Research on Innovative Freshwater Generation Through Hygroscopic Solar Chimney

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Abstract

This study focuses on the design of a novel freshwater-generating system using a hygroscopic solar chimney. The system will use solar chimneys and desiccant dehumidification methods to capture water vapour from the surrounding air and create freshwater. The study looks at the operation characteristics of the liquid desiccant system, such as air flow rate, desiccant solution, humidity, and regeneration. Meteorological data from the Gaza region are used to assess the system's performance. Calculations are performed to estimate water vapour partial pressure, air volume, mass of dry air, the mass of water vapour, specific humidity, moisture content, and moisture absorption. The results show that the suggested system may generate freshwater from ambient air in arid and semi-arid environments, contributing to a sustainable water supply.

1. Introduction

Water is a vital natural resource for all living things, including humans, and is a key global resource problem. With the world's population projected to reach 9 billion in the next 30 to 50 years, the demand for energy and water resources is set to rise. A transformative system that generates electricity and provides a sustainable source of fresh water is needed. A solar chimney system, which combines a turbine, chimney, and solar collector, maximises water generation by harnessing solar energy and the hygroscopic properties of certain materials [1, 2]. Hygroscopic substances absorb moisture, capture water vapour and promote condensation, enhancing water collection efficiency. This innovative synergy demonstrates the potential of combining renewable energy technologies with hygroscopic principles to address water scarcity [3].

The research explores the inadequacies and environmental impacts of current freshwater generation techniques in Gaza, exacerbated by dry weather and dwindling traditional water sources. The study proposes a creative solution using a solar chimney and hygroscopic materials [4] to provide a sustainable, energy-saving alternative to fossil fuel-fuelled desalination operations. This innovative approach aims to address water scarcity issues by offering a more flexible and sustainable method of freshwater production.

Fig. 1 *The Solar Up Trust Tower*

There were mainly two objectives, which were to conduct detailed moisture content calculations under various climatic conditions to optimise the hygroscopic solar chimney-based freshwater generation system and to evaluate the scalability and practical feasibility of the optimised hygroscopic solar chimney system in regions with severe water scarcity.

The literature review of this investigation about the solar chimney and hygroscopic material was done thoroughly. Many variables need to be considered in this investigation. Many previous studies investigating solar chimneys and desiccant systems have been done, as summarised in Table 1. So, this study will calculate the moisture absorption of hygroscopic material using the previous design of solar chimney. In this study, the main content of this investigation will be the material of the desiccant and the amount of water absorption produced by the hygroscopic system. The moisture absorption rate will be affected by the type of material desiccant. According to the previous research data, the meteorological data of Gaza [1, 4, 5] in January 2023 were used to calculate the moisture absorption using the relative humidity (RH) and the temperature, which is maximum and minimum RH is 87% and 87%, respectively and for the maximum and minimum temperature is 31.7 °C and 9.2 °C respectively. The key operating parameters and the physical properties of the solar chimney used for the calculation are in Table 2 and Table 3.

Table 1 *Previous studies related to moisture extraction from the atmosphere*

Year	Author	Finding
2023	Weather Atlas [4]	Gaza experiences a subtropical steppe climate with varying temperatures, rainfall, and humidity levels. The best time to visit is spring, with moderate temperatures and reduced rainfall.
2023	Mortadi, M., & Fadar, A. E. [1]	The chapter highlights the potential of solar energy to meet global energy demands and address energy security and environmental concerns, while also highlighting the role of solar thermal systems.
2020	S. Mahal, et al. [2]	The study explores a novel integrated solar chimney and liquid desiccant system, revealing insights into efficiency, power generation, and freshwater production, but not specific key findings.
2019	Kumar, G. [1]	The study highlights the effectiveness of desiccant cooling systems in controlling moisture content, offering benefits like ozone-depleting coolants, lower energy consumption, and potential for hybridization.
2007	Burek, S. A. M., & Habeb, A. [6]	The mass flow rate and thermal efficiency of a solar collector are influenced by both heat input and channel depth.

Table 2 *Operating condition fixed in parametric*

Case	Value of the inlet parameter				
	T_{al}	m_a	y_{al}	T_{sl}	X_I
	°C	kg/s	kg_{wv}/kg_a	°C	kg_d/kg_s
Desiccant inlet concentration, X_I	33	0.037	0.0221	32	0.302-0.400
Desiccant inlet temperature, T_{sl}	33	0.037	0.0221	28-38	0.302
Inlet air humidity ratio, y_{al}	33	0.037	0.0175-0.020	32	0.302
Inlet air mass flow rate, m_a	33	0.037-0.047	0.0221	32	0.302
Inlet air temperature, T_{al}	28-34	0.037	0.0221	32	0.302

Table 3 *Chimney Parameters*

Component	Value/description
Construction land dimensions, (Length (m) x Width (m))	10 m × 10 m
Collector radius (RC), (m)	2.5 m
Collector canopy height (hC), (m)	0.5 m
Chimney radius (RT), (m)	0.1 m
Chimney height (HT), (m)	6.5 m

2. Methodology
2.1   Water Vapor Partial Pressure

We determined water vapour partial pressure using the relative humidity equation. The RH for the air is defined as:

$$RH = \frac{p_v}{p_s} \tag{1}$$

The Arden Buck approximate equation calculates the saturated partial pressure of water vapour, where "t" represents the ambient temperature.

$$p_s = 611.21 \cdot \exp\left(\frac{\left(18.678 - \frac{t}{234.5}\right) \cdot t}{257.14 + t}\right) \tag{2}$$

2.2   Volume of Air
A particular formula must be employed to calculate the dry air volume within the collector.

$$V = \pi r^2 \cdot h \tag{3}$$

V = Volume of air (m³)
r = Radius of collector (m)
h = Height of collector (m)

2.3   Mass of Dry Air

To determine the partial pressure of dry air (pd) at a given relative humidity, we can subtract the vapor pressure (pv) from the total atmospheric pressure (p).

$$pd = p - pv \tag{4}$$

To determine the mass of dry air, we can use the ideal gas equation PV = nRT, where P is the pressure, V is the volume, n is the number of moles, R is the ideal gas constant, and T is the temperature

$$n = \frac{(PV)}{(RT)} \tag{5}$$

Finally, to determine the mass of dry air at both temperatures:

$$\text{Mass of dry air} = n \times \text{molar mass of dry air} \tag{6}$$

2.4   Mass of Water Vapor

We determined the amount of water vapour by utilizing the provided equation, which calculates the mass of water vapour.

$$mass\ of\ water\ vapor = \frac{p_v \times volume\ of\ air}{(Gas\ constant \times T_{ambient} + 273.15)} \tag{7}$$

2.5   Specific Humidity

To determine the specific humidity, which is the ratio of kilograms of water vapour per kilogram of dry air (kg/kg), we can use the following equation

$$SH = \frac{mass\ of\ water\ vapor}{(mass\ of\ water\ vapor\ +\ mass\ of\ dry\ air)} \tag{8}$$

2.6   Moisture Content

Using the provided equation to calculate the moisture content, which is the product of specific humidity (kg/kg) and volume of air (m^3), we can determine the values for the minimum and maximum temperatures.

$$Moisture\ content = Specific\ humidity\ \left(\frac{kg}{kg}\right) \times volume\ of\ air\ (m3) \tag{9}$$

3. Results and Discussion

3.1 Mathematical calculation

We have calculated a detailed analysis of the mass of water absorbed by clay paint in a solar chimney system. The analysis considers several critical data points, including the relative humidity range (74% to 87%), ambient temperature (t_a), Water Vapor Adsorption Capacity (20% by weight), and Equilibrium Moisture Content (10% by weight). These parameters help researchers understand the moisture dynamics within the system, accurately model the system's design and performance, and optimise water absorption and storage. The study also considers the impact of varying thermal conditions on the paint's water adsorption behaviour. The findings apply to various real-world scenarios and can be applied to various solar chimney systems. The detailed analysis of these key data points contributes to the overall efficiency and effectiveness of the solar chimney system.

3.2 Water Vapor Partial Pressure

The calculated water vapour partial pressures are shown in Table 4.

Table 4 *Results of water vapor partial pressure*

RH (%)	Ambient Temperature (°C)	Saturated Water Vapor Partial Pressure (Pa)	Water Vapor Partial Pressure (Pa)
74	9.4	1092.063	808.127
87	31.7	3381.136	2941.588

3.3 Volume of Air

The calculated volume of air in the collector is shown in Table 5.

Table 5 *Result of the volume of air in the collector*

Collector Radius (m)	Collector Height (m)	Volume of Air (m^3)
2.5	0.5	9.815

3.4 Mass of Dry Air

The calculated mass of dry air is shown in Table 6.

Table 6 *Mass of dry air in the collector*

RH (%)	Ambient Temperature (°C)	Partial Pressure of Dry Air (kPa)	Mass of Dry Air (kg)
74	9.4	100.492	12.154
87	31.7	98.358	11.037

3.5 Mass of Water Vapor

The calculated mass of water vapour is shown in Table 7.

Table 7 *Calculated mass of water vapour in the collector*

Ambient Temperature (°C)	Water Vapour Partial Pressure (Pa)	Volume of Air (m^3)	Mass of Water Vapour (kg)
9.4	808.127	9.817	0.0971
31.7	2941.588	9.817	0.330

3.6 Specific Humidity

The calculated specific humidity is shown in Table 8.

Table 8 *Calculated specific humidity*

Ambient Temperature (°C)	Specific Humidity (kg/kg)
9.4	0.0079
31.7	0.0290

3.7 Moisture Content

The calculated moisture contents are shown in Table 9.

Table 9 *Calculated moisture contents*

Ambient Temperature (°C)	Specific Humidity (kg/kg)	Volume of Air (m^3)	Moisture Content (kg)
9.4	0.0079	9.817	0.0776
31.7	0.0290	9.817	0.2847

3.8 Moisture Absorption

The predicted water absorption quantity is shown in Table 10

Table 10 *The predicted water absorption quantity*

Ambient Temperature (°C)	Mass of Water Vapor (kg)	Water Vapor Adsorption Capacity (%)	Mass of Clay Paint Required (kg)	Equilibrium Moisture Content (%)	Mass of Water Absorbed by Clay Paint (kg)
9.4	0.0971	20	0.4855	10	0.0486
31.7	0.330	20	1.65	10	0.165

3.9 Discussion

Understanding the interaction between clay paint and moisture in solar chimney systems is crucial for optimal performance [7, 8]. Clay paint, known for its natural and environmentally friendly properties, helps maintain moisture equilibrium within these structures [9]. Its ability to absorb water vapour changes with temperature, requiring careful consideration of environmental parameters. Equilibrium moisture content helps engineers and designers manage moisture levels effectively, ensuring efficient performance in various climatic conditions. Clay paint's scalability allows for changes in application volume based on weather conditions, ensuring durability and effectiveness. Educating stakeholders on clay paint's role in solar chimney systems can improve performance and reduce environmental impact, making it a valuable resource for engineers, architects, and environmentalists.

4. Conclusion

The study investigated creating an innovative freshwater generating system that combines a liquid desiccant dehumidification device with a solar chimney. The study examined the important elements that influence the performance of a liquid desiccant dehumidification system, including air flow rate, desiccant characteristics, humidity, and the regeneration process. Detailed mathematical modelling and calculations were performed to estimate the proposed system's water vapour partial pressure, air volume, dry air, the mass of water vapour, specific humidity, moisture content, and moisture absorption capacity. Data from the Meteorological Department in Gaza was utilized to evaluate the system's performance under local climate circumstances. The findings illustrate the viability and promise of the hygroscopic solar chimney system for producing freshwater, particularly in areas with high humidity and sun irradiation.

The hygroscopic solar chimney system is being developed to improve its freshwater generation capabilities. The system will be tested through experiments and trials to validate mathematical models and optimise design parameters. The researchers suggest integrating renewable energy sources like photovoltaic solar panels to enhance efficiency and self-sufficiency. The system's scalability and geographic feasibility will be assessed to determine its potential for widespread deployment in diverse regions facing freshwater scarcity. A comprehensive techno-economic study will evaluate the system's cost-effectiveness, identifying key cost drivers and financial hurdles. The system must also collaborate with stakeholders to ensure it addresses the specific freshwater needs and challenges of target regions. By addressing these recommendations, the researchers aim to improve, optimise, and evaluate the hygroscopic solar chimney system, paving the way for its successful deployment and widespread adoption as a long-term solution to freshwater scarcity.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

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