Modeling and Performance Analysis of a Solar Collector Supported De-salination System Coupled With Multi-effect Humidification

M.K.Manglam[1], A.Ganguly[2*]

Abstract: Water is one of the most abundant resources on the earth surface. About two third of earth's surface is covered with water, but unfortunately most of them are saline and unfit for human consumption. So there is an acute shortage of fresh potable water in many coun-tries of the world including India. Contaminated water also leads to many enteric diseases like Typhoid, Cholera, etc. Thus, inadequate availability of fresh water poses a major chal-lenge towards sustainable development of a country like India. For this reason purification of saline water becomes extremely important. In this paper, a thermal model of a solar col-lector supported desalination system coupled with multi effect humidification has been presented. The model is based on the various heat and mass transfer equations. A computer program based on C language has been developed for the thermal model. The program takes ambient temperature and intensity of solar radiation as inputs and predicts the mass flow rate of the fresh water obtained through desal-ination from the given system. The per-formance of such a system has been analysed for the climatic conditions of Gangetic Ben-gal for a representa-tive day in summer season. The study reveals that the proposed system can yield substantial amount of fresh water through distillation using the solar energy.

Keywords: *Solar collector, Desalination, Multi-effect humidification, Heat exchanger,Evaporator, Condenser, Solar radiation.*

1. Introduction

Water is the basic necessity for human beings along with food and air. About two third of earth‟s surface is covered with water, but unfortunately most of them are saline and unfit for human consumption. So there is an acute shortage of fresh potable water. For this rea-son, purification of water is extremely important. The plains of Indian subcontinent receive abundant solar radiation for a considerable part of a year. This solar energy can be har-nessed to produce fresh water through desalination. Solar desalination with humidification-dehumidification technique is one of the promising technologies for fresh water produc-tion. In a Multi Effect Humidification (MEH) system, the air is allowed to pass over a source of saline water. The humidity of air increases due to evaporation of water from the source. When the humidified air comes in contact with a relatively cold surface, the ab-sorbed water vapour gets condensed resulting in dehumidification of air and production of distilled water.

The objective of this paper is to propose the scheme of a solar assisted desalination system coupled with multi-effect humidification. The proposed scheme is shown in Fig.1. Saline water enters the condenser

coil as a cold fluid at temperature T1 where it is preheated by the hot air coming from the humidifier. The saline water leaves at temperature T2 which is higher than T1 .Then it passes through a heat exchanger where it is further heated to temperature T3. A rotameter is placed between the condenser and the heat exchanger to measure the flow rate of the saline water. The hot water is stored in a storage tank. If the temperature of the hot saline water does not reach the desired value, then an auxiliary heater placed in the storage tank is switched on. The hot water leaving the storage tank is sprayed in a humidifier over a packed bed and falls through the packing such that a part of it gets evaporated in the air flowing in the opposite direction. The cold air passing through the humidifier is subjected to heating and humidification and leaves the humidifier under saturated condition. This warm, moist and saturated air then passes through the condenser where it gets cooled (to temperature T5) and undergoes dehumidification to produce fresh water which is collected at the bottom of the condenser. The latent heat of condensation is used to preheat the saline water entering the heat exchanger which reduces the load on the solar collector.

A thermal model for the proposed system has been developed. The model considers am-bient temperature and intensity of solar radiation as input and predicts the mass flow rate of fresh water obtained through desalination at a particular instant of time. The perfor-mance of the system has been analysed (using the model) for a representative day in the summer season.

2. Literature Review

Nawayseh et al. [1, 2] developed a simulation program to study the effect of area of dehu-midifier, humidifier and solar collector surface on the production of the fresh water through desalination. Ben Bacha et al. [3] developed a model of solar assisted humidifica-tion-dehumidification desalination system. The results of the thermal model were validated through experiments. They concluded that perfect insulation of the unit, high water tem-perature along with high flow rates at the entrance and injection of water at the top of the evaporation tower can improve the production of fresh water from the system. Muller-Holst et al. [4] described the performance of a solar collector assisted optimized humidifi-cation-dehumidification desalination system. The continuous operation of the unit required the use of a heat storage system. The system was designed for operation under low tem-perature which minimized the rate of scale formation. Dal and Zhang [5] conducted an experiment on solar desalination unit based on humidification-dehumidification principle. The performance of the system was found to depend strongly on the temperature of inlet saline water to the humidifier, the mass flow rate of saline water and the mass flow rate of the air. They used honey comb packing material in the humidifier section.

Thus, it is evident that though a number of works have been reported in literature which discuss the use of solar energy for distillation with multi effect humidification (MEH) process but no model study has been done for the climatic conditions of Gangetic Bengal which receives abundant solar insolation for considerable part of a year. This is the moti-vation behind the present work.

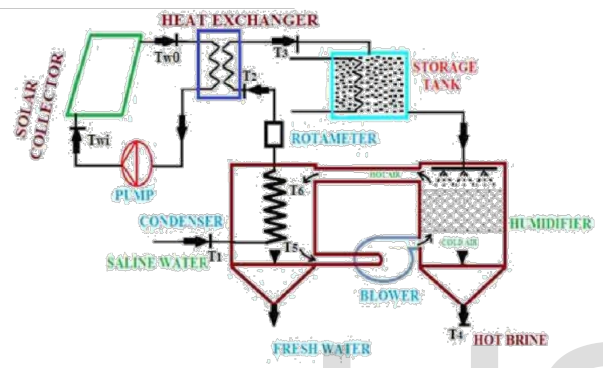

Fig. 1:- Schematic of water desalination with humidification dehumidification using solar energy

3. Thermal Model Development

Following assumptions have been made while developing the thermal model:

i) The modeling has been done under steady state condition.

ii) The overall loss coefficients have been assumed to be same for both the humidifier and the condenser.

iii) Air is assumed to be saturated at the top and bottom of the humidifier.

iv) To calculate the heat loss to the surrounding, the condenser and the humidifier have been assumed to operate between the same temperatures and their operating temperature is assumed to be the mean of T5 and T6.

The proposed system has four components: a flat plate solar collector, a heat exchanger, humidifier and a condenser. The performance of the flat plate solar collector can be given by: [6]

$$S = I_b R_b (\tau\alpha)_b + \{I_d R_d + (I_b + I_d) R_r\}(\tau\alpha)_d \quad (1)$$

Where and are the intensities of beam and diffused radiation respectively, while S is the incident solar flux absorbed by the absorber plate. The terms, and denote the radiation tilt factors for beam, diffused and reflected radiation respectively which can be determined from the radiation geometry of the concerned surface considering the parameters such as declination angle, hour angle and surface tilt angle. and represents the transmissivity-absorptivity product for the beam and diffused radiation falling on the collector plate respectively.

Thus, the useful heat gain rate for the collector can be given by:

$$Q_U = F_R A_P [S - U_l (T_{wi} - T_a)] \quad (2)$$

In Eq. (2), FR represents the collector heat removal factor and represents the collector loss coefficient. The value of is assumed to be 5.0 W/m2-K [6] in the present work. The term Ta represents the ambient temperature and denotes the temperature of water at the inlet of the collector. In the present work its value has been assumed to be 40◦c.

The temperature of water at the outlet of the collector can be given by:

$$Q_U = m_w C_{pw} (T_{wo} - T_{wi}) \quad (3)$$

The temperature of saline water after flowing through heat exchanger can be expressed as:

$$C_c (T_3 - T_2) = \varepsilon C_{min} (T_{wo} - T_2) \quad (4)$$

Where, for parallel flow heat exchanger the effectiveness (ε) can be given by:

$$\varepsilon = \frac{1 - \exp[-NTU(1 + C)]}{1 + C}$$

The energy balance in the condenser can be given by:

$$m_a C_{pa} (T_6 - T_5) = m_{sw} C_{Psw} (T_2 - T_1) + U_{LC} A_C (T_{avgC} - T_a) \quad (5)$$

Where, and represent the mass flow rates of air and saline water respectively. In the present work their values have been considered to be 0.01 and 0.1kg/s respectively [1].In the condenser, the rate of heat transfer can be expressed as: [1]

$$m_{sw} C_{Psw} (T_2 - T_1) = U_C A_{Con} \left[\frac{(T_6 - T_2) - (T_5 - T_1)}{ln\frac{(T_6 - T_2)}{(T_5 - T_1)}} \right] \quad (6)$$

In Eq. (6), represents the overall heat transfer coefficient in the condenser whose value is assumed to be 45.37 W/m2-K [7] in the present work.

Similarly, the energy balance in the humidifier can be given by:

$$m_a C_{pa}(T_6 - T_5) = m_{sw} C_{Psw}(T_2 - T_1) + U_{LH} A_H \left(T_{avgH} - T_a\right) \quad (7)$$

The mass transfer rate in the humidifier can be represented as: [1]

$$m_a(H_6 - H_5) = K_m a V \left[\frac{(H_3-H_6)-(H_4-H_5)}{ln\frac{(H_3-H_6)}{(H_4-H_5)}}\right] \quad (8)$$

Where, Km denotes the mass transfer coefficient, is the packing area in the humidifier per unit volume and is the volume of the humidifier. In the present work the value of „ ‟ is as-sumed to be 4.2 m2 [7]. In Eq. (8), the term enthalpy (H) can be replaced by:

$$H_3 = C_{Psw}T_3,\ H_4 = C_{Psw}T_4,\ H_5 = C_{Pa}T_5 \quad \text{and} \quad H_6 = C_{Pa}T_6,$$

The empirical relation for mass transfer coefficient (Km) in the humidifier can be given by: [3].

$$K_m = (2.09 m_a{}^{0.11515} m_{sw}{}^{0.45})/a \quad (9)$$

The unknowns T2, T3, T4, T5 and T6 have been calculated by solving equation (4), (5), (6), (7) and (8). The system of equations being non linear, needs to be solved numerically. In the present work, Newton-Raphson method has been used to solve the given set of eq-uations.

The humidity of the saturated air at the top and the bottom of the humidifier is a function of its temperature (T6 and T5) and can be given by the following empirical correlation: [1]

$$\omega_6 = 2.19 \times 10^{-6} T_6{}^3 - 1.85 \times 10^{-4} T_6{}^2 + 7.06 \times 10^{-3} T_6 - 0.077 \quad (10)$$

$$\omega_5 = 2.19 \times 10^{-6} T_5{}^3 - 1.85 \times 10^{-4} T_5{}^2 + 7.06 \times 10^{-3} T_5 - 0.077 \quad (11)$$

The mass flow rate of the desalinated water can be obtained from the mass balance across the condenser considering the difference of specific humidity between the air entering and leaving the condenser as given by:

$$m_f = m_a(\omega_6 - \omega_5) \quad (12)$$

4. Results and Discussion

Computer code in C language has been developed based on the thermal model presented in the earlier section to analyze the performance of the solar collector supported desalination system. The model considers the hourly values of solar radiation intensities and ambient air temperature as input and predicts the mass flow rate of fresh water. In the present work the weather data of Kolkata, as obtained from Regional Meteorological Centre (RMC), Kolkata, for the year 2009 has been used. Fig. 2 shows the variation of production of fresh water with the time of the day for a representative day in summer (15th April) for given values of mass flow rate of saline water and air. It is found that the rate of production of fresh water first increases with the time of the day reaching a maximum value of about 4.2 kg/h at 12 Noon and then again decreases. This means that the rate of production of fresh water heavily depends on the intensity of solar radiation, higher the radiation intensity more is the rate of production of desalinated water.

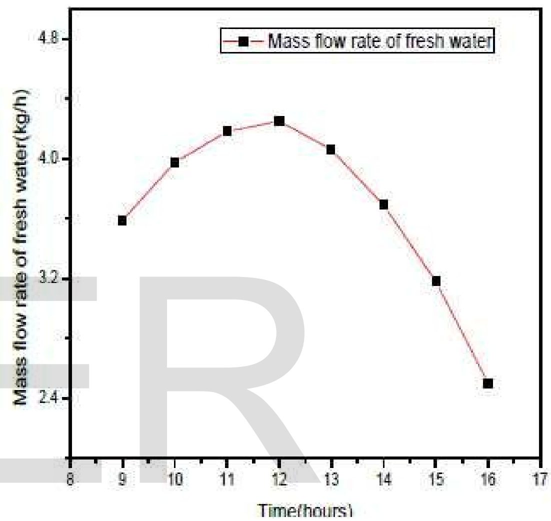

Fig.2: Variation of production rate of fresh water with time of a day

Fig. 3 shows the variation of air and water temperature of the desalination system with the time of the day on 15th April, 2009 for given values of mass flow rate of saline water and air. The temperature of saline water at the inlet of condenser is assumed to be 30◦C throughout the day. As evident from the figure, the water temperature at the outlet of the heat exchanger (T3) is substantially higher than the inlet temperature of saline water (T2) all through the day. Also, it is observed that the variation of the air temperature at the inlet (T5) and exit of the humidifier (T6) with the time of the day is marginal because of the mass exchange with the saline water, while the temperature of water at the exit of the heat exchanger (T3) varies considerably with the time of the day. Figure 3 also reveals that the saline water temperature rises (by about 50C) through the condenser, which is an evidence of the good utilization of the latent heat of condensation of air.

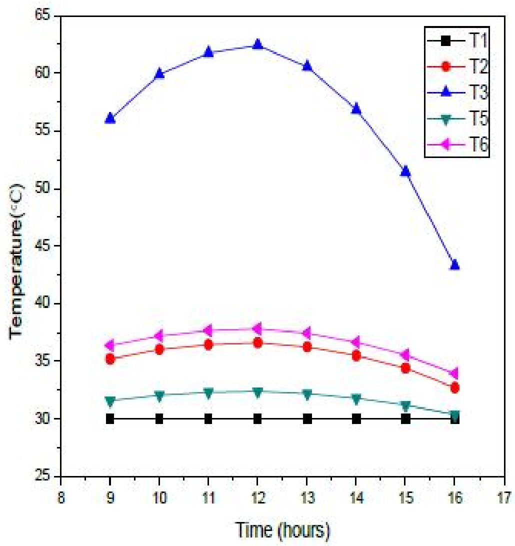

Fig.3: Variation of water and air temperature of desalination system with time of a day

5. Conclusion

A desalination system using solar energy and working under humidification dehumidifica-tion principle has been developed and presented in this paper. It has been concluded that the performance of the desalination system depends considerably on intensity of solar rad-iation, ambient temperature, and the mass flow rate of saline water. The study reveals that substantial quantity of fresh water can be generated by the proposed system. The study thus reinforces the viability of production of fresh water from solar thermal energy for the plains of Gangetic Bengal which receives abundant solar radiation for greater part of a year.

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