Simulation Study on the Wet-bulb Humidification-Dehumidification Cycle for Desalination

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Simulation Study on the Wet-bulb Humidification-Dehumidification Cycle for Desalination

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Abstract: *The present study aims to investigate the wet bulb humidification-dehumidification cycle for treating seawater for mitigating the freshwater crisis; sustainably and energy-efficiently. A python code is developed to explore the potential of the proposed desalination system using thermodynamic equations. The developed model was used to compute the water production rate with climatic conditions of two major cities of Pakistan populated closer to the coastal line. The results show that the investigated desalination conception is capable to produce 7.2 kg/day and 6.3 kg/day of freshwater corresponding to Karachi and Gwadar climatic conditions. The energy required to produce freshwater has been computed at 1.2 kWh/kg and 1.06 kWh/kg. In addition, Köppen–Geiger's climatic classification of the desert (Bwh) and humid subtropical (Cfa) climate were explored considering the effect of velocity and effectiveness. The results show that the Bwh region is more promising having a water production capacity of 0.83 g/s as compared to Cfa (1.33 g/s).*

Keywords: Effectiveness method; Humidification-dehumidification; Wet bulb desalination; Water treatment

1. INTRODUCTION

Earth's surface is 71% covered by water, 96.5% of which is salt water, and the rest is freshwater [1]. Two-thirds of the freshwater in the world is inaccessible due to its existence in the form of snow, ice, glaciers, and other natural occurrences. By 2050, it is estimated that five billion people would be impacted by water shortages as a consequence of population expansion [2,3]. Fig. 1 shows the global distribution of the regions that have been affected by the severe water shortage issues. Desalination is prescribed as a remarkable and pragmatic solution to the problem of water shortage because of being extracted the water beyond the natural freshwater cycle [4,5]. In this context, worldwide more than 16,000+ industrial-scale plants are constructed [6].

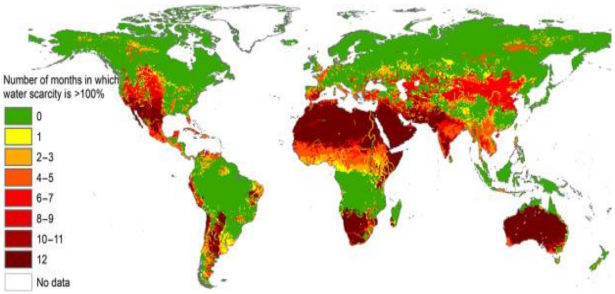

Fig. 1. Global distribution of regions affected by water scarcity [2].

There are two major categories of desalination systems that have been actively practiced in the desalination markets: (i) thermally driven desalination systems and (ii) mechanical driven desalination systems. Among the thermally driven desalination systems, Muti-stage flash (MSF) desalination [7], and multi-effect desalination (MED) [8] hold high market footprints and high production capacity, however massive thermal energy consumption. On the other hand, reverse osmosis (RO) desalination systems are the solo rival of the MSF and MED due to their massive production capacity [9]. However, the membrane biofouling, shorter durability, and life cycle of expansive membranes are the bottlenecks that need to be addressed [10,11]. On the other hand, erosion of system components, high thermal energy consumption, and massive brine discharges are the technological hurdles that need to encounter to achieve the United Nations (UN), 2030 sustainable development goals. In this context, researchers explore the alternatives of the thermally driven desalination technologies which include adsorption desalination (AD) [12,13], humidification-dehumidification desalination [14] system, and dewpoint desalination [15] are the potential options.

Various efforts are reported in reputed journals from the perspective of developing an optimized system that could be commercialized in the longer run [16]. For instance, Wang et al. [17] developed an experimental prototype of an AD system that has the potential to produce 4.7 cubic meters of water per ton of silica-gel per day (m^3/ton/day). Alsaman et al. [18] reported that the system AD system capable to produce 4 m^3/ton/day. The adsorbent coupled in the AD system is the prime entity of the AD system [19]. Therefore, CPO-27(Ni) was employed and found the production capacity of the AD system was up to 23 m^3/ton/day [20]. The technology is still in the development phase and has not yet met the system readiness level norms.

Dewpoint evaporative desalination conception was also investigated for producing salt-free water [21]. Pandelidis et al. [15] report the proposed system can be functional in any climatic region and have the capacity to produce 0.7 m^3/day per m^3/sec mass flow rate of the air by the specific energy consumption of less than 1.5 kWh/m^3 electric energy

Humidification-dehumidification (HDH) conception was also explored for the separation of the salts from the seawater from the perspective of developing energy-efficient, cost-effective, and high productive desalination technology. In this context, Cipollina et al. [22] brine evaporative cooler principally works on the humidification of the process. The study reported that the brine evaporative cooler is capable to produce 5 m^3/day in Italy's climatic conditions [22]. Qasem et al. [23] investigate a hybrid configuration that integrates the HDH + AD system to produce fresh water. It was realized that the HDH+AD system can produce 25 kg/hr with a payable cost of 0.64 €/L. However, Capocelli et al. [24]

report that the HDH+AD has the potential to produce 30 m^3/day of salt-free water.

The present study aims to investigate a low-cost, sustainable energy efficient desalination system entitled as wet bulb humidification-dehumidification cycle. For this purpose, a code is written in the Python language to solve the thermodynamic equations and efficiently utilized libraries that stored the thermodynamic properties of the working dry and humid air. The studied system was analyzed based on the water production rate corresponding to changes in temperature and relative humidity. Furthermore, the study, investigates the potential of the studied desalination cycle in two major cities of Pakistan namely, Karachi and Gwadar. The temporal variation in the water production capacity was analyzed based on the maximum and minimum potentials. Furthermore, the study explores the impact of the velocity and direct evaporative system effectiveness on the water production rate under two different climatic scenarios desert (Bwh) and humid subtropical climate (Cfa) classified based on the Köppen–Geiger climatic system.

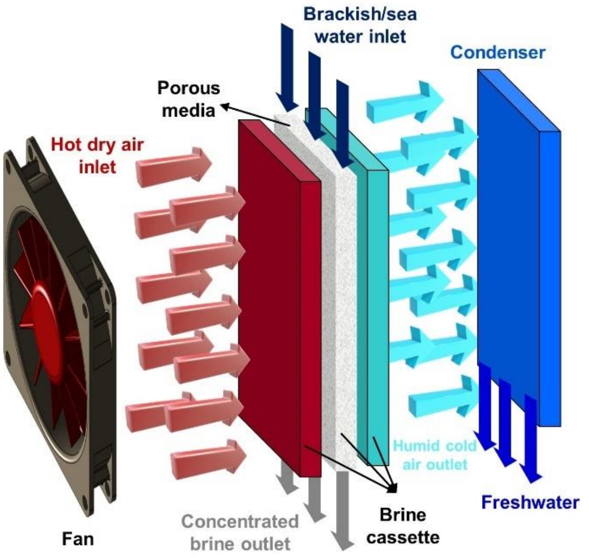

Fig. 2. Schematic illustration of the wet bulb humidification-dehumidification cycle for salt separation.

2. SYSTEM DESCRIPTION

Fig. 2 shows the schematic illustration of the wet bulb humidification-dehumidification cycle for developing a sustainable energy-efficient desalination system. As observed, the system comprises on a hot dry air supply fan, brine cassette, and condenser mounted with a heat exchanger. The hot dry air either free or in the forced state is passed through the brine cassette where the brackish water is flow under the action of gravity. The brine cassette contains a porous media to hold the brackish water molecules for a small interval of time. Once the hot dry air is in direct contact with the brackish water molecules it evaporates due to the vapor pressure difference and causes evaporation of water molecules from the brine cassette. Consequently, cool humid air is produced which is directed to the condenser. Inside the condenser, the cool humid air is being dehumidified. For this purpose, a heat exchanger is installed carrying coolant for scavenging the latent heat of the cool humid air discharge from the brine cassette in order to produce the condensate or freshwater. The temperature of the residential coolant must be 2-5 ºC low from the wet bulb temperature of the supplied dry hot air. In this manner, desalinated water is being produced. The brine water was collected from the bottom of the brine cassette. The attributes of the wet bulb humidification-dehumidification cycle are as follows:

- Scavenge the sensible heat from the system surroundings to convert it into latent heat
- Minimize the operational cost of desalination
- Non-payable or waste energy is being utilized to produce salt free water
- No erosion and maintenance cost of the system
- Mitigate the water scarcity and environmental degradation

3. METHODOLOGY

For investigating the wet bulb humidification-dehumidification cycle, a thermodynamic model was developed using Python programming language. The python libraries such as ‘CoolProp’ and ‘psypy’ are used in the model for incorporating the realistic thermal properties of dry and humid air. The effectiveness method is employed in order to explore the potential of the proposed salt separation system. The supplied air is in direct contact with the brine cassette; therefore, the effectiveness of the direct evaporative system has been utilized ranging between 65%-95% [25–28]. Eq. (1) is used for determining the outlet air temperature of the brine cassette.

$$\varepsilon = \frac{T_{in} - T_{out}}{T_{in} - T_{w,in}} \tag{1}$$

In Eq. (1), T_{in} , and T_{out} are the inlet and outlet temperatures of supplied air, respectivel where, $T_{w,in}$ is the inlet wet bulb temperature corresponding to the supplied ambient conditions (T_{in} and RH_{in}) and ε is the system effectiveness. The water production rate (m_{evap}) was computed by incorporating Eq. (2);

$$m_{evap} = \left(\rho_{h_{air}}\, v_{h_{air}}\, x_{h_{air}} - \rho_{d_{air}} v_{d_{air}}\, x_{d_{air}}\right) \cdot A \tag{2}$$

where, ρ, v, and x are the density, velocity and humidity ratio of the humid air (using subscript h_{air}) and dry air (using subscript d_{air}), respectively and A is the cross-sectional area of the direct evaporative system having value of 0.087 m^2. The sensible heat flux (Q_{sen}) and latent heat flux (Q_{lat}) utilized to evaporate the brackish water are calculated by Eq. (3) and Eq. (4), respectively:

$$Q_{sen} = m_{air}\, c_{p_{air}}\,(T_{out} - T_{in}) \tag{3}$$

$$Q_{lat} = m_{evap}\, h_{fg}(T) \tag{4}$$

where, m_{air} is the mass flow rate of air, and $c_{p_{air}}$ is the specific heat capacity of air. It has been assumed that there is no pressure drop in the system, which means that $v_{h_{air}} = v_{d_{air}}$. However, the $c_{p_{air}}$ is utilized corresponding to T_{out} and T_{in}. The h_{fg} is the latent heat of vaporization at T. The sensible heat factor (SHF) which is the ratio of the sensible flux to cumulative heat is calculated by using Eq. (5). Similarly, latent heat factor (LHF) is measured by Eq. (6) as given:

$$SHF = \frac{Q_{sen}}{Q_{sen} + Q_{lat}} \tag{5}$$

$$LHF = \frac{Q_{lat}}{Q_{sen} + Q_{lat}} \tag{6}$$

The payable flux, such as fan electrical energy and heat flux required to maintain the temperature of the residential coolant is not considered in this thermodynamic model.

4. RESULTS AND DISCUSSION

Fig. 3 shows the water production rate that could be produced from the wet bulb humidification-dehumidification cycle. The constant free state of air velocity (0.16 m/s) has been assumed for solving the governing equations. The temperature and relative humidity scale vary from 5-50 ºC and 30-98% in accordance with the climatic scenarios in most Asian regions. From Fig. 3, it has been observed that the water production rate could vary between 0.0016 to 0.135 g/s. As the relative humidity increases the water production capacity decreases due to the increase of humidity content in the supplied air. Alternatively, an increment in dry bulb temperature produces a positive impact on water production rate due to increasing the water holding capacity of hot dry air. In this context, high temperature and low relative humidity areas could be feasible localities to successfully drive the presented desalination system.

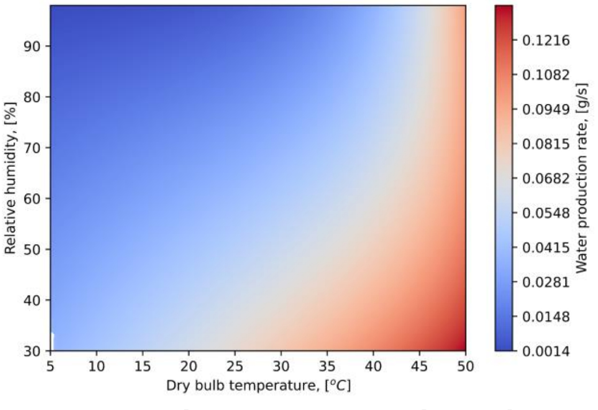

Fig. 3. Water production rate corresponding to change in dry bulb temperature and relative humidity considering 95% effectiveness of the direct evaporative system.

In order to explore the potential applicability of the wet bulb humidification-dehumidification cycle in Pakistan, the aforementioned governing equations are used to anticipate performance indicators. In this context, the climatic conditions of two major cities of Pakistan; Karachi and Gwadar which is being populated near the coastal line of the Arabian sea were taken for thermodynamic investigation. The direct evaporative effectiveness of 95% is assumed to calculate the temporal variation of the water production rate. Fig. 4 (a) and Fig. 4 (b) contains inlet and outlet temperature/ relative humidity states of Karachi and Gwadar city, respectively. From both figures, it has been realized that the relative humidity measure at the outlet of brackish cassette found 96% to 98%. As compared to inlet relative humidity, the outlet relative humidity magnifies by several folds which indicates the effective saturation of supplied dry air. Similarly, if focused on the outlet dry bulb temperature, the values have been dropped by 4 ºC to 5 ºC.

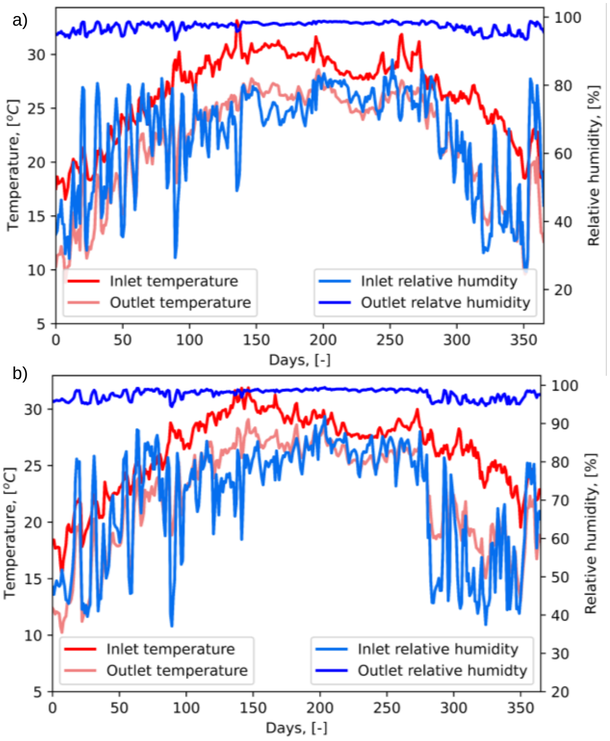

Fig. 4. Temporal operating regimes (temperature and relative humidity) of the Karachi (a) and Gwadar (b).

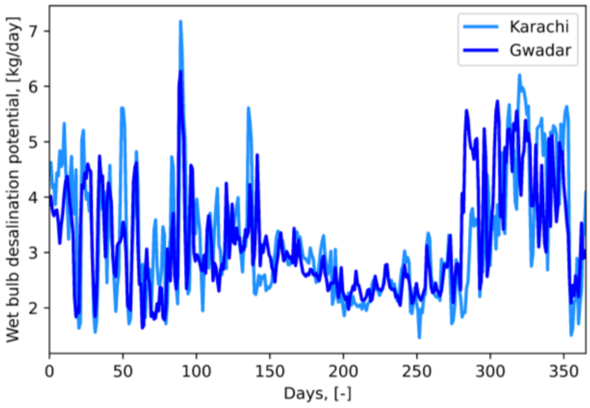

Fig. 5. Wet bulb desalination potential (WBDP) in Karachi and Gwadar.

Fig. 5 illustrates the temporal wet bulb desalination potential (WBDP) that possibly achieved from the wet bulb humidification-dehumidification desalination cycle. The maximum water production of 7.2 kg/day and 6.3 kg/day could be produced in Karachi and Gwadar climatic conditions. On the other hand, the minimum water production of and 1.46 kg/day and 1.632 kg/day, respectively produced in Karachi and Gwadar climatic conditions. From, mentioned results, it has been explored that the Karachi climatic conditions are more superior for proposed desalination configuration. In addition, it has been realized the water production rate is highly sensitive to driving conditions and fluctuates correspondingly to changes in operating temperature and relative humidity. The maxima of water production could be identified at low relative humidity and high operating temperature, vice versa.

Fig. 6 shows the sensible and latent heat fluxes required and produced, respectively in order to acquire the specific amount of fresh water. It has been realized that; heat fluxes produced under climatic conditions in Karachi are more as compared to Gwadar. The maximum latent heat flux of 0.203 kW is produced followed by 0.178 kW under the climatic conditions of Karachi and Gwadar, respectively. Similarly, if focused on the sensible heat, it has been identified that a maximum of 0.178 kW and a minimum of 0.0196 kW sensible heat flux is scavenged from the ambient environment of Karachi. Similarly, in the case of Gwadar, a maximum of 0.145 kW and a minimum of 0.002 kW of sensible heat is scavenged. However, it has been important to note that, corresponding to fluctuation in the sensible heat fluxes of both climatic conditions, the water production rate varies from maximum to minimum depending upon the driving temperature. The higher the driving temperature higher will be the sensible heat flux and more fresh water could be produced. The average cumulative non-payable sensible heat scavenged from the Karachi surrounding environment for producing one cubic meter of fresh water was estimated at 1.2 kWh/kg. Whereas in the case of Gwadar, the value is estimated at 1.066 kWh/kg. Similarly, the latent heat fluxes that could be restored were computed at ~66 kWh/kg from the studied climatic conditions during the condensation process. This is the additional heat flux that could balance payable electric and residential heat fluxes. This reflects that Karachi and Gwadar are promising geographical localities for the wet bulb humidification-dehumidification cycle.

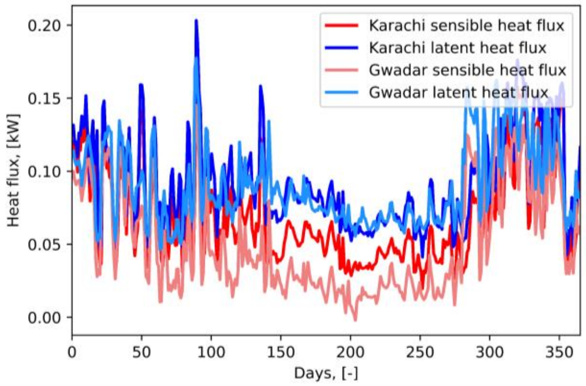

Fig. 6. Sensible and latent heat flux produced under the two different studied climatic scenarios of Pakistan.

Fig. 7 shows the SHF and LHF estimated for the studied climatic scenarios. The SHF could be defined as the ratio of the supplied sensible heat to the total heat whereas the LHF is the ratio of the latent heat to the total heat. It has been realized that the SHF decreases as the driving dry bulb temperature increases. This is because at higher temperatures the water holding capacity of the air increases which reflects more humidity transfer gradient from the brine cassette to the supplied air. Consequently, more water vapors will evaporate by scavenging the supplied sensible heat and stored in the form of latent energy. The SHF values for both climatic conditions vary between 0.5 to 0.01. Conversely, the LHF fluctuates from 0.55 to 1.0. In other words, fractional values emphasize the specific amount of supplied heat flux that has been converted into sensible heat flux and latent heat flux. Higher LHF indicates that more potential to produce freshwater. From Fig. 7 it has been analyzed that, at 200th day the SHF iis zero whereas the LHF is equal to 1 which reflects that, the total heat available in the surrounding environment has been converted into the latent heat.

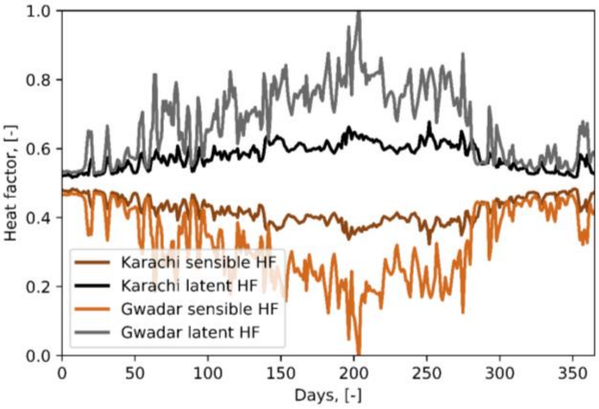

Fig. 7. Sensible and latent heat factor generates under-studied climatic scenarios of Pakistan.

Table 1 contains the input conditions for evaluating the performance of the developed direct evaporative desalination system in accordance with the Köppen–Geiger's climatic scenarios.

Table 1. Climatic conditions of the humid subtropical region (Cfa) and arid climate (Bwh)

Climate classification	Dry-bulb temperature (°C)	Relative humidity (%)
Cfa	30	43.51
Bwh	36.9	25.06

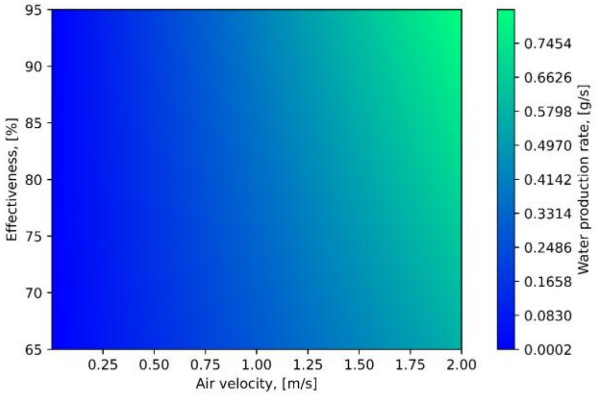

Fig. 8. Water production rate in humid subtropical climate (*Cfa*).

Fig. 8 depicts the effect of the air velocity and effectiveness of the direct evaporative system on water production rate under the humid subtropical region (*Cfa*) classified based on the Köppen–Geiger climatic system. From Fig. 8, it has been realized that an increment in air velocity imposes a positive effect on the water production rate. At 65% effectiveness the increment in air velocity from 0.01 m/s (free state) to 2 m/s (forced state) increase the specific water production rate from 0.0002 g/s to 0.828 g/s. Similarly, the increment in the effectiveness of 65%-95% leads to a positive attribute on the overall production capacity.

Fig. 9 reflects the water production rate in the humid desert or arid climate (*Bwh*) classified based on the Köppen–Geiger climatic system. It has been realized the *Bwh* region is more promising as compared to the *Cfa* which mostly exist in most region of Pakistan. The water production capacity mounted up to 1.327 g/s.

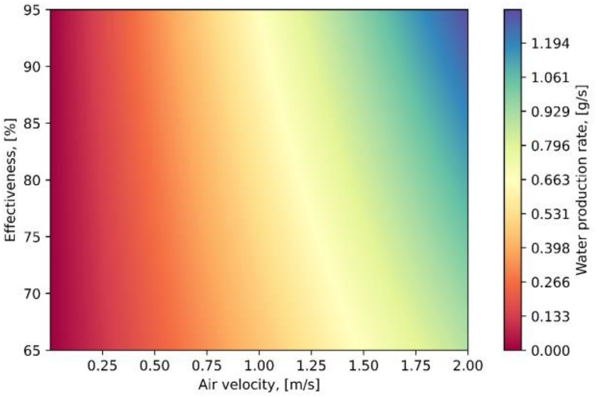

Fig. 9. Water production rate in humid desert or arid climate (*Bwh*).

5. CONCLUSION

The stunning conclusion of the United Nations (UN) 2015 study, which said that 40 percent of the world's freshwater supplies will be depleted by 2030, accelerates the researchers to explore alternative solutions for suppressing the water scarcity thrust. Desalination was prescribed as a remarkable solution, particularly for non-landlocked areas. However, the practiced technologies for desalination are non-energy efficient and entailed high production costs. In the present study, the wet bulb humidification-dehumidification cycle was investigated from thermodynamic perspectives in order to separate the salts from brackish/seawater. The effectiveness method of the direct evaporative system has been utilized to analyze the performance of the studied cycle. It has been realized that the cycle is capable to produce freshwater of 0.135 g/s, depending upon the driving temperature and relative humidity states of the supplied air. In addition, the performance of the two major cities of Pakistan, populated closer to the coastal line was analyzed considering 95% system effectiveness. It has been realized that the studied system is sensitive to temperature and relative humidity and could produce a maximum of 7.2 kg/day and 6.3 kg/day of desalinated water in Karachi and Gwadar climatic conditions, respectively. The average sensible heat fluxes scavenged from the surrounding environment vary between 1.2 kWh/kg to 1.066 kWh/kg. Furthermore, the study explores the effect of velocity and system effectiveness in the desert climate (Bwh) and humid subtropical climate (Cfa) classified based on the Köppen–Geiger climatic system. The results show that the Bwh could be a more promising region as compared to Cfa for operating the wet bulb humidification-dehumidification cycle while acquiring production capacity of 1.327 g/s.

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Conflict of interest

The authors declare no conflict of interest.

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