Received: 28 June 2019 | Revised: 20 September 2019 | Accepted: 23 September 2019
DOI: 10.1002/er.4931

RESEARCH ARTICLE

WILEY INTERNATIONAL JOURNAL OF ENERGY RESEARCH

Theoretical and experimental investigation of bubble column humidification and thermoelectric cooler dehumidification water desalination system

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Summary

The desalination of adulterated water for potable water is very important and in-demand because of the scarcity of the potable water. The bubble column (BC)–type humidification-dehumidification (HDH) desalination systems have shown promising results for low quantum need of fresh water. The present work consists of bubbler humidifier for increasing the humidity of atmospheric air and thermoelectric cooling (TEC) modules for the dehumidification of the humidified air. The air and water have been heated through external device for the sake of performance enhancement. The work of the proposed HDH system has been assessed experimentally as well as theoretically in order to identify the impact of system operational parameters like temperature of air and water, diameter of hole on the periphery of circling tube, height of hot water column, and the air mass flow rate on the production of fresh water. The daily distillate production achieved during the investigation was in the range of 7 to 13 L/d for different operational parameters although the best experimental productivity of the system was reported 12.96 L/d for 2 mm of hole diameter, 0.016 kg/s of air mass flow rate, 60°C of temperature of water, 27°C of temperature of air, and 7 cm of water column height in the humidifier. The gained output ratio of the system was 0.8 for 0.016 kg/s of mass flow rate of air. A theoretical model of the system is also proposed, and results of model are validated against experimental results, which have shown the great agreement.

Nomenclature Notation: A, water area, m^2; a_s, specific surface area, 1/m; C_p, specific heat, J/kg K; D, diameter, m; d_o, diameter of hole on spiral tube, mm; D_{AB}, diffusion coefficient, m^2/s; G, gravitational acceleration, m/s^2; h, specific enthalpy, J/kg; h_{fg}, latent heat of evaporation, J/kg; h_t, heat transfer coefficient, W/m^2 K; I, current, A; j, mass flux, kg m^{-2} s^{-1}; K_l, mass transfer coefficient, m/s; K, module thermal conductance, W/K; Le, Lewis factor; P, power, W; Q, heat transfer, J; q, heat transfer rate, W; Q_{total}, total heat pumped from cold side of TEC modules, J; R, module resistance, Ω; T, temperature, °C; t, surface renewal time, s; t_f, bubble residence time, s; V_g, air superficial velocity, m/s; V_c, liquid circulation velocity, m/s; V_b, bubble velocity, m/s; V, volume of bubble column, m^3; W, specific humidity, kg/kg of dry air; x, mass flow rate, kg/s; z, height of water column in humidifier, cm

Greek letters: ε, void fraction; P, density, kg/m^3; σ, surface tension of water, N/m; α, Seebeck coefficient, V/K

Subscript: 1, air at humidifier inlet; 2, air at humidifier outlet (dehumidifier inlet); 3, air at dehumidifier outlet; a, air; b, bubble; c, cold side; D, dew point; h, hot side; i, inlet; lat, latent; max, maximum; o, outlet; sat, saturation; st, stored; sen, sensible; w, water

Abbreviations: BF, bypass factor; COP, coefficient of performance; HDH, humidification-dehumidification; GOR, gained output ratio; TEC, thermoelectric cooler; BC, bubble column; ST, shell and tube

KEYWORDS
bubble column, desalination, HDH, humidification-dehumidification, thermoelectric cooler

1 | INTRODUCTION

The most critical issues faced by human beings are shortage of potable water, escalating energy demand, and global warming. The matter is severe in the developing countries because of higher population and incompetent exposure to technology. Pure water demand hikes with the world populations, which is assumed to be around 6899 billion m^3 by the year 2029.[1] The current global clean water accessibility is around 4200 billion m^3 that is far beneath the actual requirements. Water is the one of the prime constituents on the earth and available in abundant amount.[2] Merely 2.5% of entire water reserve of the earth is fresh, and the remnant 97.5% is the brackish water.[1] Out of that 2.5%, a large share is inaccessible because of being frozen in polar region. Additionally, a significant part of the mankind has no availability of potable water.[3] There are several approaches accessible for purification of unsanitary solutions, namely, humidification-dehumidification (HDH) distillation, mechanical vapour squeezing distillation, multiple effect desalination, multiple stage flash desalination, reverse osmosis (RO), and electrodialysis reversal.[2] Except HDH, the cost linked with energy utilization of all above methods is huge and also has atmospheric issues because of the usage of nonrenewable fuels.[4] The impurities lying in the water can be removed through the solar desalination system.[4]

Among available methods, HDH desalination is very promising means for small-scale water requirements.[5] The HDH systems have many advantages like simple and adaptable nature, beneficial easy finances, and capability to utilize low-grade energy like waste heat[6] and solar energy. Therefore, HDH system can be ordained for recovering waste heat from thermal systems by direct or indirect means (by using the electric power generated through thermoelectric cooler [TEC] modules).[7] The arrangement contains a humidification chamber, a dehumidification chamber, and a heat supply.[8] The decent regulation makes HDH apparatus much more preferable over solar still.[9] Current HDH technology exhibits lower yield[10] and needs performance enhancement measures for the high capacity distillate generation.

Deckwer in 1979 introduced a notion of heat transfer through bubble column (BC).[11] Deckwer theoretically established a heat transfer expression for the control volume composing of bubbles.[11] An innovative plan for the HDH systems to be used for distillation of saline water was proposed by Narayan and Lienhard[12]; the study presented enhanced heat balance and BC dehumidifier performance. Another similar research proposed a novel BC vapour–gas dehumidifier for condensation of vapour in the presence of a large percentage of noncondensable gas.[13] Liu and Sharqawy[14] experimentally investigated HDH desalination technique. They observed that pressure, temperature of air and water, and air velocity have significant effect on the performance of HDH system. They have also found that performing the humidifier below the environmental pressure and the dehumidifier at elevated pressure results in greater energy transfer rate and efficiency of the HDH system.

Rajaseenivasan et al[15] analytically investigated the HDH water distillation system. They have used solar energy for air heating. They observed that specific humidity and system productivity are increased with increasing mass flow rate of air and water, temperature of air, and temperature of water. Also, solar energy has powerful effect on the performance of HDH system. In an ongoing investigation, Rajaseenivasan and Srithar[5] used biomass stove as energy source in HDH desalination system. They have found that performance of humidifier and HDH system is increased with height of water column, water and air flow rate, and temperature of air and water and decreased with hole diameter. Srithar and Rajaseenivasan[16] represented HDH distillation arrangement using energy from solar. They have analyzed that HDH system productivity is directly proportional to air mass slow rate and air and water temperature. They also observed that existence of solar air heater with turbulators increased the system productively.

Various researchers have performed experimentation and theoretical investigations upon the HDH desalination systems in order to evaluate the productivity of diverse system configurations and designs. Xiong et al[17] formulated a theoretical model for a desalination system consisting of shell and tube (ST)–type heat exchangers exhibiting the HDH processes in thermally appended chambers. As a part of the model study, the coefficient of mass transfer during the process of humidification along with total coefficient of heat transfer during the HDH process was elaborated and compared with the experimental observations.

With the aim of evaluating the impact of diverse operating conditions on HDH desalination system attached to double pass solar air heater, Yamali and Solmuş[18] conducted a theoretical study. They have theoretically investigated the influence of different parameters of system, different types of air heaters, and condition of weather on the performance of HDH system by using MATLAB software. They have found that productivity of fresh water is hiked by raising mass flow rate of air and water in humidifier. The arrangement with double pass air heater exhibited 8% and 30% higher productivity as analyzed to the system with one pass air heater and without air heater, respectively. Kabeel and El-Said[19] performed a numerical analysis of HDH system with water flashing arrangement. The study indicated that the air HDH unit and flash evaporation unit to be significantly compatible for exhibiting the maximum yield of HDH system.

As a pioneer work in the field, Garg et al[20] experimentally analyzed the design of multieffect HDH distillation system along with a computer simulation model, which is very useful for the estimation of desalinated yield and the optimization of various system configurations. Yamali and Solmus[21] executed a comparative study on the solar-based HDH desalination process for theoretical and experimental performance with different system configurations and operating conditions. The study pointed that the use of double pass air heater boosts the productivity by 5%. Zhani and Ben Bacha[22] proposed a novel design of an HDH desalination system and conducted experimentation over the test setup consisted of a solar air heating device, a water heater, a humidification chamber, an evaporating compartment, and a condenser. The outcomes presented that the yield of the system enhances at greater solar radiation. Vivek et al[23] experimentally and theoretically investigated the bubbler humidifier for HDH system. They have analyzed that relative humidity (RH) at the outlet of the system is exactly comparable with water column height in the humidifier, air mass slow rate, and temperature of air and water and inversely proportional to diameter of hole on the periphery of tube.

TECs consist of N-type and P-type semiconductor material joined electrically in series. When direct current (DC) is moved through the TEC, difference of temperature develops because of Peltier effect. TECs are very small in size, quiet, free from maintenance, and reliable. They do not require to chlorofluorocarbon (CFC) or any other refrigerant gases. Because of these advantages, TECs are used for many refrigeration-related applications. Basic insight and the analysis of TECs are explained by Riffat and Ma.[24,25]

Vian et al[26] explored the performance of a prototype TEC-based dehumidifier. They have studied the optimization of the TECs and supply voltage of fan and calculated the coefficient of performance (COP) of the system and flow rate of condensed water. They concluded that TECs may have powerful potential in the use of dehumidification systems. Milani et al[27] explored the feasibility of a TEC-based dehumidifier to yield clean water from atmospheric moisture. They have correlated psychrometric parameters of the system by developing algorithm and calculated the production of fresh water, needed energy, and fresh water production cost. Esfahani et al[28] investigated a novel TEC-based portable solar desalination system. Portable parabolic collector is used for water heating and evaporated in a coated evaporation zone. The TEC modules are used as a dehumidifier. They noticed that the fresh water production is hiked with atmospheric temperature and solar radiation. However, the fresh water yield of the system is negatively affected by increasing wind speed. Rahbar and Esfahani[29] tested a new handy desalination system with a TEC and a heat pipe. The condensation of air is done by TEC. Yıldırım et al experimentally investigated a TEC-based portable desalination unit.[30] The power utilization of the system was 110.26 W, and the maximum daily fresh water production was 748 mL/m^2. Dehghan et al linked a TEC module with novel handy solar still to raise the difference of temperature between evaporation and condensation zones.[31] The daily fresh water production was 2.4 L/m^2/d.

From the literature survey, it is analyzed that the productivity of HDH system is greatly influenced by the performance of humidifier and it is possible to achieve humidity of the air near to saturation condition. Bubbler humidifier offers higher energy and mass exchange rate compared with other kinds of humidifiers at low cost. In almost all HDH systems, the ST types of heat exchangers are used as a dehumidifier. But ST type of heat exchangers has very high maintenance cost because of scaling and circulation of external cooling water, occupies very large space, and is suitable for large capacity plant only. Hence, it is difficult to produce fresh water at low cost with ST-type heat exchanger. So, to overcome the disadvantages related to ST type of heat exchanger, solar-operated TEC can be used for the dehumidification of air for small-scale systems. From the literature survey, a novelty is found to make use of BC in humidifier section and the arrangement of TEC modules in the dehumidifier section. Also, bubbler humidifier and TEC-based dehumidifier have not been investigated altogether experimentally and theoretically so far for water desalination.

With the aim of fling the aforementioned research gap, the experimental and theoretical investigation has been conducted on BC-type humidification and TEC-based dehumidification water desalination system. A new design of BC humidifier has been selected to improve air humidification by improving the energy and mass exchange rate between air and water column. The TEC run by solar energy has been used as dehumidifier. The theoretical model of bubbler humidifier for air humidification and TEC-based dehumidifier has been proposed to investigate the system performance in terms of distillate production rate and gained output ratio (GOR).

2 | PROPOSED HDH WATER DESALINATION SYSTEM

The schematic representation of the proposed experimental setup has been depicted in Figure 1. Unsaturated atmospheric air travels through the holes drilled on the periphery of circular tube to generate air bubbles in the column of hot water inside the humidifier. As air bubbles moving through hot water, the energy and mass transfer between hot water and unsaturated air raise the RH of air. The formation of bubbles increases surface contact area, which also accelerates air humidification process. As an end result, warm and moist air moves out from the BC humidifier. The humidified air is then passed through the cold section of TEC-based dehumidifier, which is run by DC supply from solar photovoltaic (PV). The solar PV panel converts solar radiation into DC to charge the battery. The TEC modules are powered directly from battery. The humid air is cooled down well below the saturation temperature in the dehumidifier; as a result, dehumidification of the air takes place. The condensate droplets are separated by gravity and collected in a distillate water tank as shown in Figure 1. The hot ends of the TEC modules are cooled by means of a separate blower to avoid overheating.

3 | THEORETICAL MODELING OF HUMIDIFICATION-DEHUMIDIFICATION SYSTEM

Theoretical modeling of BC humidifier and TEC dehumidifier is proposed to predict the temperature of air, specific humidity of air at outlet of humidifier, and fresh water yield of HDH system. Energy flow diagram of HDH system is shown in Figure 2. The air enters the humidification chamber where the air bubbles are generated. The air bubbles undergo through energy and mass exchange with the preheated water in the chamber, and hence, the air gets humidified. The humidified air is then fed the dehumidification chamber, where it rejects the heat and moisture gets condensed. The condensate is collected as the distillation product and relatively dry air is exhausted in the surrounding.

3.1 | Mathematical modeling of BC humidifier

The theoretical model of BC humidifier has been established to calculate specific humidity and temperature of air at the exit of humidifier. The planned theoretical modeling for a BC humidifier is predicated on the following guesses:

1. The water temperature in bubbler humidifier is constant throughout the tank.
2. While moving upward in bubbler humidifier, bubbles unite with neighboring bubbles.
3. Bubbles and water in humidifier are in thermal equilibrium.

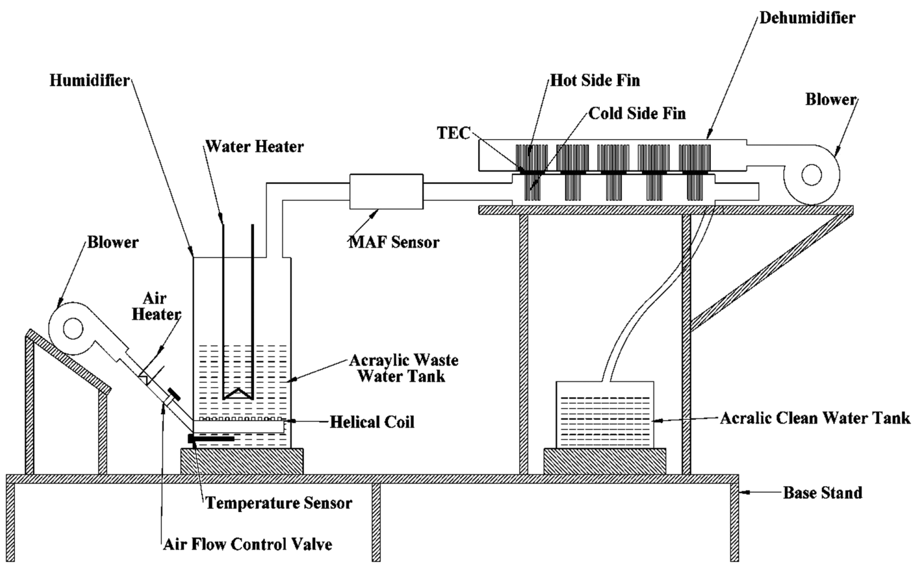

FIGURE 1 Proposed HDH system. HDH, humidification-dehumidification; TEC, thermoelectric cooler

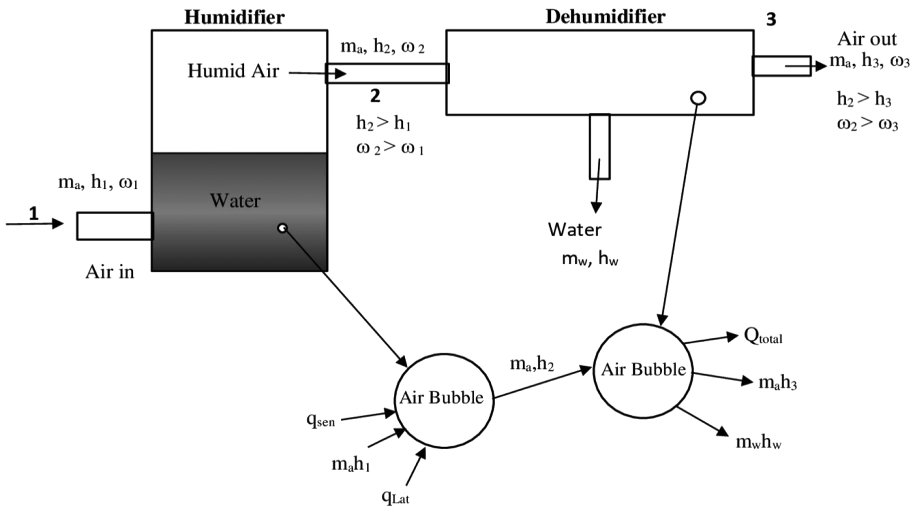

FIGURE 2 Energy and mass flow diagram

Figure 2 shows the simplified diagram of energy and mass flow in bubbler humidifier. The mathematical model for humidification process is developed under steady-state condition by equating energy and mass exchange on a bubble as a system.

As per the mass conservation law,

Mass of air at entry of the system = Mass of air at exit of the system

$$x_{a_i} = x_{a_o} = x_a \tag{1}$$

In the humidifier, the hot saline water exchanges energy and mass to the air bubbles. The energy balance can be written by following equation, by considering the air bubbles as a system.

$$Q_i - Q_o = Q_{st} \tag{2}$$

Because of very small volume of air bubble, the energy stored in the air bubble can be ignored. Therefore, Equation (2) can be written as

$$Q_i = Q_o \tag{3}$$

The generalized heat balance equation for the bubbler humidifier can be addressed as follows:

(Energy of air at the inlet of humidifier) + (Sensible heat exchange from hot water column to air bubble) + (Latent heat exchange from hot water column to air bubble) = (Energy of air at the outlet of humidifier)

$$x_a h_1 + q_{sen} + q_{lat} = x_a h_2 \tag{4}$$

For humidification process, the mass balance equation can be written as follows:

$$x_{wi} + x_a(W_2 - W_1) = x_{wo} \tag{5}$$

Latent heat transfer in the humidifier can be given by[23]

$$q_{lat} = j \times h_{fg} \tag{6}$$

where mass flux is indicated by j[23]

$$j = \frac{x_a \times (W_2 - W_1)}{A} \tag{7}$$

Sensible heat exchange from hot water column to air bubble in the humidifier can be given by[5]

$$q_{sen} = h_t \times A \times (T_w - T_1) \times a_s \times Z \tag{8}$$

The specific surface area a_s is the bilateral contact area between the water and air bubble in the humidifier and can be calculated by following equation [5]

$$a_s = \frac{6 \times \varepsilon}{D_b} \tag{9}$$

The volume fraction picked up by the air bubbles in water column can be calculated by following expression [13]

$$\varepsilon = \frac{V_g}{0.3 + 2V_g} \tag{10}$$

The air bubble diameter is calculated by using following equation [23]

$$D_b = \left[\frac{6 \times \sigma \times d_o}{G \times (\rho_w - \rho_a)}\right]^{\frac{1}{3}} \tag{11}$$

The artificial flow velocity of air can be calculated as follows[13]:

$$V_g = \frac{x_a}{\rho_a \times A} \tag{12}$$

The generalized expression of coefficient of heat transfer can be obtained by considering the Lewis factor and expressed as follows[23]:

$$h_t = L_e \times (\rho_1 \times C_{p1} \times K_l) \frac{a_s \times V}{A} \tag{13}$$

Lewis factor is generally in the range of 0.8 to 0.9[13] for bubbler humidifier, and we have taken $Le = 0.9$[13] for our calculations. The coefficient of mass transfer can be obtained from following equation

$$\frac{1}{K_l} = \frac{1}{K_{l_1}} + \frac{1}{K_{l_2}} \tag{14}$$

The mass transfer resistances can be calculated from following expression [13]

$$K_{l_1} = D_{AB} \frac{2}{D_b} \tag{15}$$

$$K_{l_2} = D_{AB} \left[\frac{D_{AB}}{t \times \pi} \right]^{0.5} \tag{16}$$

The surface renewal time of hot water column can be computed from following equation [13]

$$t = \frac{D_b}{V_c} \tag{17}$$

From the following correlation, the liquid circulation velocity can be calculated[23]:

$$V_c = 1.36 \times G \times z \times (V_g - \varepsilon V_b) \tag{18}$$

The following equation has given the bubble velocity[13]:

$$V_b = \left[2 \frac{\sigma}{\rho_w D_b} + g \frac{D_b}{2} \right]^{\frac{1}{2}} \tag{19}$$

At the outlet of bubbler humidifier, the humidity ratio of air can be computed from the following correlation[23]:

$$(W_2 - W_{sat}) \times e^{(K_l \times a_s \times t_f)} = (W_1 - W_{sat}) \tag{20}$$

The bubble residence moment can be computed from the following expression [13]:

$$t_f = \frac{z}{V_b} \tag{21}$$

3.2 | Mathematical modeling of thermoelectric cooling dehumidifier

The mathematical model of TEC-based dehumidifier, which is run by solar PV energy, has been developed to investigate fresh water production rate.

The working principle of TEC is shown in Figure 3. TEC is a device that works on the Peltier effect. In TEC module, between two ceramic plates, numbers of P-type and N-type semiconductors are placed. The components of semiconductor are associated thermally in parallel and electrically in series. TEC includes the cooling or heating of junction of two thermoelectric materials by fleeting DC through the junction. During process, DC moves through the TEC module creating heat to be conveyed from one side to the other and generating a cold and hot side.

The energy flow diagram of dehumidifier is shown in Figure 2. Humid air from the BC humidifier is supplied to the cold section of TEC modules, which are working as dehumidifier. The humid air gets dehumidified by transfer of energy and mass, and fresh water is gathered in the form of condensate. In the dehumidifier section, total five thermoelectric modules are connected in series for our study, and DC power is supplied through solar PV panel.

The specifications of thermoelectric modules (TEC 12715) specified by manufacturers are given in Table 1.

The energy absorption from heated side and the energy rejected from the chilled side can be found by using energy balance equation under steady state for chilled and heated sides of TEC module.[30]

The energy rejection from chilled side of the TEC module is calculated by

$$Q_c = (\alpha_{\max} \times I_{\max} \times T_c) - \left(\frac{1}{2} \times I^2{}_{\max} \times R_{\max} \right) - (K_{\max} \times (T_h - T_c)) \tag{22}$$

The energy absorption from the heated side can be found by[30]

$$Q_h = (\alpha_{\max} \times I_{\max} \times T_h) - \left(\frac{1}{2} \times I^2{}_{\max} \times R_{\max} \right) - (K_{\max} \times (T_h - T_c)) \tag{23}$$

By applying the first law of thermodynamics across the TEC modules, the input power to TEC modules can be defined as

Power input to TEC modules = (Heat absorbed from cold side) + (Heat dissipated from hot side)

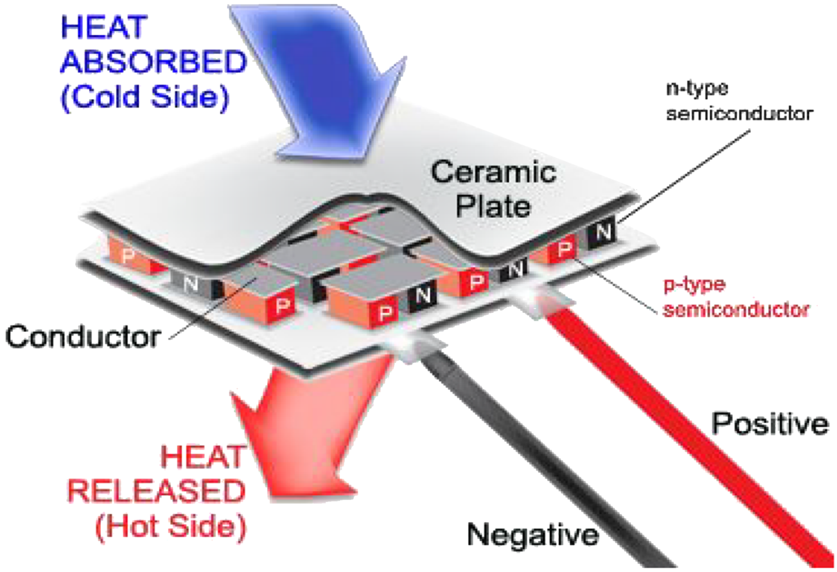

FIGURE 3 Working principle of thermoelectric cooler (TEC)[30] [Colour figure can be viewed at wileyonlinelibrary.com]

$$P_i = Q_h - Q_c \tag{24}$$

The COP of the TEC modules can be determined by using following expression:

$$COP = \frac{Q_c}{P_i}$$

In dehumidifier section, total five TEC modules are linked in series, so total heat absorbed from cold side of TEC modules is given by

$$Q_{total} = Q_c \times 5 \tag{25}$$

The heat balance equation for the dehumidification can be expressed as follows:

(Energy of air at inlet of dehumidifier) = (Energy taken away by TEC modules) + (Energy taken by fresh condensate water) + (Energy of air at outlet of dehumidifier)

$$m_2 h_2 = Q_{total} + m_w h_w + m_a h_3 \tag{26}$$

TABLE 1 Specification of the TEC 12715 module (data source: module manufacturers)

Parameters	Specifications
Seebeck coefficient, α_{max}	0.012 29 V/K
Module thermal conductance, K_{max}	0.1815 W/K
Module resistance, R_{max}	0.344 Ω
Input power, I_{max}	15 A
Input voltage, V_{max}	12 V
Hot side maximum temperature, T_h	60°C

The mass balance equation for dehumidification process can be expressed as follows:

$$m_a \omega_2 = m_w + m_a \omega_3 \tag{27}$$

The bypass factor (BF) of dehumidifier section is

$$BF = \frac{T_3 - T_D}{T_2 - T_D} \tag{28}$$

GOR can be calculated by dividing the total energy of evaporation of fresh water condensate by heat taken away by TEC modules. It is evaluated by[13]

$$GOR = \frac{m_w h_{fg}}{Q_{total}} \tag{29}$$

4 | EXPERIMENTAL SETUP AND METHODOLOGY

Figure 4 illustrates the actual HDH desalination system with the nomenclature of the components. The HDH system consists of air blower, water tank with a water heater, multispan temperature control system, air heater, MAF sensor, TEC modules, hot and cold fins, and condensed water collection tank. The specifications of the various parts of the proposed system are presented in Table 2. The preheated air is fed to the water tank through a helical coil, which is placed at the bottom of the tank with holes on the surface to generate air bubble. The energy and mass exchange between water column and air bubbles has occurred, as bubbles of air move up in column of water. The water temperature in the bubbler humidifier is managed constant by temperature control system. The

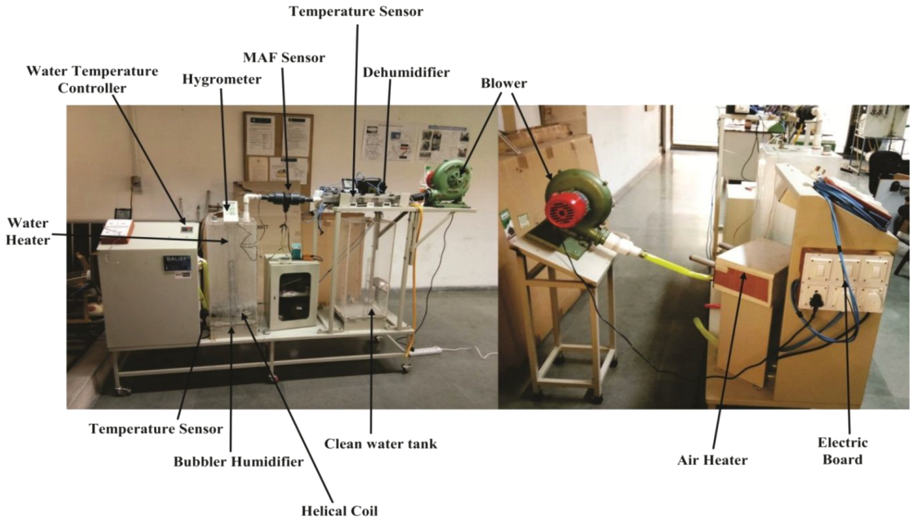

FIGURE 4 Experimental setup of humidification-dehumidification (HDH) system [Colour figure can be viewed at wileyonlinelibrary.com]

humidifier air from the BC humidifier is supplied to the dehumidifier chamber consisting of cold section of TEC modules. In the dehumidifier section, total five thermoelectric modules are connected in series for our study, and DC power is supplied through solar PV panel. The solar PV panel converts solar radiation into DC power to charge the battery. The TEC modules are powered directly from battery. The humid air from the humidifier passes over the cold side of TEC where there is a transfer of heat and mass from moist air to the cold side of TEC. As a result, the humid air gets dehumidified by condensation of moisture in the air. The condensate generated is collected in a distillate water tank. The hot ends of the TEC modules are cooled by a separate blower. Amount of distilled water accumulated in the distillate water tank is measure of performance of the system. The operational parameters of the system such as air temperature, water temperature, the hole diameter, air mass flow rate, and the height of water column were varied in order to identify their effect on the productivity. Furthermore, the working range and the accuracy of the calibrated measuring instruments have been presented in Table 3.

5 | RESULTS AND DISCUSSION

The productivity of the BC-based humidification and TEC-based dehumidification water desalination system has been measured experimentally and studied theoretically. The predictions of the mathematical model are compared with experimental data for validity of the proposed model. A parametric study has been carried out to analyze the effect of different operational parameters such as temperature of water, hole diameter, height of water column, air temperature, and air mass flow rate on the yield of fresh water of the system. The experiments were repeated for same operation conditions to see the repeatability of system productivity and percentage deviations in the results. The results are presented with error bars to show the maximum and minimum possible deviations of system productivity with mean productivity when operated under prescribed conditions.

Figure 5 depicts the comparison of experimental and modeling results of variation of water temperature on the productive capacity of fresh water of the HDH system. The experiment was carried out with air mass flow rate of 0.016 kg/s, hole diameter of 2 mm, BC height of 5 cm, and keeping the inlet air at 27.83°C temperature. The temperature of water is altered from 45°C to 60°C in the interval of 5°C. The result indicates that the fresh water yield of the system rises with raising the water temperature. At greater water temperature, the energy and mass exchange rates rise from hot water column to air bubbles and so that boosted RH of air at humidifier exit and the production of fresh water of the system gets enhanced. The maximum experimental productivity of the HDH system was 11.28 L/d at 60°C of water temperature. The

TABLE 2 Specifications of the system components

Component Name	Design Capacity
Humidifier tank	60 L
Dehumidifier tank	30 L
Water heater	1000 W
Blower	180 W
TEC (DC power)	180 W/TEC
Air heater	2000 W
Solar PV panels	500 W

Abbreviations: DC, direct current; PV, photovoltaic; TEC, thermoelectric cooler.

TABLE 3 The instrumental accuracy of the system components

Instrument	Range	Accuracy	Measurement Error
Humidity sensor	10% to 100%	±2%	±2%
Temperature sensor	−40°C to 100°C	±2°C	±1°C
MAF sensor	1 to 200 g/s	±1 g/s	±0.5 g/s

experimental results show 2% to 10% deviation of fresh water yield with the mean value. Further, it is also examined that the modeling results are in reasonable agreement with the experimental results. The difference between the experimental and modeling results is due to simplification assumptions in the model.

Figure 6 illustrates the comparison of experimental and modeling results of variation of temperature of air on the productive capacity of fresh water of the system. The experiment was carried out with air mass flow rate of 0.016 kg/s, diameter of hole of 2 mm, height of water column of 5 cm, and water temperature of 60°C. The air temperature is altered from 35°C to 50°C in the interval of 5°C. The result shows that fresh water productivity of HDH system hikes with raising air temperature at entry of humidifier. At higher air temperature, the water particles holding capacity of air increased, and thereby, RH of air goes very nearer to saturation, which eventually leads to the better performance of the whole system. The maximum experimental fresh water productivity was of around 11.73 L/d at 50°C. The experimental results show 1% to 10% deviation of fresh water yield with the mean value. Here, the variation between theoretical and experimental outcomes is below 5%, which validates the theoretical model to be used for more exhaustive explorations.

Figure 7 depicts the comparison of experimental and modeling results of variation of diameter of hole on the periphery of spiral tube on the productive capacity of fresh water. The experiment was carried out with air mass flow rate of 0.016 kg/s, water column height of 5 cm, air temperature of 24.7°C, and water temperature of 60°C. The hole diameter used are 1, 2, and 3 mm. The result indicates that the productivity of the system goes down with hike in the hole diameter. This is because the small diameter holes generated higher turbulence in the water column that lead to more effective transfer of heat and mass among water molecules and air bubbles and thereby increased RH of air at humidifier exit and the productivity of the system gets enhanced. The maximum experimental fresh water productivity of 11.28 L/d is achieved at 1-mm hole diameter. The experimental results show 1% to 10% deviation of fresh water productivity with the mean value. Unlike the prior parameters, the theoretical and experimental observations for variable hole diameter exhibited negligible difference of 2.4%.

Figure 8 depicts the comparison of experimental and modeling results of variation of water column height on the productive capacity of fresh water. The experiment was carried out with air mass flow rate of 0.016 kg/s, hole diameter of 2 mm, air temperature of 24.7°C, and water

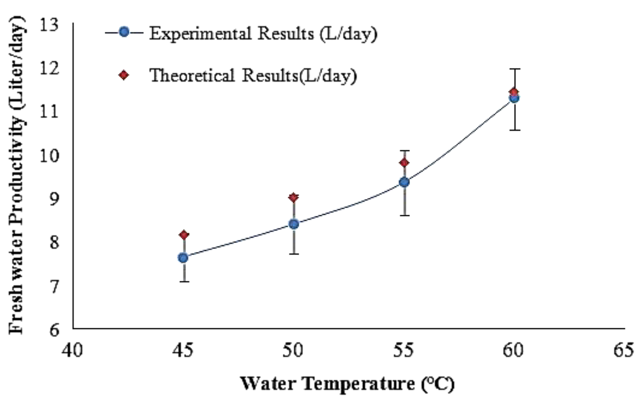

FIGURE 5 Relation between water temperature and fresh water productivity [Colour figure can be viewed at wileyonlinelibrary.com]

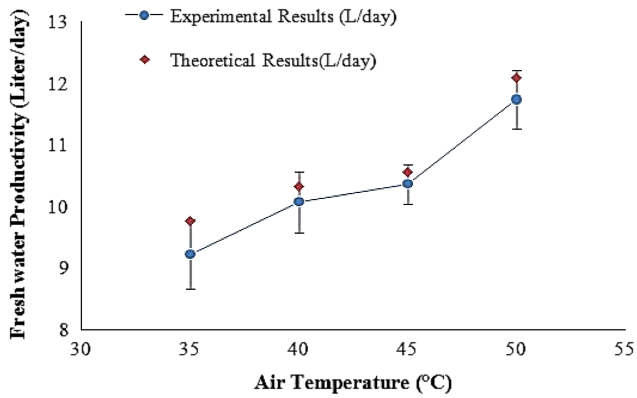

FIGURE 6 Relation between temperature of air and fresh water productivity [Colour figure can be viewed at wileyonlinelibrary.com]

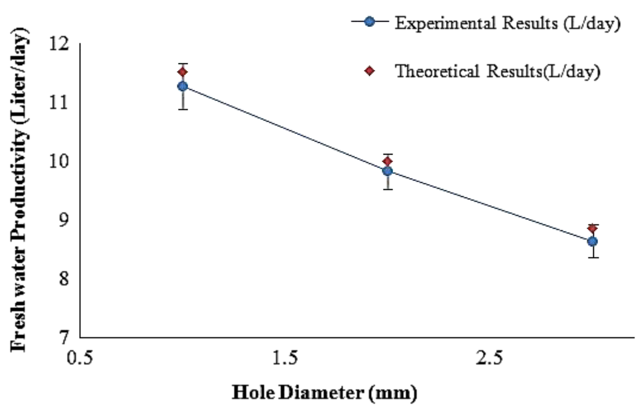

FIGURE 7 Relation between hole diameter and fresh water productivity [Colour figure can be viewed at wileyonlinelibrary.com]

temperature of 60°C. The height of water column is altered from 3 to 7 cm in the interval of 2 cm. The result indicates that fresh water yield hikes with raising the height of water column. At higher height of water column, the meeting time of air with water is improved and appeared in the higher energy and mass exchange rate, which increases air RH and which eventually leads to the better performance of the whole system. The maximum experimental fresh water productivity was 12.96 L/d at 7 cm of water column. The experimental results show 8% to 20% deviation of fresh water productivity with the mean value. The gap observed between the theoretical and experimental values of the fresh water productivity was in the range of 5% to 7%.

Figure 9 depicts the comparison of experimental and modeling results of variation of air mass flow rate on the fresh water productivity. The experiment was carried out with 2-mm hole diameter, BC height of 5 cm, air temperature of 26.45°C, and water temperature of 60°C. The range of mass flow rate of air is varied from 0.004 to 0.016 kg/s. The result indicates that fresh water production of the system hikes by hiking mass flow rate of air. This is because the hike in air mass flow rate resulted in the hiked velocity and increases the mixing rate of air and water in humidifier. It leads to the greater transfer of mass by diffusion between the air and water and raised RH at the outlet of humidifier and fresh water yield of the system. The best fresh water productivity of 11.36 L/d is obtained for 0.016 kg/s air flow rate. The experimental results show 5% to 12% deviation of fresh water yield with the mean value. The gap observed between the theoretical and experimental values of the fresh water productivity was in the scope of 5% to 9.5%.

The variation in experimental and theoretical GOR with reference to the variable air mass flow rate has been illustrated in Figure 10. The GOR indicated linearly

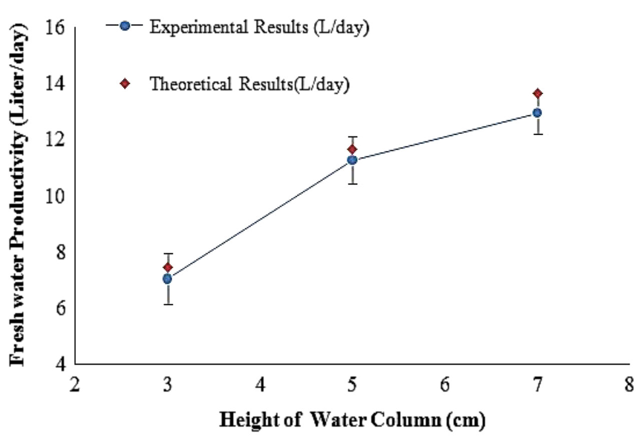

FIGURE 8 Relation between height of water column and fresh water productivity [Colour figure can be viewed at wileyonlinelibrary.com]

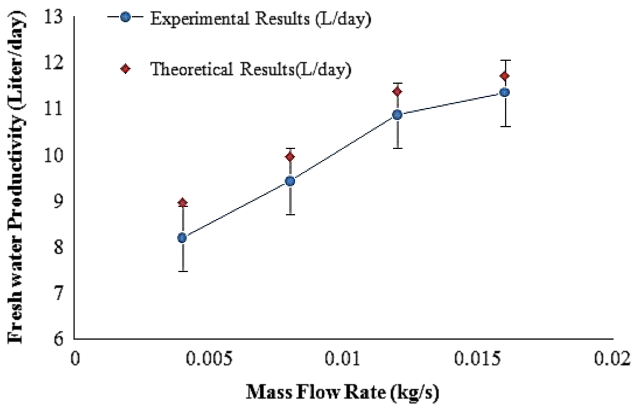

FIGURE 9 Relation between mass flow rate of air and fresh water productivity [Colour figure can be viewed at wileyonlinelibrary.com]

proportional relation with the aim mass flow rate. The air mass flow rate of 0.016 kg/s corresponds to the theoretical and experimental GOR range of 0.75 to 0.80 and 0.80 to 0.85, respectively. The average variation of 8.25% among the experimental and theoretical values of the GOR with reference to the mass flow rate of air has been observed.

6 | ECONOMIC ANALYSIS OF HDH SYSTEM

Economics is one of the essential aspects for finding desalination decisions; therefore, it is a considerable concern to learn the present desalination systems economically. The desalination cost covers the overall fresh water production cost, capital investment, and operation and maintenance cost. The cost of desalination is affected by many local parameters like financing circumstances, cost of labor and pretreatment, market position of solar systems, and charges of electricity.

The fresh water production price of the desalination system would be found by the capital investment, operation and maintenance cost, and production of fresh water

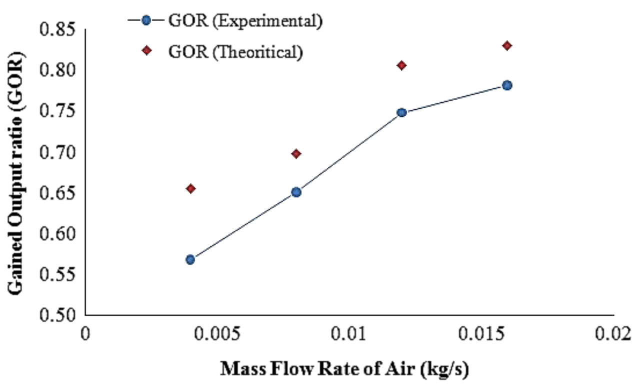

FIGURE 10 Rate of change of gained output ratio (GOR) with reference to mass flow rate of air [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Capital cost list of the HDH system

Component Name	Capital Cost, Rs
Solar PV panel	30 000
TEC modules	30 000
Humidifier chamber	12 000
Battery	12 000
Blower	8000
Air heater	5000
Acrylic tanks	20 000
Water heater	3000
Dehumidifier	17 000
Metal structure	30 000
Temperature controller	8000
Total cost	175 000

Abbreviations: HDH, humidification-dehumidification; PV, photovoltaic; TEC, thermoelectric cooler.

and lifetime of system. Here, the rate of interest is not considered. Table 4 shows total capital cost of the HDH system, and it is Rs 175 000/-. Here, we guess 20 years' lifetime of the desalination system; 365 days per year are the effective working days of the system. The production price of fresh water is about Rs 2.21/- per liter, based on above assumptions, which are less than cost expressed for earlier HDH distillation systems.

The total capital cost of the HDH system is Rs 175 000/-.

Maintenance and operating cost = 20% of Capital cost = Rs 35 000/-

Total cost = 175 000 + 35 000 = Rs 210 000/-

The fresh water to be produced in liters

= Productivity per day × Period of production × Lifetime of system

= 13 L/d × 365 d/y × 20

= 94 900 L

Cost of fresh water/liters

= Total cost/The fresh water to be generated in liters

= 210 000/94 900

= 2.21 Rs/L

Cost of fresh water generated per day

= Cost of water per liter × Productivity

= 2.21 × 13 = 28.73 Rs/d

Market cost per liter in India = Rs 20/-

Net profit = Market cost per liter − Cost of water per liter

= 20 − 2.21

= 17.79 Rs

Payback period in liters = Total cost/Net profit

= 210 000/17.79 = 11 804 L

Payback period in days = Payback period in liters/Productivity

= 11 804/13 = 908 days = 2.5 years

7 | CONCLUSION

Theoretical and experimental performance evaluation of BC humidification and TEC dehumidification water desalination system has been conducted. The daily distillate production achieved during the investigation was in the range of 7 to 13 L/d for different operational conditions while the best experimental productivity of the system was registered 12.96 L/d for 2 mm of hole diameter, 0.016 kg/s of air mass flow rate, 60°C of water temperature, 27°C of air temperature, and 7 cm of water column height in the humidifier. The GOR of the system was 0.8 for 0.016 kg/s of mass flow rate of air. The results indicate that the daily production is directly proportional to temperature of air, temperature of water, water column height, and mass flow rate of air, whereas inversely proportional to the bubble generation hole diameter. This outcome helps in designing a BC humidification and TEC dehumidification water desalination system configurations that will lead to maximum possible daily productivity. Further, the preheating of air and water can be achieved by the use of energy from solar in order to utilize sustainable energy and reduce the input electricity cost. The capacity of the proposed desalination system can be increased by installing multiple helical coils in the humidifier chamber with blowers and multiple dehumidifier units connected with humidifier chamber. It is also analyzed that reasonable amount of energy from the hot side of dehumidifier is lost to the atmosphere. Hence, future work can also be carried out to use the waste energy from heated side of dehumidifier section.

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How to cite this article: Patel V, Patel R, Patel J. Theoretical and experimental investigation of bubble column humidification and thermoelectric cooler dehumidification water desalination system. *Int J Energy Res*. 2019;1–12. https://doi.org/10.1002/er.4931