



Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

Khalid Alrbaey¹,²Nuri Abosag, ³Faisal Alfagi,

¹College of Engineering Technology, Surman, Email:- moga_kh2001@yahoo.com

Higher Institute of Engineering Technology, Gharian Email:- Nori.abosag @ gmail. Com

Higher Institute of Engineering Technology, Gharian Email:- faissel2100sgh@gmail.com

Received: 05/9/2026 Revised: 10/9/2026 Accepted: 03/10/2026 Publication: 08/10/2026

Abstract

Freshwater scarcity is an growing problem, especially in faraway, dry and rural places where large-scale multi-stage flash (MSF) or reverse osmosis (RO) desalination methods are not affordable, expensive and need special technical help, This detailed research study looks at, Improves the performance of a solar-powered desalination plant that uses the Humidification-Dehumidification (HDH) closed-air open-water method, The HDH process is known for being simple to run easy to design using low-grade heat and good for small-scale uses The math, numerical model includes basic rules of mass, movement and energy fluid mechanics, psychrometric rules and heat and mass transfer in all parts, A lot of computer simulations were done in the summer weather in Tripoli, Libya using weather data from the Solar Energy Research Center in Tajoura, The computer results show that the amount of water made each day by the solar HDH system is reliably between 10 and 12 kg per day when the system is running best.

Index Terms—Humidification-Dehumidification (HDH), Solar Desalination, Renewable Energy, Numerical Simulation, Heat and Mass Transfer

I. INTRODUCTION

Freshwater scarcity is a problem for sustainable growth protecting nature and keeping people healthy especially in dry places like North Africa, Freshwater that people can use is needed for city water, farming and factories. Big desalination plants work well in cities by the sea, They cost a lot of money use a lot of power and need strong buildings, Small local desalination units that run on energy—like the closed-air open-water humidification-dehumidification (HDH) system—are cheaper, dependable and good for villages that are far from the grid, HDH systems work like the natural water cycle, Air is pushed through water picks up water vapor and gets warmer and more humid, That wet air then goes to a condenser where it cools, releases heat to water or air and the water droplets fall out as clean freshwater Adding thermal collectors and heat-storage tanks lets the HDH system keep running and give steady output even when the sun is not bright.

Scientists have looked closely at solar-powered HDH systems to make them work better and last longer Earlier research studied how to set up HDH units in areas showing that the height of the packed bed and the ratio of air to water flow have a big effect on how much freshwater the system makes [1], Computer models of conditions proved that better heat-storage tanks can smooth out the ups and downs of solar power [2], More work on how heat and mass move inside beds gave basic equations that help design HDH systems [3], Finally studies of combined

Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

storage tanks show that they are essential, for getting the freshwater each day and keeping the system steady [4].

II. Meteorological Data and Climatic Conditions of Tripoli

The simulations and mathematical models incorporate rigorous meteorological data corresponding to June 21st—statistically the peak solar insolation and thermal load day of the year in Tripoli, Libya—obtained from the Solar Energy Research Center in Tajoura. Environmental conditions directly govern the thermal performance of solar collectors and heat exchange units, Environmental conditions have an impact on how well solar collectors and heat exchange units work, Figures (1.1) and (1.2) show the ambient air temperature, wind speed and total global solar radiation that was recorded on this specific day.

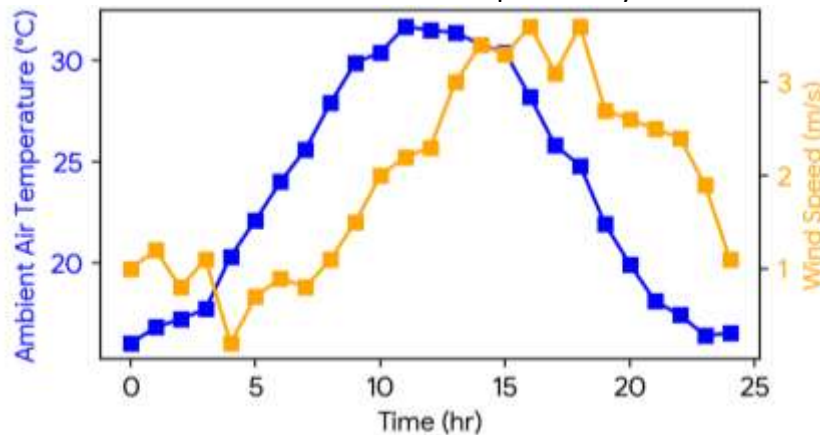


Figure. (1.1): Climatic Data (Ambient Air Temperature and Wind Speed) for Tripoli.

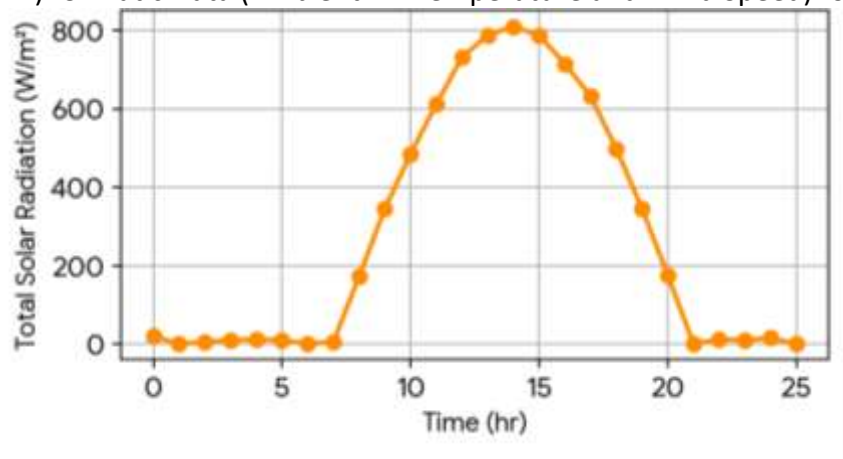


Figure. (1.2): Total Solar Radiation Profile on June 21st.

III. System Methodology and Theoretical Mathematical Modeling

The theory behind the humidification-dehumidification (HDH) desalination system is based on the laws of mass and energy, These laws are applied to each part of the system including the air heater, packed-bed humidifier, finned-tube dehumidifier and thermal storage tank.

- Overall Conservation Equations

Total Mass Conservation:

Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

The total mass balance says that all the mass coming in equals all the mass going out of the system:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

Total Energy Conservation (Enthalpy Balance):

The total energy conservation equation includes thermal heat input and work terms, It is written as:

$$\dot{Q} - \dot{W} = \sum (\dot{m}_{out} \cdot h_{out}) - \sum (\dot{M}_{in} \cdot h_{in})$$

- **Humidifier Conservation Equations**

In the packed-bed humidifier the mass of air coming in is the same as the mass of dry air going out:

$$\dot{m}_{da\ in} = \dot{m}_{da\ out} = \dot{m}_{da}$$

Heat and mass transfer equations are used to study how water evaporates into the air. These equations take into account changes in humidity, The transfer coefficients at the surface.

- **Dehumidifier Heat Exchanger Modeling**

The rate at which water vapor condenses in the dehumidifier is calculated using the Log Mean Temperature Difference (LMTD) method and the effectiveness-NTU (ϵ -NTU) method, This connects the heat rejection performance directly to the efficiency of moisture condensation.

- **Solar Thermal Collector and Storage Tank Integration**

plate solar collectors take in solar energy and pass the heat to the working fluid, An insulated storage tank helps store energy, This tank follows energy storage equations to keep the system stable.

IV. Numerical Simulation and Solution Procedure

The equations that control the system were solved using a Python simulation, The simulation is optimized to run, The solution is considered accurate when the error for temperature, humidity and mass flow is than 10^{-6} , The simulation runs in steps over a full day.

V. Comprehensive Results and Parametric Discussion

The parametric study shows how the system behaves under conditions, These include operating parameters, weather conditions and storage setups.

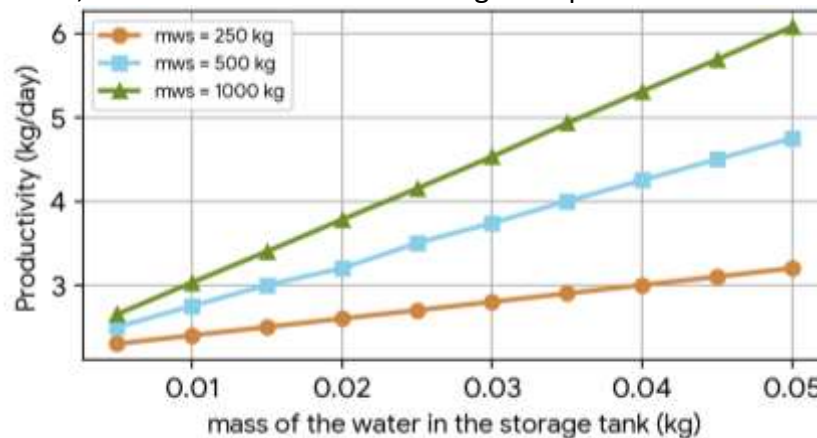


Figure. (1.3): Effect of Initial Water Mass in the Storage Tank, on System Productivity.

Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

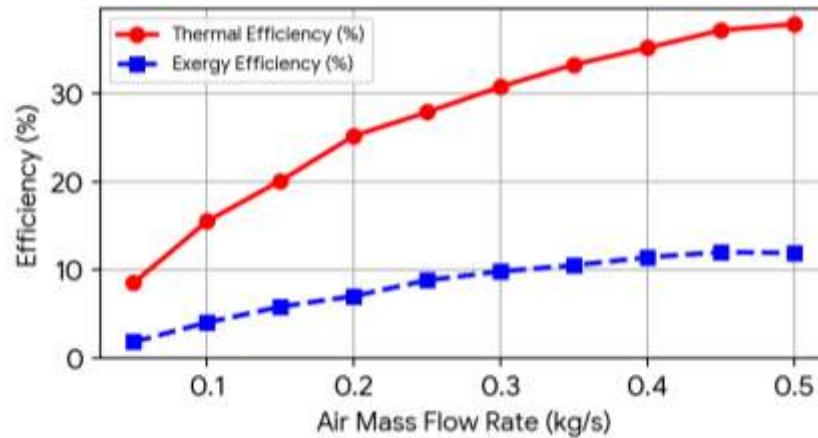


Fig. (1.4): Effect of Air Mass Flow Rate on Thermal and Exergy Efficiencies.

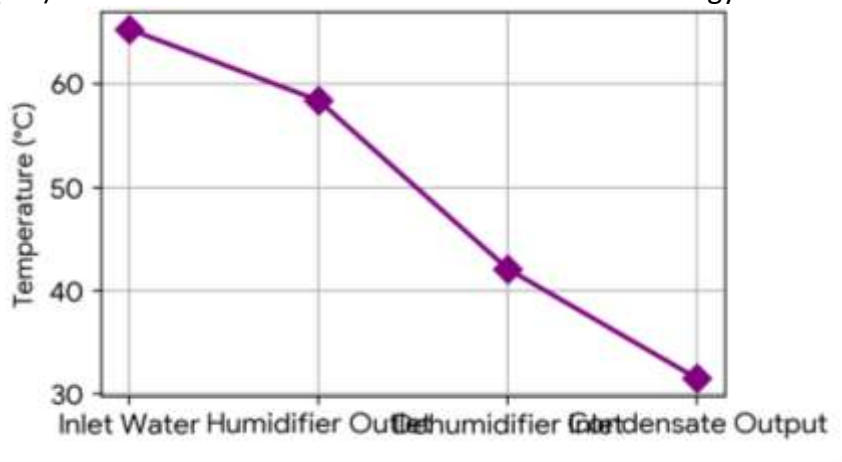


Figure. (1.5): Temperature Distribution along HDH System Components.

• Effect of Air Mass Flow Rate

Figure (1.6) illustrates the effect of the air mass flow rate ($\dot{m}_a$) on system productivity. It is observed that system productivity increases proportionally with the air mass flow rate. Specifically, at an air mass flow rate of $\dot{m}_a = 0.005$ kg/s, the productivity is approximately 3.25 kg/day, whereas at $\dot{m}_a = 0.05$ kg/s, it reaches approximately 11.25 kg/day—representing an approximate fourfold increase. The underlying thermodynamic mechanism can be explained as follows: Generally, the wet-bulb temperature of the air exiting the solar air heater decreases as the air mass flow rate increases. For a constant water mass flow rate supplied from the tank to the humidifier, the dry-bulb temperature of the air leaving the humidifier drops, approaching the wet-bulb temperature of the incoming air, which subsequently lowers the water temperature in the tank. Consequently, the evaporation rate within the humidifier declines, leading to a reduction in the moisture content of the exiting air. Furthermore, a higher air mass flow rate increases the relative humidity of the air leaving the dehumidifier, which would otherwise tend to depress productivity. However, the dominant competing effect is that the air leaving the humidifier—despite its lower specific humidity—carries a substantially greater total mass flow of water vapor to the dehumidifier, resulting in a net increase in overall system productivity.

Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

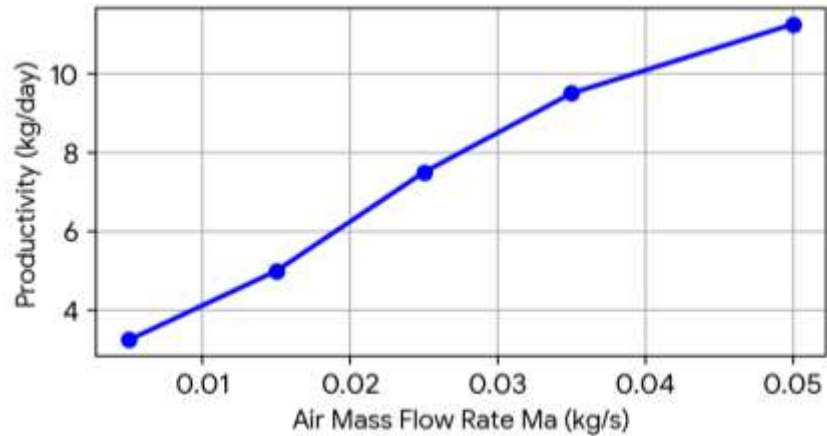


Figure. (1.6): Effect of air mass flow rate on productivity.

- **Effect of Humidifier Water Inlet Mass Flow Rate**

Figure (1.7) depicts the impact of the water mass flow rate entering the humidifier on system productivity. System productivity exhibits an upward trend as the inlet water mass flow rate increases, rising from approximately 7.75 kg/day at $M_{w1} = 0.005$ kg/s to about 9.3 kg/day at $M_{w1} = 0.05$ kg/s.

This behavior occurs because the temperature of the water entering the humidifier is higher than the wet-bulb temperature of the incoming air. Upon direct contact within the humidifier, the water temperature decreases while the wet-bulb temperature of the saturated exit air rises toward the incoming water temperature. This thermal interaction enhances the moisture content of the air leaving the humidifier, thereby driving a corresponding increase in overall system productivity.

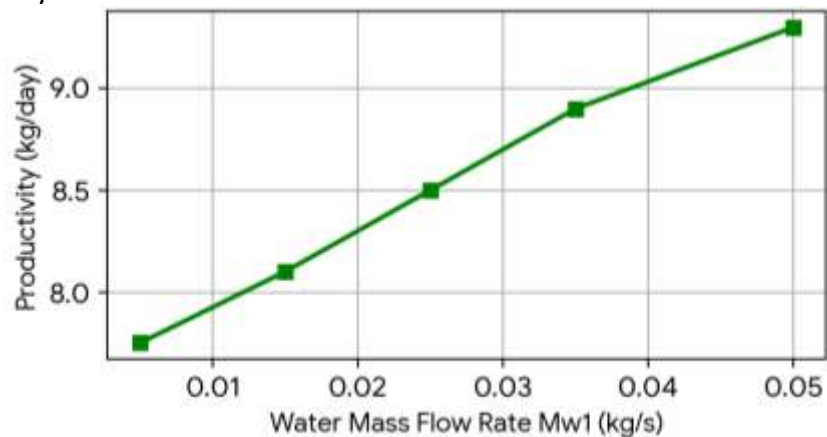


Figure. (1.7): Effect of the water mass flow rate entering the humidifier on system productivity.

- **Effect of Dehumidifier Cooling Water Mass Flow Rate**

Figure (1.8) shows the influence of the cooling water mass flow rate within the dehumidifier on system productivity. System productivity increases significantly with the flow rate of the cooling water entering the dryer coil, escalating from approximately 2.5 kg/day at $M_{w3} = 0.005$ kg/s to 9.0 kg/day at $M_{w3} = 0.05$ kg/s. This enhancement is driven by higher water velocities within the

Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

coil, which intensify forced-convective heat transfer from the moist air stream to the cooling fluid. Consequently, the rate of water vapor condensation on the tube surfaces accelerates, yielding a proportional increase in freshwater production.

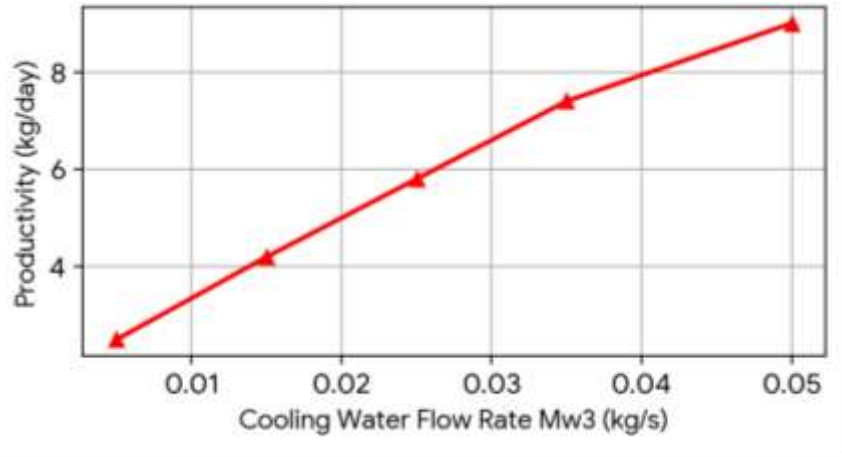


Figure. (1.8): Effect of cooling water mass flow rate on system productivity.

- **Effect of Initial Tank Water Temperature**

Figure (1.9) demonstrates the effect of the initial water temperature in the storage tank on system productivity. System productivity rises markedly with higher initial water temperatures, increasing from approximately 7 kg/day at an initial temperature of 25°C to about 16.5 kg/day at an initial temperature of 50°C. Raising the initial tank water temperature elevates the temperature of the water entering the humidifier, which increases the specific humidity of the air exiting the humidifier and directly enhances system output.

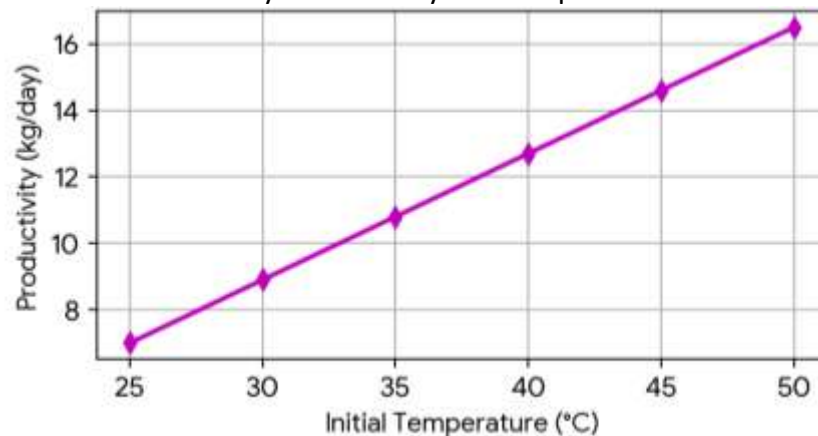


Figure. (1.9): Effect of initial water temperature in the storage tank on system productivity.

- **Effect of Cooling Water Inlet Temperature**

Figure (1.10) illustrates the effect of the cooling water inlet temperature (T_{w3}) entering the dehumidifier on system productivity. Increasing the cooling water or coil inlet temperature leads to a pronounced reduction in system productivity, dropping from approximately 10 kg/day at $T_{w3} = 14^\circ\text{C}$ to about 2.25 kg/day at $T_{w3} = 23^\circ\text{C}$. This inverse relationship is attributed to the elevation of the cooling coil surface temperature, which reduces the thermal gradient

Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

necessary for vapor condensation, thereby diminishing the condensation rate and overall system yield.

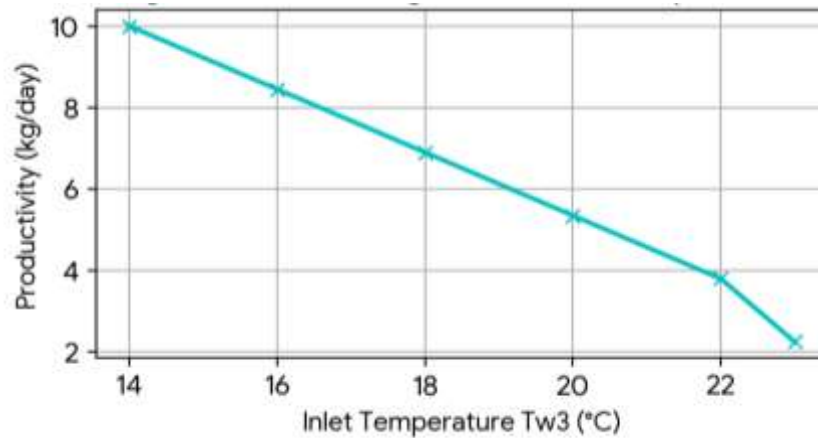


Figure. (1.10): Effect of the cooling water inlet temperature on system productivity.

- **Effect of Solar Air Heater Surface Area**

Figure (1.11) highlights the impact of the solar air heater surface area (A_c) on system productivity. Expanding the surface area of the solar air heater substantially enhances system output, increasing productivity from approximately 9 kg/day at $A_c = 0.5 \text{ m}^2$ to about 11 kg/day at $A_c = 2 \text{ m}^2$. The enlarged surface area increases the thermal energy absorbed by the air stream, elevating the exit temperature of the air heater and enhancing its moisture-carrying capacity within the humidifier.

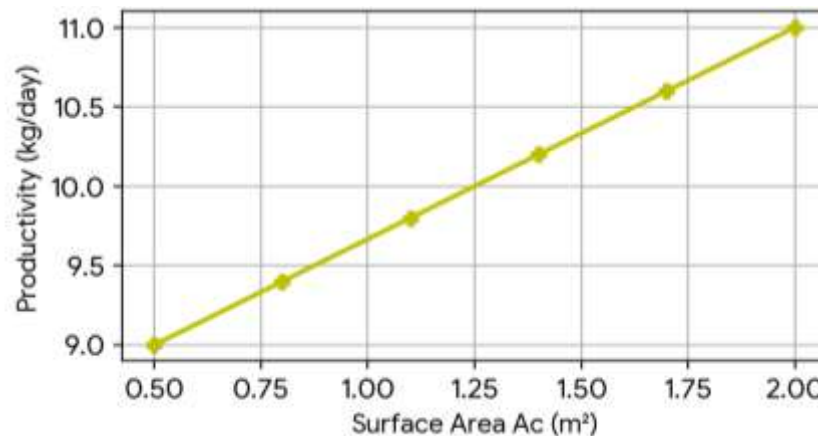


Figure. (1.11): Effect of the solar air heater surface area on system productivity.

- **Effect of Initial Water Mass in the Storage Tank**

Figure (1.12) presents the variation of system productivity as a function of initial water mass in the storage tank (m_{ws}) across different humidifier water mass flow rates. System productivity improves with an increase in the initial water mass within the tank, particularly when coupled with higher water mass flow rates entering the humidifier. Maintaining a larger initial water mass—at a constant initial temperature—mitigates the transient temperature drop that ordinarily occurs as water circulates into the humidifier. As a result, the supply temperature entering the humidifier remains elevated, preserving high evaporation rates and maximizing

Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

system productivity, provided the water temperature exceeds the incoming air's wet-bulb temperature.

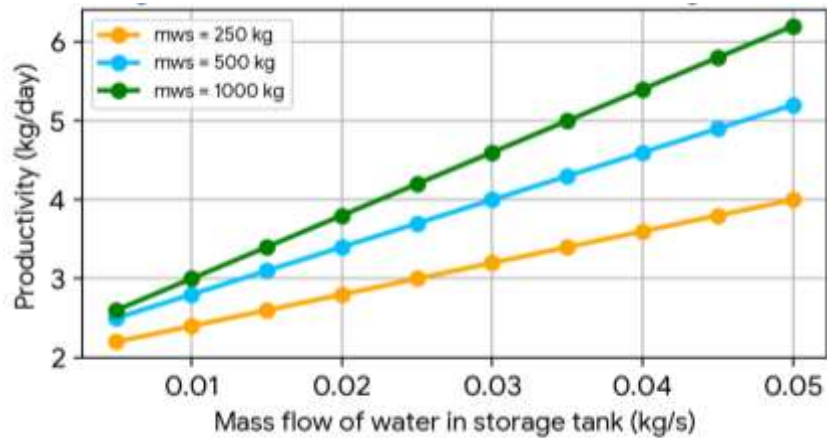


Figure. (1.12): Effect of initial water mass in the storage tank on system productivity.

VI. ENERGY AND EXERGY PERFORMANCE ANALYSIS

Looking at the systems energy use shows where the biggest losses happen, The humidifier and solar panel have the losses because of the temperature differences during heat and mass transfer, Changing the flow of air and water helps reduce these losses and makes the system better.

VII. ECONOMIC AND FEASIBILITY ASSESSMENT

Looking at the cost of the HDH system shows it is a good choice for rural areas, The costs are lower because there is no fuel and not much maintenance is needed, Calculating the cost to make water shows the system is good for making water in areas in North Africa.

VIII. CONCLUSION

This study looked at how a solar-powered Humidification–Dehumidification (HDH) desalination system works in the hot summer weather of Tripoli, Libya. The results from the computer simulations show that how the system operates and the way the main parts are designed make a difference in how much freshwater it can produce.

When the mass flow rates of the air and water go up the amount of freshwater produced also goes up. The same thing happens when the water in the storage tank is warmer and theres more of it at the start. This happens because more thermal energy is available to run the desalination process and keep the system going during the day.

Cooling conditions also matter a lot. Lower temperatures for the cooling water and higher flow rates help the condensation process. This is because the heat transfer between the air and the cooling surface becomes better. As a result more water vapor turns into liquid. Can be collected as freshwater.

Increasing the surface area of the air heater helps to gather more solar thermal energy. This gives the HDH unit heat energy to work with. This shows that choosing the size for the solar air heater is very important when building the system for the local climate.

Performance Analysis and Numerical Simulation of a Solar-Powered Humidification-Dehumidification (HDH) Desalination System under Tripoli Climate Conditions

In the conditions tested in this study the system produced about 10 to 12 kilograms of freshwater each day during the summer in Tripoli. These results suggest that this solar-powered HDH system could be an option for small-scale and off-grid freshwater production. It could be especially useful in remote areas where regular water supplies or large desalination plants are not easy to get.

In all the study shows that picking the right air and water flow rates setting up the thermal storage properly managing the cooling water conditions and choosing the right size for the solar air heater can all boost the performance of the HDH desalination system. More testing under conditions in Libya along, with a full techno-economic and environmental analysis would help give a better idea of how well this system could work in practice.

REFERENCES

- [1] Y. Al-Juhaibi et al. 'Performance optimization of solar-powered HDH desalination systems in arid microclimates,' *Water Treatment*, vol. 312 P. 114520 2024.
- [2] H. Ben Bacha and H. H. El-Ghetany 'Numerical and thermo-economic assessment of air open-water HDH desalination cycles in North African climates,' *Renewable Energy*, vol. 204, Pp. 345–358, 2023.
- [3] M. A. Darwish and N. Al-Najem 'Heat and mass transfer analysis in packed-bed humidifiers for desalination' *Applied Thermal Engineering*, vol. 240 P. 122104 2025.
- [4] M. Zamen et al., 'Impact of storage tanks on the productivity and stability of solar-driven HDH systems' *Energy Management*, vol. 253 P. 115160 2022.
- [5] A. E. Kabeel et al. 'Advances in solar-driven humidification-dehumidification desalination technologies,' *Journal of Cleaner Production*, vol. 380 P. 134950 2023.
- [6] M. H. Sharqawy et al. 'Thermo-performance of scale-decentralized solar desalination systems for rural communities' *Energy* vol. 288 P. 129712 2024.
- [7] G. P. Narayan et al., 'Analysis of humidification-dehumidification desalination cycles,' *Desalination* vol. 321 Pp. 100–115, 2022.
- [8] A. Chafidz et al. 'Performance enhancement of HDH desalination systems using packed-bed configurations' *Applied Energy*, vol. 355 P. 122290 2025.
- [9] A. Dahmani et al. 'Numerical aspects of a air open-water HDH desalination unit, under African weather conditions' *Renewable Energy*, vol. 210 Pp. 512–525, 2023.
- [10] M. M. Farid et al. 'Multi-stage humidification-dehumidification desalination coupled with collectors focusing on energy and exergy' *Thermal Engineering Progress*, vol. 45 P. 102140 2024.