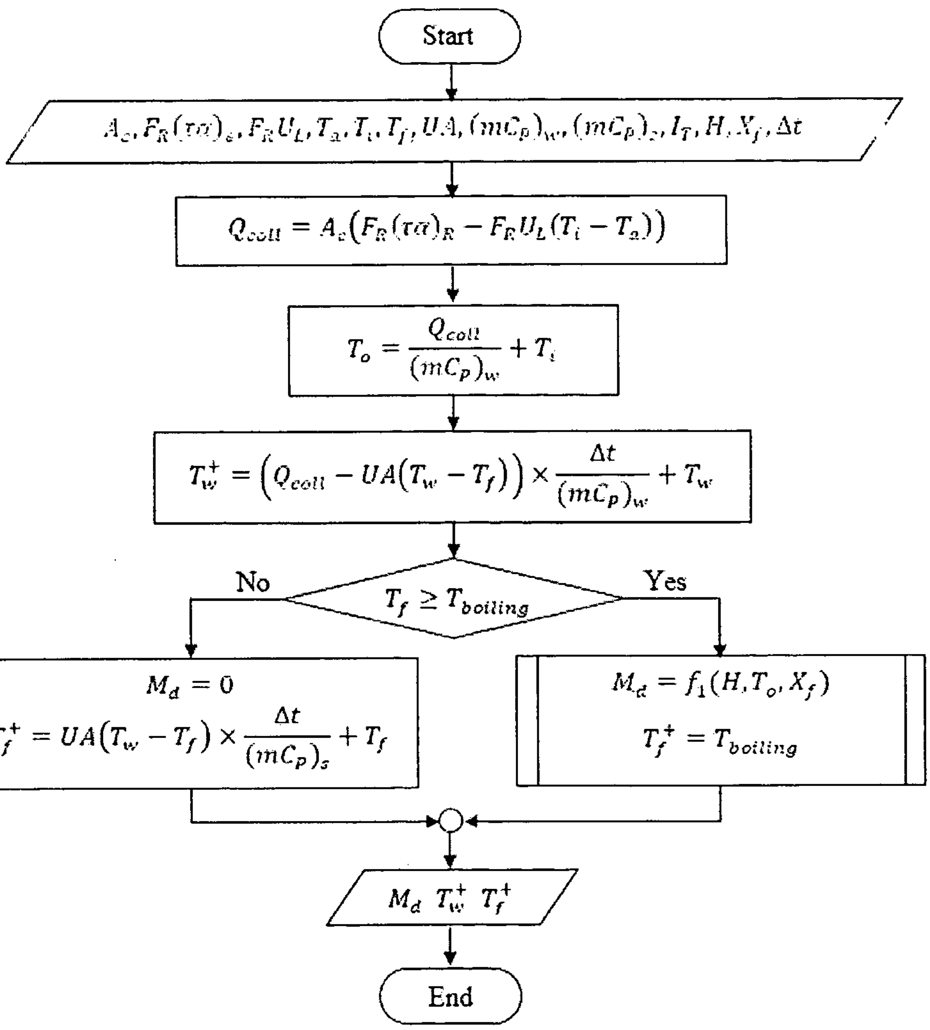

Figure 2.5 Calculation of distilled water rate.

2.2.2 Calculation Step of Brine Water Rate and its Salinity

Once the distilled water rate (M_d) was known, as calculated in Figure 2.5, the brine water rate (M_b) and its salinity (X_b) could be calculated. During the boiling stage, all quantity 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

$$M_f = M_b + M_d \tag{2.7}$$

$$M_f X_f = M_b X_b \tag{2.8}$$

where, M_f : Mass flow rate of feed salt water $[ml/s]$.
M_b : Mass flow rate of rejected brine $[ml/s]$.
M_d : Mass flow rate of feed distilled water $[ml/s]$.
X_f : Concentration of feed salt water[%].
X_b : Concentration of rejected brine[%].

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:

$$Q_{coll} = M_d h_d + M_b h_b - M_f h_f \tag{2.9}$$

$$or \quad Q_{coll} = M_d h_d + M_b h_b - (M_b + M_d) h_f \tag{2.10}$$

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

$$M_b = \frac{Q_{coll} - M_d(h_d - h_b)}{h_b - h_f} \tag{2.11}$$

where, Q_{coll} : Heat gain from the solar collector $[W]$.
h_b : Specific enthalpy of the rejected brine $[J/°C]$.
h_f : Specific enthalpy of inlet feed salt water $[J/°C]$.
h_d : Specific enthalpy of the steam at the saturated water $[J/°C]$.

The specific enthalpy of salt water can be calculated from IAPWS [15]

$$h_{sw} = h_w - X(a_1 + a_2 X + a_3 X^2 + a_4 X^3 + a_5 t + a_6 t^2 + a_7 t^3 + a_8 X t + a_9 X^2 t + a_{10} X t^2) \tag{2.12}$$

$a_1 = -2.348.10^4,\ a_2 = 3.152.10^5,\ a_3 = 2.803.10^6,\ a_4 = -1.446.10^7,$
$a_5 = 7.826.10^3,\ \ a_6 = -4.417.10^1,\ a_7 = 2.139.10^{-1},\ a_8 = -1.991.10^4,$
$a_9 = 2.778.10^4,\ \ a_{10} = 9.728.10^1$

$$h_w = 2.501.10^6 - 2.369.10^3 t + 2.678.10^{-1} t^2 - 2.079.10^{-5} t^4. \qquad (2.13)$$

h_{sw} and h_w in $(J/kg\ K)$; $10 \le t \le 120\ °C$; $0 \le X \le 0.12\ kg/kg$

The diagram showing calculation for evaluating the amount of distilled water was shown in Figure 2.6.

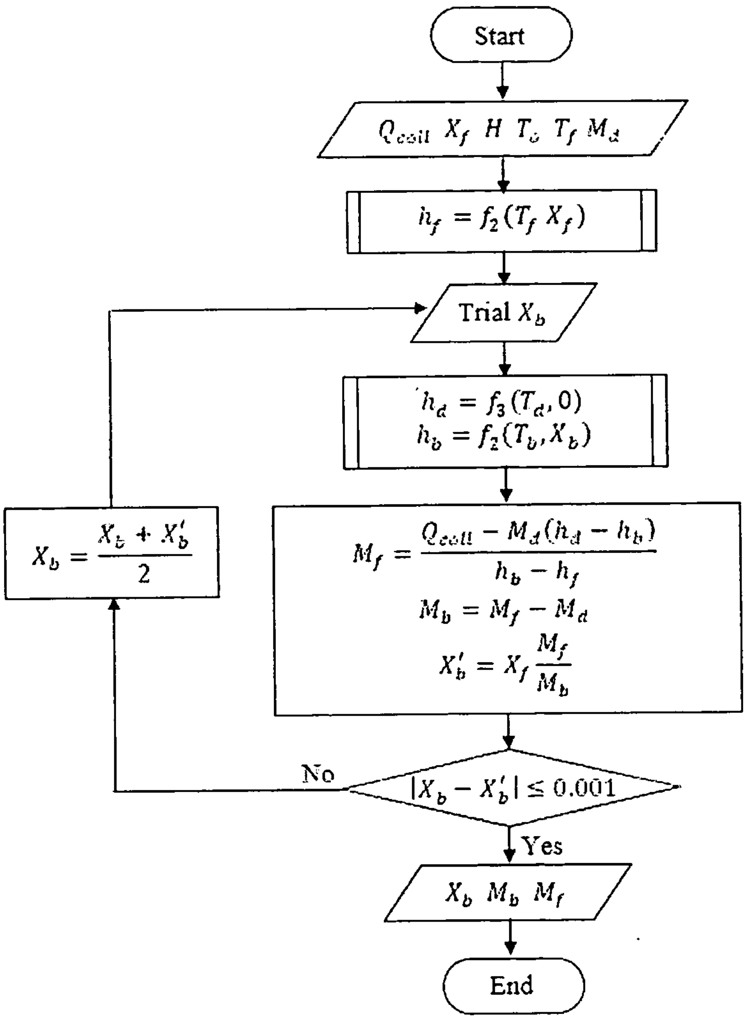

Figure 2.6 The process of finding the amount of brine water and its salinity.