

Performance Analysis of Solar Desalination System for Improved Productivity by using Waste Heat of Household Chimney



Taranjeet Sachdev, Vivek Kumar Gaba, Anil Kr Tiwari

Abstract: This work deals with the analysis of the proposed innovative humidification-dehumidification (HD) desalination unit in which waste hot air of kitchen chimney has been used for heating brackish water. The proposed system is configured with solar air heater also, thus both heated air and heated water has been used to improve the water yield of desalination unit compared to conventional system. Mathematical modeling of propose unit based on energy balance of flat plate air heater, humidifier, dehumidifier and brackish water tank has been used to evaluate the effect of operating condition. Potable water yield found to increase (with highest productivity of 6.5 kg/day) when mass flow rate of process air increases from 0.6 kg/min to 3 kg/min. Strong dependency of water mass flow rate has also been found as productivity increases (with maximum value of 6.7 kg/day and 7.5 kg/day) by increasing the mass flow rate of brackish water in humidifier and cold water in dehumidifier respectively. The higher initial temperature of brackish water also found beneficial as it increases productivity. Finally, the thermal performance of desalination unit has been evaluated in terms of Gain in Output Ratio and comparison has been made with conventional system. The higher GOR of the proposed system ensures the better utilization of thermal energy in potable water production.

Keyword: air heater, desalination, dehumidification, heat transfer, humidification, solar energy.

I. INTRODUCTION

Nature has blessed mankind with many blessings to survive on earth. Solar energy and seawater are such two resources which can help to face water crisis arise due to surge in industrialization and growth in population. Many desalination techniques are available to convert the huge resource of saline

water into potable water but most are facing the problem of high energy requirement. Humidification dehumidification (HD) desalination system has emerged as simple yet effective technique for potable water production with characteristics to easily couple with solar energy for thermal energy requirements. The improved devices for utilization of solar energy and innovation in system design can play an important role in productivity enhancement of HD desalination systems. This work presents the performance analysis of an innovative solar HD unit that uses the waste hot air of household kitchen chimney for heating water before supplying it to the humidifier whereas process air has been heated by flat plate solar air heater. Thus proposed system utilizes the fact that increased air and water temperature increases the moisture absorbing capacity of air which finally turns into higher yield of potable water.

Many studies and innovations have been done to enhance the productivity of systems working on HD principle. Bourouni et al. and Ettony et al. [1] - [3] presented the state of art of HD desalination system and evaluated the scope of renewable energy in potable water production. Cemil et al. [4] analyzed the performance of the solar humidification dehumidification unit to find the key parameters and their effect on water yield. Tiwari et al. [5] numerically evaluated the performance of solar HD system to find the optimum rate of air and water flow in the system. Mohamed et al.[6] investigated solar HD sytem with the help of experimental setup and productivity found to 25 % more in theoretical analysis compared to experimental results.

Hamed et al. [7] performed an experiment to study the solar HD unit equipped with water heater which found beneficial with productivity of 22 L. Zubair et al. [8] presented performance and cost analysis of solar-driven HD unit at multi locations of Saudi Arabia with maximum productivity of about 20000 L. Xin [9] investigated the influence of mass flow rate ratio on energy consumption of the HD unit and presented the graphical method to find the optimum value of operating parameters method.

Zhani [10] performed an experimental analysis of new solar desalination working on humidification dehumidification principle. The HD unit was designed and fabricated to perform an experimental study under different operating conditions. An economic study was also conducted, to determine the cost of potable water and payback period. Sachdev et al. [11]

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performed mathematical analysis to identify the performance of solar HD system using waste heat of air-conditioners in climatic conditions of coastal areas. The effect of various operating and design parameters on productivity has been studied.

The aim of the present work is to analyze the proposed innovative solar humidification-dehumidification desalination unit with the help of mathematical modeling to find suitable air and water mass flow rate. The proposed system uses waste hot air of kitchen chimney of restaurant for heating waste water. The effect of key system parameters on productivity has been analyzed and thermal performance of the proposed system has been evaluated in terms of GOR.

II. DESCRIPTION OF PROPOSED SYSTEM

Figure 1 shows the schematic arrangement of proposed system using waste heat of kitchen chimney for heating the waste water before spraying it on the process air for humidification. The proposed system is configured with flat plate solar air heater, humidifier, condenser (dehumidifier), and brackish water storage tank. The storage tank has been designed with internal tubes and hot air from kitchen chimney passes through these tubes. These tubes are surrounded by the brackish water so that water may be heated by waste hot air. Proposed system is equipped with blower and water pump to control the flow of air and water in the system.

During operation, initially the ambient air enters in the solar air heater so that it can gain temperature with the help of thermal energy of sun. The fact that higher temperature of air results in increase of moisture carrying capacity of air has been utilized here to improve the performance HD unit. This heated air then passes through the humidifier and here, brackish water is sprayed from the upper portion of humidifier so that air may enrich with moisture. The brackish water is supplied from the storage tank which allows the hot air from chimney without mixing with water. However, due to heat transfer that takes place between air and water in storage tank water temperature increases before entering in humidifier. The required flow rate of brackish water has been maintained with the help of pump positioned at the exit of storage tank.

After humidifier, the moisture enriched air now passes through the dehumidifier. In dehumidifier, cooling water flows through the bundle of pipes that are surrounded by moisture-laden air. The moisture condenses over the surface of pipes and potable water can be collected and supplied to storage from dehumidifier. The fan provided at the outlet of dehumidifier ensures the proper flow of air throughout the system.

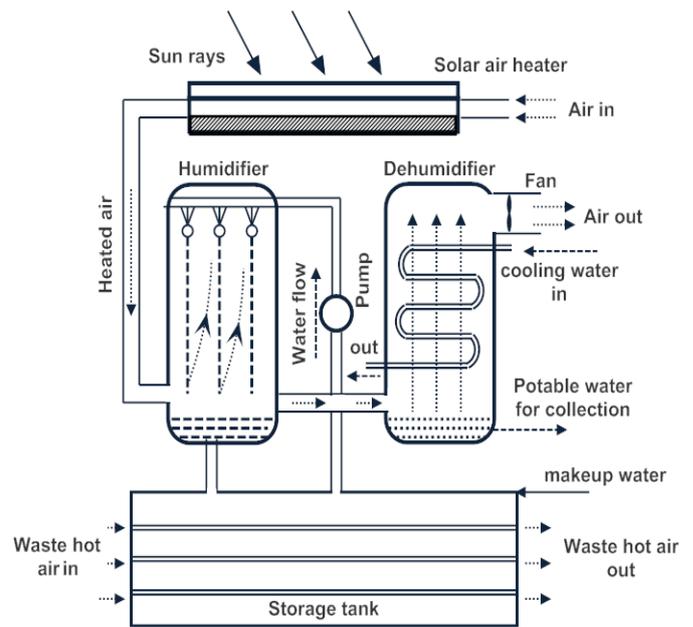


Fig.1. Proposed solar desalination system

III. MATHEMATICAL MODEL

The performance of the proposed desalination unit can be analyzed by considering energy balance and mass conservation of system components so that air and water temperature can be calculated at key states. Finally, productivity can be calculated by mass balance in dehumidifier. The energy balance equations for air heater parts involve the energy interactions (E) between glass cover (g), air (a), absorber plate (p), base plate (b) and ambient or sky.

Glass cover

$$m_g \cdot C_g \frac{dT_g}{dt} = E_g + E_{p/g} - E_{g/amb} - E_{g/sky} + E_{g/a} \quad (1)$$

Air

$$m_a C_a \frac{dT_a}{dt} = E_{air} + E_{p/a} + E_{g/a} - M_a C_a (T_{ao} - T_{ai}) \quad (2)$$

Absorber plate

$$m_p \cdot C_p \frac{dT_p}{dt} = E_p - E_{p/a} - E_{p/g} - E_{p/b} \quad (3)$$

Base plate

$$m_b \cdot C_b \frac{dT_b}{dt} = E_{p/b} - E_{b/a} - E_{b/surr} \quad (4)$$

Energy balance of water storage tank

$$m_{w1} C_w \frac{dT_{w1}}{dt} = M_{w2} C_w T_{w2} + M_{mw} C_w T_{mw} - M_{w1} C_w T_{w1} - E_{w1/amb} \quad (5)$$

Energy balance of humidifier

$$m_a (h_{a3} - h_{a2}) = M_{w,in} C_w T_{w1} - M_{w,out} C_w T_{w2} \quad (6)$$

Energy balance equation of De-humidifier

$$m_a(h'_{a3} - h'_{a4}) = M_{w3} C_w(T_{w4} - T_{w3}) + M_c C_w T_{w5} \quad (7)$$

Mass balance (water) equation for humidifier

$$M_{w,out} + M_a W_3 = M_{w,in} + M_a W_1 \quad (8)$$

Productivity of potable water from the desalination system (P_w) is equal to rate of condensation of moisture in dehumidifier

$$P_w = M_a(W_3 - W_4) \quad (9)$$

The various heat interaction terms in equations 1-5 can be calculated by relations mentioned below [12]-[15]-

$$E_{g/amb(conv)} = A_c (2.8 + 3V_i)(T_g - T_{amb}) \quad (10)$$

$$E_{g/sky} = A_c \epsilon_g \sigma (T_g^2 + T_{sky}^2) (T_g + T_{sky})(T_g - T_{sky}) \quad (11)$$

$$E_{g/air} = A_c N u_{g/a1} \frac{K_a}{D_h} (T_g - T_{a1}) \quad (12)$$

$$E_{p/g} = (A_c) \frac{\sigma(T_g^2 + T_p^2)(T_g + T_p)}{\frac{1}{\epsilon_g} + \frac{1}{\epsilon_p} - 1} (T_g - T_p) \quad (13)$$

$$E_{p/a} = A_c h_{p/a} (T_p - T_a) \quad (14)$$

$$E_{p/b} = (wl) \frac{\sigma(T_p^2 + T_b^2)(T_p + T_b)}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_b} - 1} (T_p - T_b) \quad (15)$$

$$E_{b/a} = A_c h_{b/a} (T_b - T_a) \quad (16)$$

To measure the utilization of thermal energy in HD desalination unit the Gain in Output Ratio can be calculated by

$$GOR = \frac{M_{fw} \cdot h_{fg}}{Q_{in}} \quad (17)$$

Where, M_{fw} = Rate of condensation of moisture.

h_{fg} = Latent heat of vaporization

Q_{in} = Rate of heat supply

The input values used for simulation are listed in Table. I

Table I. Input values for simulation

Parameter	Value
Width of absorber plate	1m
Thickness of glass cover	3 mm
Tilt angle of collector	30 degree
emissivity of absorbing plate	0.9
emissivity of glass cover	0.88
emissivity of bottom plate	0.9
thickness of insulator	0.05 m
Heat conductivity of insulator	0.045 W/m-K
Size of humidifier	60 cm x 40cm x 50 cm
Size of dehumidifier	50 cm x 40cm x 40 cm
Storage tank capacity	500 L

Fan	Seep size 25 cm, 30 W
Pump	220 V , 40 W, 10L/min

IV. RESULTS AND DISCUSSION

Mathematical model of the proposed unit has been simulated in MATLAB to study the effect of important operating parameters on productivity and results are shown in Fig. 2 to Fig. 6.

Fig. 2 reveals the effect of air mass flow rate on productivity of proposed unit. It is clear from Fig. 2 that productivity increases from 0.9 kg/day to 6.5 kg /day as mass flow rate of air increases in range 0.5 kg/min - 1.9 kg/min. However, this increase has been enjoyed only up to airflow rate of 1.9 kg/min as thereafter productivity was found to decrease. This decreasing nature of productivity with air mass flow rate is due to decreased retention time of air in flat plate heater which causes reduced outlet temperature, thus ultimately water production decreases. The productivity of proposed unit has been found 20% - 30% higher compared to conventional unit.

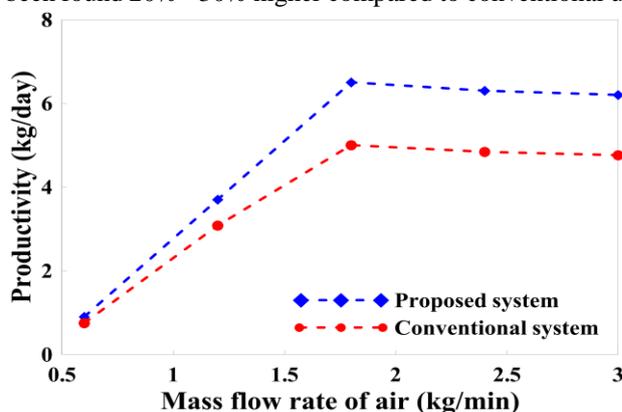


Fig. 2. Effect of mass flow rate of air on productivity

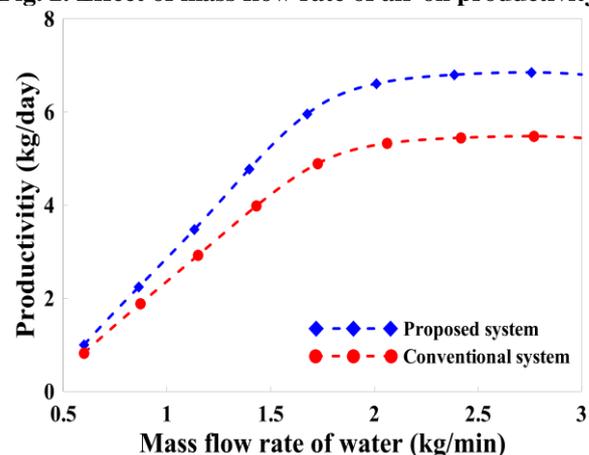


Fig. 3. Effect of mass flow rate of brackish water in humidifier on productivity

Fig. 3 shows the effect of mass flow rate of brackish water in humidifier. The increase in flow rate of water found to be beneficial as productivity increases from 0.8 kg/day to 6.7 kg/day when mass flow rate of water increases from 0.5 kg/min to 3 kg/min. Increase in water mass flow rate provides the conditions in which air can absorb more amount of moisture which ultimately results in higher yield. Fig.4 shows the effect of mass flow rate of cooling water on potable water yield.

Increase in mass flow rate of cooling water has shown positive influence on productivity. The productivity of proposed unit has been found 22% - 25% higher compared to conventional unit.

It is clear from Fig. 4 that productivity increases from 0.9 kg/day to 7.5 kg/day when mass flow rate increases in range 0.5 kg/min - 3 kg/min. This increase in productivity is due to reason that higher flow rate of cooling water results in more condensation of moisture as potable water over the tube surface thus yield increases. The productivity of proposed unit has been found 25% - 31% higher compared to conventional unit.

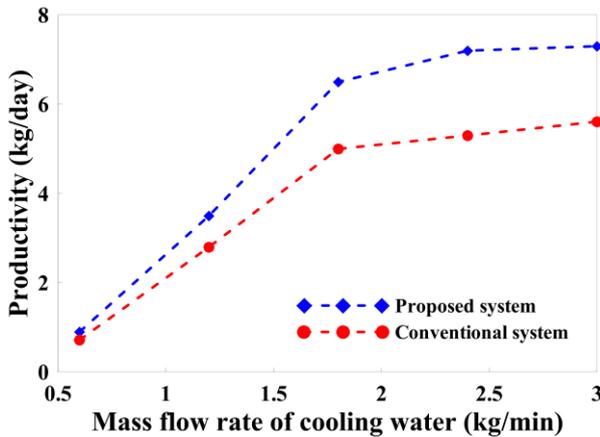


Fig. 4. Effect of mass flow rate of cooling water on productivity

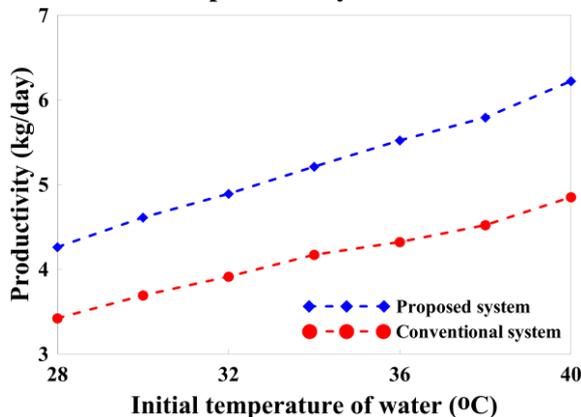


Fig. 5. Effect of initial temperature of water

It is clear from Fig. 5 that productivity increases from 4 kg/day to 6.5 kg/day when initial temperature of brackish water increases from 28 °C to 40 C. This increase in productivity is due to fact that higher initial temperature of brackish water enhances the moisture absorbing capacity of air which ultimately leads to higher yield of water. The productivity of proposed unit has been found 25% - 28% higher compared to conventional unit.

Finally, the advantage of using hot air from kitchen chimney has been studied by Gain in Output Ratio (GOR) values and shown in Fig. 6. It can be observed that increased temperature of brackish water by the waste hot air leads to improve the thermal performance of desalination unit. The GOR of proposed unit is 70% higher than the conventional HD unit.

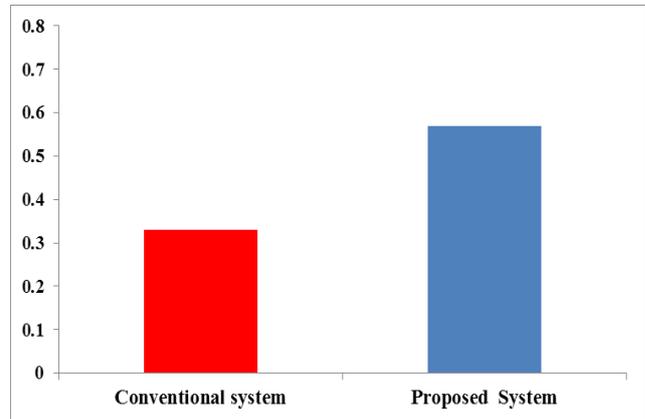


Fig. 6. Comparison of Gain in output ratio

V. CONCLUSION

Proposed solar HD desalination unit has been analyzed for water yield variation with mass flow rate of process air, mass flow rate of brackish water, cooling water and initial temperature of brackish water. Results are proved the benefit of using hot air from chimney for heating water and summarized below-

- The increase in air mass flow rate in desalination unit found beneficial with optimum mass flow rate around 2 kg/min and water yield of 6.5 kg/day.
- The increase in mass flow rate of brackish water in humidifier has shown positive influence on productivity with an optimum flow rate of 1.9 kg/min
- The increase in flow rate of dehumidifier water increases the water yield up to 7 kg/day when mass flow rate ranges between 0.5 kg/min - 7 kg/min.
- The productivity of proposed system increases by 55% when initial temperature of brackish water increases by 12 °C.
- The thermal performance of desalination unit improves by 70 % with the use of waste hot air of the chimney.

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