Thermal Modelling And Economic Analysis Of Solar Collector Assisted Desalination System With Humidification- Dehumidification

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Abstract - Water is one of the most abundant resources on Earth's surface, covering approximately 75% of the planet. Unfortunately, the majority of this water is saline and unsuitable for human consumption, resulting in an acute shortage of potable water in numerous countries, including India.This paper presents a 'thermal model of a solar collector-assisted desalination system employing humidification-dehumidification.' The study evaluates the payback period of this proposed system, utilizing a solar collector and heat exchanger to consistently supply hot water to the desalination unit. The model is constructed based on various heat and mass transfer equations, and a computer program has been developed using the C language to simulate the proposed system.This program utilizes ambient temperature and solar radiation intensity as inputs to predict the fresh water's mass flow rate obtained through desalination. The system's performance has been analyzed under different climatic conditions, specifically those of Gangetic Bengal in the Indian subcontinent.The study demonstrates that this proposed system, utilizing solar energy for distillation, can generate a significant amount of fresh water.
Keywords: Solar collector, Desalination, Heat exchanger, Humidification-Dehumidification, Solar radiation, Payback period.

1. INTRODUCTION

Water, alongside food and air, stands as a fundamental necessity for humans. Unfortunately, only a relatively small portion of the Earth's water remains naturally safe to drink without purification. Hence, ensuring the purification of water supplies becomes paramount. In remote arid areas of India, fresh water is scarce. This scarcity intensifies in hot climates where solar radiation is high, making solar-powered water desalination a practical solution. Utilizing the humidification-dehumidification technique,solar desalination emerges as a promising technology for producing fresh water. Desalination is the process through which pure water is extracted from saline water, employing various energy forms. The fundamental principle behind the humidification-dehumidification process involves the mixing of air with water vapour. As the temperature rises, the air's capacity to carry vapour increases. When this warm, moistened air encounters saline water, it extracts water vapor, becoming humidified. Subsequently, when this humidified air meets a cooled surface, some vapor condenses, leading to dehumidification and the production of distilled water.

This work aims to present a thermal model and conduct an economic analysis of a desalination system operating on the principle of humidification-dehumidification. The thermal model factors in ambient temperature and solar radiation intensity as inputs, predicting the fresh water's mass flow rate obtained through desalination across different seasons in a complete climatic cycle. The system's performance has been analyzed using the thermal model, examining representative days across various seasons within a complete climatic cycle.

1.1 Literature Review

Nawayseh et al.[1, 2] developed a simulation program in which set of nonlinear equations describing the desalination unit was solved numerically. The results of simulation found to agree with the experimental results for the two different units. They studied the effect of the dehumidifier, humidifier and solar collector surface area on the daily production of desalinated water in the unit. Ben Bacha et al.[3] presented a comprehensive work including modelling, simulation and experimental validation of a solar humidification-dehumidification desalination system. They concluded that with perfect insulation of the unit, high water temperature and flow rate at the entrance of evaporation tower, low temperature of water at the entrance of condenser and hot water recycling by injection at the top of evaporation tower can improve production of system. Muller-Holst et al.[4] described the performance of a humidification-dehumidification desalination system. The system associated with a solar collector. Therefore, for continuous operation of the unit requires the use of a heat storage system. The system is designed for operation in low temperature operation which minimizes the rate of scale formation. Dal and Zhang[5] conduct an experiment on solar desalination unit based on humidification and dehumidification principle. The performance of the system was strongly depending on the temperature of saline water at the inlet of the humidifier, the mass flow rate of saline water, and the mass flow rate of the air. The unit improved the effect of evaporation and overcame the difficulty of increasing the evaporation temperature and decreasing the condensation temperature at the same time by using a falling film humidifier with a large evaporation surface area and forced convection to enhance the heat and mass transfer. Chaibi et al.[6] developed the method to determine the cost effectiveness of the desalination plant by considering the present value method. The present value cost (PVK) can be determined by considering investment cost of plant, personnel cost, maintenance cost and present value factor. Eslamimanesh and Hatamipour[7] presented the economic study of humidification–dehumidification desalination (HDD) pilot plant and estimate the economic benefits of the process in comparison with a small-scale reverse osmosis (RO) system. They proposed that with some theoretical modifications to the HDD system reduced the energy costs of the unit. Al-Hallaj et al.[8] reviewed the solar desalination with humidification dehumidification cycle economically.

2. PROPOSED SYSTEM

The present system was operated using a closed air cycle. Figure 1 shows the configuration of proposed system. Saline water first enters through the condenser coil as a cooling fluid at temperature T_1 preheated and leaves the condenser at temperature T_2 then it passed through the heat exchanger where preheated saline water is heated to a temperature T_3. In the heat exchanger the hot water is coming from the solar collector and relatively cold saline water is coming from the condenser where the preheated saline water is heated. The hot water leaving the heat exchanger 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 T_5) 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. The excess amount of hot brine water is collected at the bottom of the humidifier.

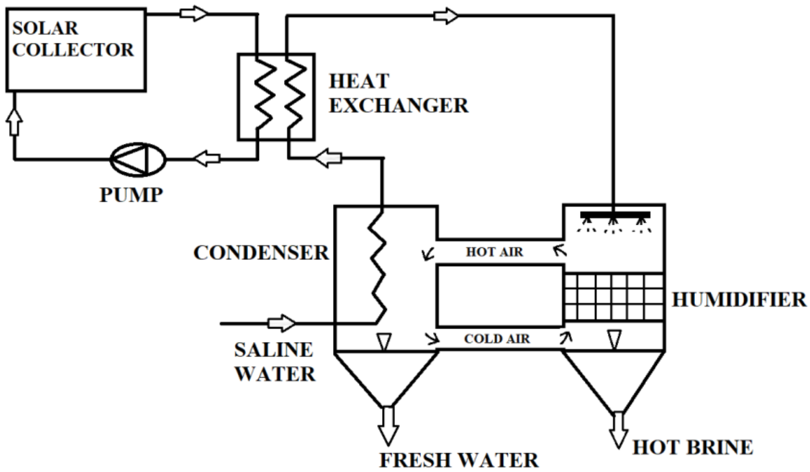

Figure 1 Schematic of water desalination with humidification- dehumidification using solar energy

2.1. Thermal Model

The following assumptions have been made while developing the thermal model:

1. The modeling has been done considering steady state condition.
2. The overall loss coefficients have been assumed to be same for both the humidifier and the condenser[9].
3. Air is assumed to be saturated at the top and bottom of the humidifier.
4. The condenser and the humidifier have been assumed to operate between the same air temperatures.
5. The mass flow rate of the air circulating across the condenser and the humidifier is constant.
6. The water mass flux remains constant throughout the system.
7. The water distribution over the packed bed is uniform.

The proposed system comprises of a flat plate solar collector, a heat exchanger, humidifier and a condenser. The incident solar flux absorbed by the absorber plate can be given by [10]:

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

The useful heat gain rate for the collector that is the rate of heat transfer to the working fluid can be given by:

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

The collector heat removal factor can be expressed as:

$$F_R = \frac{\dot{m}_w c_{Pw}}{U_l A_P}\left[1 - \exp\left\{-\frac{F' U_l A_P}{\dot{m}_w c_{Pw}}\right\}\right] \quad (3)$$

In Eq. (3), 'F'' represents collector efficiency factor, which can be given by the following equation:

$$F' = \frac{1}{W U_l \left[\frac{1}{U_l\left[(W - D_0)\phi + D_0\right]} + \frac{\delta_a}{k_a D_0} + \frac{1}{\pi D_i h_f}\right]} \quad (4)$$

The expression for plate effectiveness (ϕ) can be expressed as:

$$\phi = \frac{\tanh\left[m(W - D_O)/2\right]}{\left[m(W - D_O)/2\right]} \quad (5)$$

Where,

$$m = \left(\frac{U_l}{k_p \delta_p}\right)^{1/2} \quad (6)$$

The temperature of water at the outlet of the collector (T_{wo}) can be obtained from the heat balance across the collector and can be written as:

$$Q_U = \dot{m}_w c_{pw}(T_{wo} - T_{wi}) \quad (7)$$

Thus, from Eq. (2) and Eq. (7), the temperature of water at the outlet of the collector (Two) can be expressed as:

$$T_{wo} = T_{wi} + \frac{F_R A_P\left[\left(S - U_l\left(T_{wi} - T_a\right)\right)\right]}{m_w c_{pw}} \quad (8)$$

The temperature of saline water after flowing through heat exchanger can be found from the following equation:[11]

$$C_{sw}(T_3 - T_2) = \frac{1-\exp[-NTU(1-c)]}{1-c\exp[-NTU(1-c)]} C_{\min}(T_{wo} - T_2) \tag{9}$$

The energy balance in the condenser can be given by:

$$\dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{loss} = 0 \tag{10}$$

$$\dot{m}_a(H_6 - H_5) + \dot{m}_{sw} c_{psw}(T_1 - T_2) - U_{LC} A_C (T_{avgC} - T_a) = 0 \tag{11}$$

In the condenser, the rate of heat transfer can be expressed as:[1]

$$\dot{m}_{sw} c_{psw}(T_2 - T_1) = U_C A_{Con} \left[\frac{(T_6 - T_2) - (T_5 - T_1)}{\ln\left(\frac{T_6 - T_2}{T_5 - T_1}\right)} \right] \tag{12}$$

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

$$\dot{m}_a(H_5 - H_6) + \dot{m}_{sw} c_{psw}(T_3 - T_4) - U_{LH} A_H (T_{avgH} - T_a) = 0 \tag{13}$$

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

$$\dot{m}_a(H_6 - H_5) = K_m a V \left[\frac{(H_3 - H_6) - (H_4 - H_5)}{\ln\left(\frac{H_3 - H_6}{H_4 - H_5}\right)} \right] \tag{14}$$

The empirical relation for mass transfer coefficient (K_m) can be given by [3]:

$$K_m = (2.09 \dot{m}_a^{0.11515} \dot{m}_{sw}^{0.45}) / a \tag{15}$$

The unknowns T_2, T_3, T_4, T_5 and T_6 are calculated by solving equation (9), (11), (12), (13), (14) and (15). Newton-Raphson method has been used to solve the given set of equations.

The specific humidity (ω) of the saturated air at the top and bottom of the humidifier is a function of its temperature and has been given by following empirical correlation [1]:

$$\omega = 2.19 \times 10^{-6} T^3 - 1.85 \times 10^{-4} T^2 + 7.06 \times 10^{-3} T - 0.077 \tag{16}$$

The mass flow rate of the desalinated water (mf) is 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:

$$\dot{m}_f = m_a(\omega_6 - \omega_5) \tag{17}$$

2.2 Model Development for Economic Analysis

The economy of the desalination unit has been analysed by considering the net present value method. The system provided different amount of fresh water for different climatic cycles. In the present work, the discounted payback period was employed to find out how long the desalination unit payback the invested money.The discounted value of money has been considered for evaluating the payback period in the present model.

The cumulative savings over a period of n years for the desalination system is obtained by summing the present worth of the annual income, subtracting the initial down payment on desalination system and subtracting the initial investment on desalination plant (other than loan amount). The cumulative savings over a period of n years for the desalination system has been given by: [10]

$$CS = c_{fw} \sum_{j=1}^{n} \frac{(1+i_{fw})^{j-1}}{(1+d)^{j}} - \frac{d_l f_l C}{\left[1-\left\{1/(1+d_l)^{n_l}\right\}\right]} \sum_{j=1}^{n_l} \frac{1}{(1+d)^{j}} - M \sum_{j=1}^{n} \frac{(1+i_m)^{j-1}}{(1+d)^{j}} - (1-f_l)C \quad (18)$$

On summing the progressions, the following equation deduced:

$$CS = \frac{c_{fw}}{(d-i_{fw})}\left[1-\left(\frac{1+i_{fw}}{1+d}\right)^{n}\right] - \frac{d_l f_l C}{\left[1-\left\{1/(1+d_l)^{n_l}\right\}\right]} \frac{1}{d}\left[1-\frac{1}{(1+d)^{n_l}}\right] - \frac{M}{(d-i_m)}\left[1-\left(\frac{1+i_m}{1+d}\right)^{n}\right] - (1-f_l)C \quad (19)$$

The main factors that affect the economic viability of desalination system by humidification-dehumidification process includes fixed capital (mainly costs of equipment) and running cost (mainly energy and maintenance cost).

The desalination unit has been produced up to an average 811 L of fresh water per month. The operation time for system is considered to be 8 hours per day so the annual fresh water production could be up to 9726 L. The system does not have any moving parts and excessive pressure drop; it is assumed the life of the system is 20 years.

The Capital cost of the desalination unit is given in table 1. The capital cost mainly includes the cost of major equipment and miscellaneous cost. The miscellaneous cost includes cost of piping, installation and insulation.

Table 1: Capital and Running cost for desalination unit

Capital cost	**Quantity**	**Unit Cost (Rs)**	**Total Cost (Rs)**	**Running cost**	
Equipment	1(Capacity 400L/day)	80000	80000	Energy consumption(kWh/yr)	3096
Heat Exchanger	1	18000	18000	Energy cost (Rs/yr)	15480
Desalination Column (Humidifier and The Condenser)	1	71000	71000	Maintenance cost (Rs/yr	4018
Pump	2	2950	5900	Total running cost (Rs/yr)	19498
Water tank	3	1500	4500		
Miscellaneous	-	-	21460		
Total capital cost(Rs)	200860				

The running cost of the system is the cost of operating and maintaining the system during life of the system. The operating cost mainly includes the cost based on the consumption of energy of the desalination system. The energy is provided free from the Sun but there is additional energy cost for the electricity consumed by the pumps. In the present work, the cost of electricity considered to be Rs 5 per kWh and maintenance cost was assumed to be 2% of total capital cost.

Table 2: Economic Parameters used in the analysis of Payback period

Economic Parameters	Values
Source of finance	Long term loan
Discount rate (d), %	10
Fraction of capital cost taken as loan(f_l)	0.8
Interest rate on loan(d_l), %	10
Rate at which the cost of fresh water increased every year (i_{fw}),%	5
Interest rate on maintenance cost(i_m) ,%	5
Number of years for repayment of loan in equal annual instalment (n_l)	10
Life span of desalination unit(n), years	20
Water selling price (Rs/L)	5

3. RESULTS AND DISCUSSION

3.1 Performance Analysis of proposed system

Computer code in the 'C' language has been developed to analyze the system's performance based on the thermal model discussed earlier. This model incorporates hourly values of solar radiation intensities and ambient air temperature as inputs to predict the mass flow rate of fresh water. For this study, the weather data from Kolkata in the year 2009 has been utilized [12].

Figure 2 depicts the temperature variation of saline water at the humidifier inlet throughout June, September, and December 2009, considering specific values for the saline water mass flow rate (m_{sw}=36Kg/h) and air (m_a=360Kg/h). During most parts of the day, the inlet temperature in June tends to be higher than in September and December, primarily due to a higher solar radiation intensity.

Interestingly, at noon, the September inlet temperature surpasses that of June, despite June having higher solar radiation intensity throughout the day. This observation is attributed to a higher radiation tilt factor in September, amplifying the incident solar flux absorbed by the collector plate, thereby leading to a higher water temperature at the collector outlet compared to June.

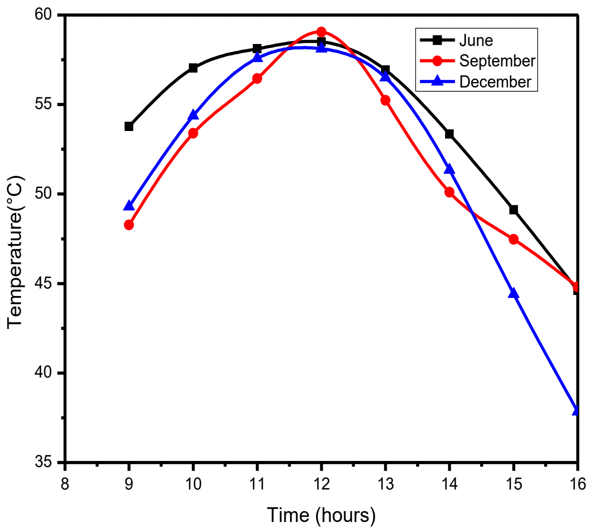

Figure 2 Variation of temperature of saline water at the inlet of humidifier with time of the day in month of June, September and December

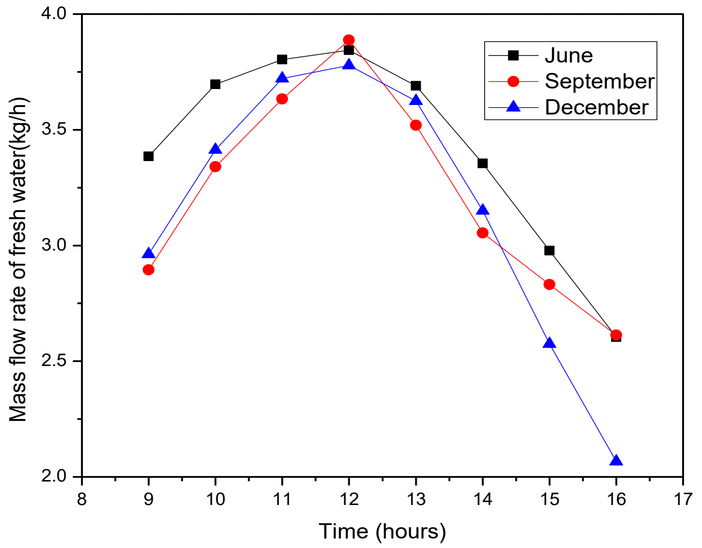

Figure 3 Variation of production rate of fresh water with time of the day in month of June, September and December

Figure 3 displays the variation in desalinated water production rates throughout June, September, and December 2009, considering specific values for the mass flow rates of saline water (m_{sw}=36Kg/h) and air (m_a=360Kg/h). An observation reveals that the hourly mass flow rate of desalinated water in June exceeds that of September and December, primarily due to the higher intensity of solar radiation during June.

Furthermore, it's evident from the figure that the peak value of fresh water mass flow rate reaches 3.9Kg/h specifically in September.

Figure 4 illustrates the impact of saline water temperature at the humidifier inlet on the fresh water production rate specifically in December 2009. The graph depicts a linear relationship between the production rate of distilled water and the temperature of the saline water at the humidifier inlet (T_3).

This correlation suggests that the rise in saline water temperature at the humidifier entrance leads to an increased vaporization of water. This phenomenon occurs because the vapor-holding capacity of air largely depends on the saturation pressure, which elevates with higher temperatures. Consequently, air can accommodate more vapor at increased temperatures, resulting in a higher production rate of fresh water

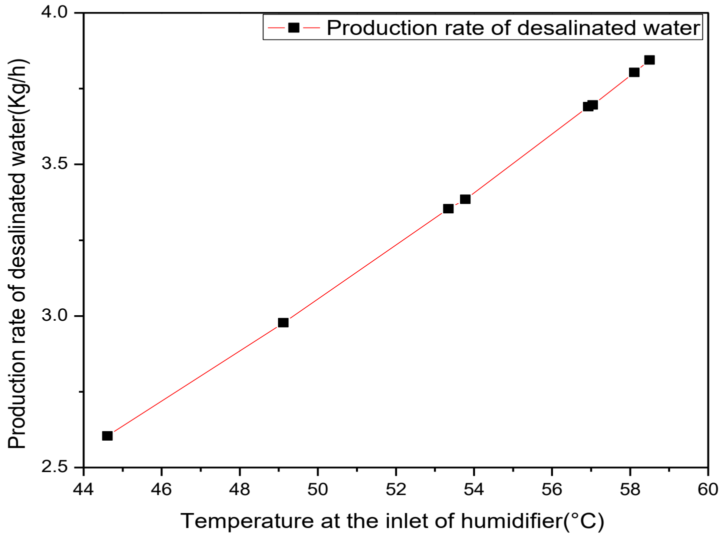

Figure 4 Effect of saline water temperature at the inlet of the humidifier on the production rate of fresh water

3.2 Economic Analysis of proposed system

The calculation of cumulative savings (CS) from one year to next has been done by substituting the value of 'n' ranging from 1 to 20 in Eq. (19). The variation of cumulative savings with number of years is shown in figure 5. It can be seen that the value of cumulative savings is negative from start and increases from first to ninth year and becomes positive at the end of tenth year then increases steadily and attains the value of Rs 108680 after 20 years. The results also indicate that by investing in the given desalination system save Rs 108680 in today's rupees value over a time period of 20 years.

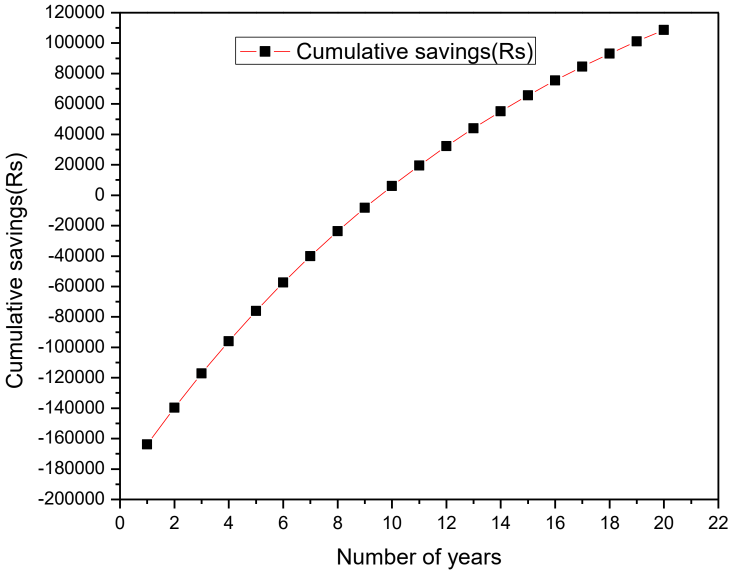

Figure 5 Variation of cumulative savings (CS) with number of years

4. CONCLUSIONS

This paper presents a desalination system utilizing solar energy and operating on the principle of humidification- dehumidification. Alongside the system's development, an economic analysis has been conducted and outlined herein.

The study concludes that the desalination system's performance is significantly influenced by solar radiation intensity, ambient temperature, and the mass flow rate of saline water. Notably, the research demonstrates the potential of generating a substantial quantity of fresh water through this proposed system.

Economic analysis results indicate an estimated payback period of approximately nine years for the proposed system. To decrease this payback period, enhancements in fresh water production, as well as reductions in both the capital and operational costs of the system, are recommended.

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.

Abbreviations

S	Incident flux absorbed in the absorber plate, W/m^2
I_b	Intensity of solar radiation for beam radiation, W/m2
I_d	Intensity of solar radiation for diffused radiation, W/m2
R_b, R_d, R_r	Radiation tilt factors for beam, diffused and reflected radiation
F_R	Collector heat- removal factor
A_p	Area of absorber plate, m^2
A_{Con}	Internal area of condenser, m2

A_H	External area of humidifier, m^2
a	Packing area in the humidifier per unit volume, m^2/m^3
V	Volume of humidifier, m^3
K_m	Mass transfer coefficient, kg/s-m^2
H	Enthalpy, J/kg
U_l	Overall loss coefficient across collector, W/m^2-K
τ	Transmissivity
α	Absorptivity
ϕ	Absorber plate effectiveness
C_{fw}	Total revenue earned in a year, Rs

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