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ANALYTICAL INVESTIGATION OF A DESALINATION SYSTEM UTILIZING BUBBLE COLUMN HUMIDIFIER

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Abstract

The abundant seawater covering approximately 97% of the Earth's surface remains largely undrinkable due to its high salinity. This study presents a thermal desalination technique, Humidification-Dehumidification (HDH), employing carrier gases, which offers promise for small-scale purification systems to enhance the productivity of the Bubble Column Heat Exchanger (BCHE) and consequently, the desalination rate. The system harnesses seawater evaporation followed by condensation of the resulting humid air, utilizing solar thermal energy as the driving force for water vapor production, subsequently condensed in a separate chamber. This methodology is particularly suited for small to medium-sized desalination plants. The objective of this research is to develop an analytical framework for computing mass and heat transfer within the bubble column humidifier integrated with an earth-air heat exchanger, while evaluating the influence of various operational parameters. A simulation is conducted to solve the mass and energy balance equations governing the proposed system, with subsequent assessment of the obtained results to gauge system performance. The analysis reveals that specific humidity at the humidifier outlet increases with rising inlet water temperature and water column height within the humidifier, while decreasing with higher air mass flow rates.

Keywords: *Bubble Column Heat Exchanger, Desalination, Humidifier, Humidity.*

1 Introduction

The escalating global population has intensified the demand for Earth's resources, particularly safe drinking water. Alarmingly, one in four individuals lacks access to safe drinking water, with over 2 billion people worldwide relying on contaminated water sources. Consequently, waterborne diseases such as diarrhea, cholera, dysentery, typhoid, and polio pose significant health risks, contributing to an estimated 0.485 million annual deaths from diarrhea alone due to consumption of contaminated water.

Humidification involves increasing the water content in the air, whereas dehumidification pertains to reducing air humidity levels. Natural solar energy drives the desalination of seawater through the process akin to the water cycle. In this natural cycle, solar irradiation facilitates the humidification of seawater, causing humidified air to rise and form clouds, which subsequently undergoes dehumidification, resulting in precipitation in the form of rain. Humans have harnessed this cycle for desalination purposes, adopting the Humidification-Dehumidification (HDH) technology.

HDH technology employed for desalination entails raising the temperature of seawater using renewable energy sources such as solar energy, thermal energy, geothermal energy, wind energy, or their combinations. This process initiates humidification followed by dehumidification, facilitated by condensers, natural phenomena, or alternative methods, culminating in the collection of desalinated water suitable for small-scale water production.

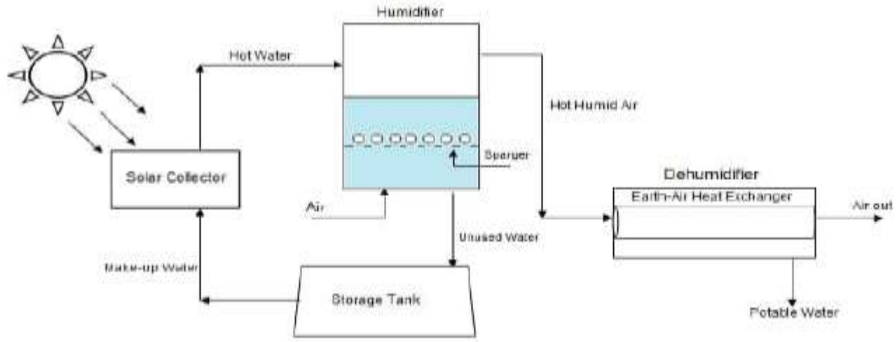

Figure 1: Schematic Diagram of HDH Technology

2 Applications of HDH Approach

The Humidification-Dehumidification (HDH) approach offers a versatile solution with various applications:

- Production of Water for Human Consumption and Irrigation: Solar desalination technology enables the production of water suitable for human consumption and irrigation purposes, addressing the growing demand for freshwater resources in regions facing water scarcity.
- Utilization in Maritime Ships and Submarines: Many maritime vessels, including ships and submarines, integrate desalination systems powered by solar energy to ensure a constant supply of freshwater for crew consumption and other onboard requirements, mitigating dependence on external water sources during extended voyages.
- Applications Requiring High-Quality Water: Solar desalination finds application in industries requiring exceptionally pure water, such as pharmaceuticals and semiconductor manufacturing. The technology ensures the production of water free from impurities, meeting stringent quality standards essential for various manufacturing processes.
- Scale-Free Water for Steam Production: Solar desalination systems can produce water devoid of scale-forming minerals, making it suitable for steam generation in boilers. This scale-free water helps maintain the efficiency and longevity of boiler systems, reducing maintenance costs and enhancing operational reliability.

3 Problem Identification

The primary goal of research in designing a small-scale water desalination unit is to achieve evaporation and condensation to boost the productivity with using various methodologies. HDH Desalination Technology is currently being researched and additional advancements are needed to enhance continuous improvement parameters in terms of water amount generated. Seawater desalination is a significant tool for addressing freshwater scarcity. The current study uses a bubble column humidifier to demonstrate a new humidification technique. Air is allowed to pass through perforated plate in humidifier for formation of bubbles at hot water column. With travel of air bubble by hot water column exchange of heat and mass takes place so to air passes in form of hot and humid characteristics. The production of bubbles increases the contact surface, which improves the humidification process' efficacy. For condensing humid air humidifier is incorporated using an Earth air heat exchanger. Earth cooling makes use of the thermal energy stored in the soil at various depths to supply the cooling demand for condensing warm humid air, decreasing the use of conventional energy sources.

4 Methodology

4.1 Principle of HDH Desalination System

By phenomenon of heat exchange between hot water and dry air evaporation occurs in humidification chamber. The warm humid air so formed is then passed to the dehumidification used chamber. For performing condensation process earth heat exchanger is utilized so to obtain fresh water.

4.2 Bubble Column Humidifier

For demonstrating this approach of direct contact humidification a bubble column humidifier is utilized in which air is pumped with sprayer for formation of bubbles in hot water column which then passes through hot water column causing heat and mass exchange. From below figure it is clear that air through outlet of humidifier is hot and humid where by the formation of bubbles contact area increases which ultimately causing effectiveness of humidification process dramatically.

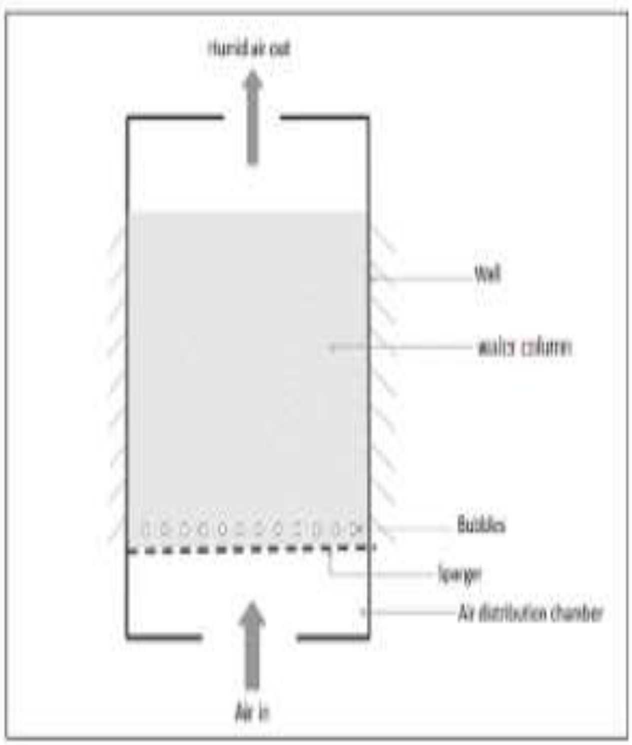

Figure 2: Bubble Column Humidifier

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5 Mathematical Model

The mass and energy balances of different systems are used in mathematical modelling. Heating and Humidification take place in a humidifier and the total heat transfer for both heating and humidification can be computed as shown in the figure below (Figure 3).

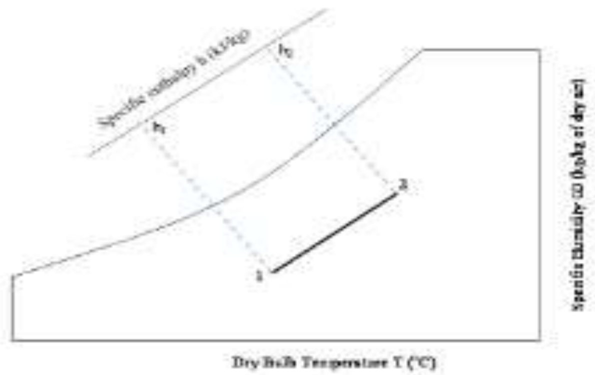


Figure 3: Heating and Humidification

For ease of calculation, we make use of the following assumptions in the Mathematical Modelling:

• Temperature of water (T_{bulk}) in the humidifier is equal to wall temperature (T_{wall}) and is uniform.

• The interface of liquid and gas experience identical temperatures as T_{bulk}. Because the residence time of bubbles in the water column is much less than the needed time to change the temperature of the water, they all experience the same temperature.

• Heat losses (or gains) from the edges of solar collector (heater), Water storage tank, humidifier, and dehumidifier to the ambient are neglected.

• There is no air leakage from the system, where air passes through the air heater, humidifier and dehumidifier in that sequence.

• The effectiveness of humidifying tower is assumed to be equal to one which means that the air leaving the humidifier is at saturation condition.

5.1 Humidifier

For a specific amount of time, the fluid is linked with the rising bubble. The Hibbies Theory for surface renewal explains how the growing bubbles behaves over time. According to this theory, mass is transferred once it comes in touch with water, and the residence time is generally equivalent to the time it takes for the bubble to move one diameter. Within the fluid element, unsteady heat diffusion occurs adjacent to the surface, which can be depicted as follows.

$$\frac{\delta T}{\delta t} = \frac{\alpha \delta 2T}{\delta 2x} \quad (1)$$

Boundary Conditions

$T = T_{bulk}$; $x = 0$; $t \geq 0$

$T = T_{air}$; $x > 0$; $t = 0$

$T = T_{air}$; $x = \infty$; $t > 0$

Laplace Transformation of Equation (1) with boundary conditions gives expression for heat flux

$$q = \frac{2}{\sqrt{\pi}} \frac{\sqrt{k\rho Cp}}{t} (\text{Tbulk} - \text{Tair}) \quad (2)$$

$\frac{kh}{t} = d_b V_c$ (3)

To calculate Surface renewal time, bubble diameter d_b & liquid circulation speed V_c needs to be found

$d_b = [\ 6\sigma dh(\rho l - \rho g)g\ ]$ (4)

V_c can be found by the following expression given by Field & Rahimi

$V_c = 1.36gH(Vg - \varepsilon V_b)$ (5)

Where ε is the volumetric gas holdup

$\varepsilon = Vg0.3 + 2Vg$ (6)

& V_b Velocity of bubbles is calculated by Mendelson's Wave Equation

$V_b = \sqrt{}2\sigma\rho ldb + gdb2$ (7)

Humidity & Enthalpy are a function of temperature & can be calculated by the Empirical formula

$\omega = 7.7 \times 10-7 \times T\ 3 - 1.95 \times 10-5 \times T\ 2 + 0.00071 \times T + 0.002$ (8)

$h = 2.82 \times 10-5 \times T\ 4 - 0.00106 \times T\ 3 + 0.00615 \times T\ 2 + 1.32T + 10.5$ (9)

Enthalpy of humid air (ha) can be calculated as

$ha = q \times A\ mha$ (10)

Where, ha is a function of Tao1.

mha= mass of humid air

$mha = ma + ma \times [\omega_{ao1} - \omega_{ai1}]$ (11)

$mha = ma + ma \times [f\ (T_{ao1}) - \omega_{ai1}]$ (12)

Where, ha and ω_{ao1} are a function of Tao1

The specific humidity of air humidifier outlet can be calculated by -

$\omega_{ao1} = 7.7 \times 10-7 \times T\ 3 - 1.95 \times 10-5 \times T\ 2 + 0.00071 \times T + 0.002$ (13)

6 Solution Procedure

6.1 Input and Output Readings for Humidifier

A python program coding has been done for calculations. Through this program, we have taken various readings by varying different operating parameters. A set of input and output readings are shown:

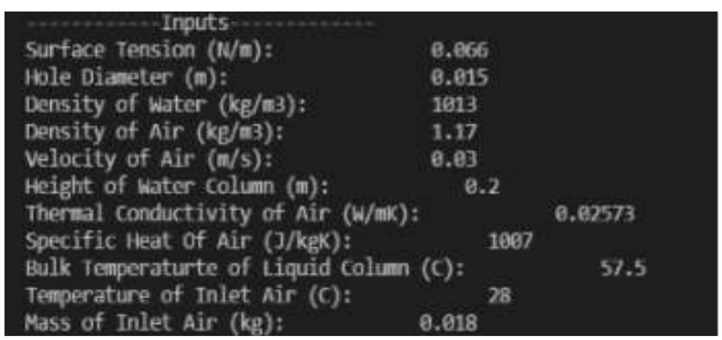


Figure 4: Input readings of humidifier

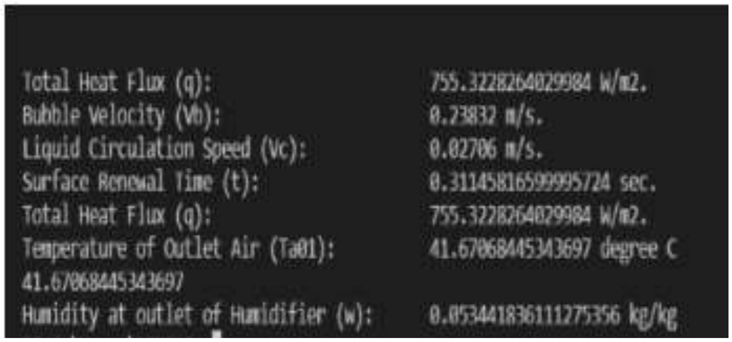


Figure 5: Output readings of humidifier

7. Results and Discussions

7.1 Variation in specific humidity with a varying inlet temperature of the water

After analysis by putting different values of inlet temperature of the water values are obtained.

Table 1: Obtained results of different values of inlet temperature of the water

At inner of humidifier, water temperature T_{wi1} (˚C)	**Density of Sea Water ρl (kg/m³)**	**Surface Tension σ (N/m)**	**At outer of humidifier, air temperature T_{a01} (˚C)**	**At outer of humidifier, air sp. humidity w_{ao1} (kgw/kga)**
57.5	1013	0.0660	41.67	0.05344
60	1012.5	0.0655	45.32	0.06580
62.5	1012	0.650	48.99	0.08053
65	1011	0.0648	52.58	0.09737
67.5	1010	0.0642	56.31	0.11764

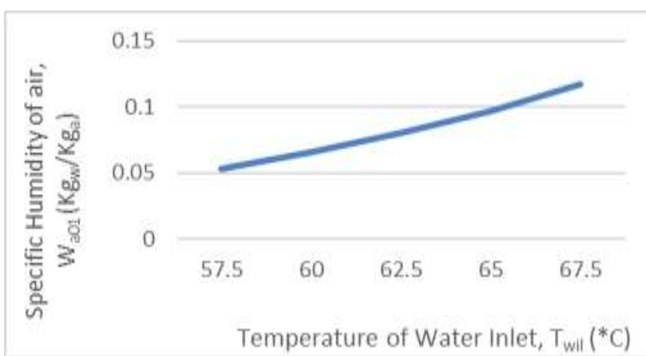


Figure 6: Specific Humidity vs. Temperature of water inlet

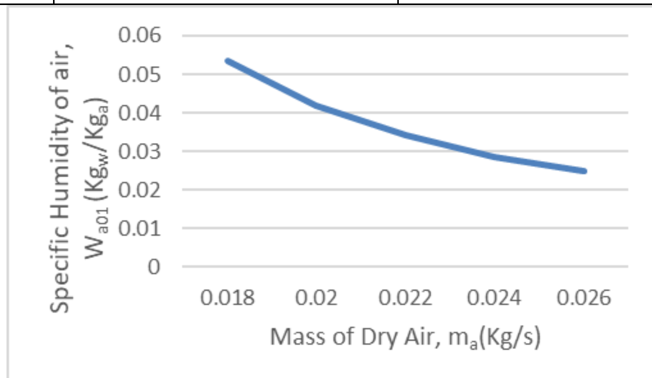
7.2 Variation in specific humidity with varying air mass flow rate

After analysis by putting different values of air mass flow rate at humidifier inlet following values are obtained.

Table 2: Obtained results of different values of air mass flow rate at humidifier inlet

Dry air mass m_a *(kg/s)*	**Inlet air temperature** T_{a01} *(˚C)*	**At outer of humidifier, air temperature** T_{a01} *(˚C)*	**At outer of humidifier, air sp. humidity** w_{ao1} *(kg_w/kg_a)*

0.018	28	41.67	0.05344
0.020	28	37.50	0.04181
0.022	28	34.09	0.03405
0.024	28	31.25	0.02864
0.026	28	28.84	0.02474



Water column height at humidifier *H(m)*	**At outer of humidifier, air temperature** T_{a01} *(˚C)*	**At outer of humidifier, air sp. humidity** w_{ao1} *(*kg_w/kg_a*)*
0.1	29.46	0.02568
0.2	41.67	0.05344
0.3	51.03	0.08980
0.4	58.93	0.13370

Figure 7: Specific Humidity vs. Mass of Dry Air

7.3 Different values of sp. Humidity with change in values of water column height at humidifier

After analysis by putting different values of water column height at humidifier following values are obtained.

Table 3: Obtained results of different values of water column height at humidifier

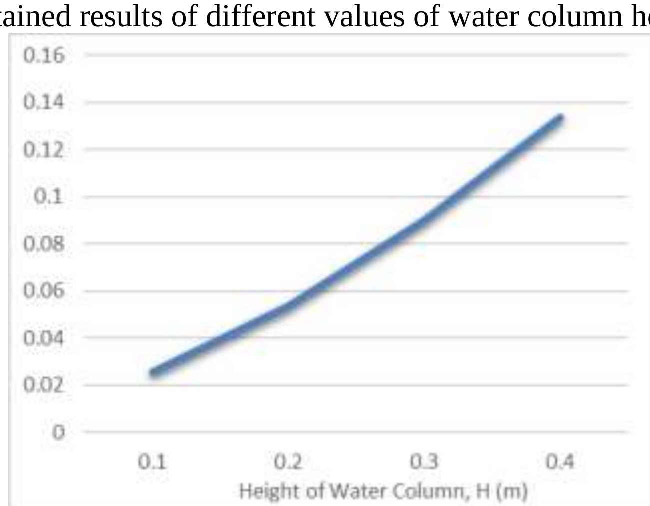


Figure 8: Specific Humidity vs. Height of Water Column

8 Conclusion

Through the comprehensive analysis and solution of various mathematical equations, several key conclusions regarding the performance of the system have been drawn:

- The specific humidity at the outlet of the humidifier exhibits an increase with rising inlet water temperature. This phenomenon underscores the significance of temperature control in optimizing the desalination process, emphasizing its positive impact on water vapor production.
- Conversely, an increase in the air mass flow rate leads to a reduction in the specific humidity at the outlet of the humidifier. This observation highlights the intricate relationship between air flow dynamics and humidity levels within the system, indicating the need for balanced airflow management to achieve optimal desalination efficiency.
- Moreover, the specific humidity at the outlet of the humidifier demonstrates a positive correlation with the height of the water column within the humidifier. This finding underscores the importance of water column height as a contributing factor in enhancing humidity levels, suggesting potential avenues for system optimization through adjustments in column design and configuration.

While this study provides valuable insights into the performance of the desalination system with a bubble column humidifier, several avenues for future research and development emerge:

- Further exploration of advanced control strategies and optimization techniques to enhance system efficiency and productivity.
- Investigation into the integration of novel materials and technologies to improve heat and mass transfer processes within the humidifier, thereby increasing overall system performance.
- Evaluation of the system's scalability and adaptability for large-scale deployment in industrial and municipal settings, addressing the growing demand for sustainable desalination solutions.
- Exploration of alternative energy sources and innovative design approaches to reduce reliance on conventional power sources and enhance the system's environmental sustainability.
- Continued research into the economic feasibility and cost-effectiveness of the proposed desalination system, considering factors such as capital investment, operational expenses, and lifecycle analysis.

By addressing these research areas, future studies can contribute to the advancement and refinement of desalination technologies, ultimately facilitating widespread access to clean and safe drinking water for populations worldwide.

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