Analysis and Validation of Fresnel-Lens based Solar Heat Accumulator for Auxiliary System of Passive Solar Distillation Device

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Abstract: This paper proposes enhancements to a thermohaline convection-based solar distillation device, aiming to maintain self-reliance. It discusses recent developments in multistage solar distillation and describes a passive system design with gravity feed and simulated thermohaline convection to reduce salt accumulation. The incorporation of an air gap between the membrane and condenser is highlighted, output regulation and improved heat transfer. The proposed conceptual design includes a dynamic Fresnel lens on an elevated platform to ensure consistent sunlight intensity across the solar absorber's surface. An auxiliary system with electronic control monitors the lens array's angle correlation using a microcontroller and two stepper motors. Closed control feedback loop is Solar panels and rechargeable batteries provide the necessary electricity and stores surplus power for future use. Overall, the enhancements provided an increased energy supply to the solar absorber, thus enhancing the distillation system's efficiency while maintaining self-sufficiency.
The proposed auxiliary system aims to provide a robust, scalable design reference for passive solar distillation devices, a necessary innovation for coastal economy upliftment.
Keywords: *thermohaline convection; solar heat intensifier; closed control feedback loop; Fresnel lens; solar tracker algorithm.*

1. Introduction

In the quest for sustainable water supply solutions, the utilization of solar energy holds significant promise. Solar distillation, a technology harnessing solar radiation to produce freshwater, has garnered attention for its potential to address water scarcity issues. Recent advancements in multistage solar distillation have demonstrated notable improvements in water production rates and diminishing salt accumulation, offering a ray of hope for regions grappling with freshwater shortages.

Thermohaline convection [9] refers to the movement of water driven by variations in temperature and salinity. In oceanography, it plays a crucial role in redistributing heat and nutrients, influencing climate patterns and marine ecosystems. The system [2] under consideration, uses it to reduce salt deposition. For energy collection, a Fresnel lens [8] is being used as they are capable of effectively collimating light rays from a point source.

2. Background

The scarcity of fresh water in islands and remote coastal economies is a pressing challenge due to limited natural groundwater sources, unpredictable rainfall, and contamination issues [2]. Despite, the potential of desalination plants to provide a solution, their high setup costs remain a barrier. Not to mention the recent humanitarian crises observed due to military conflicts; leaving thousands if not millions without proper access to potable water. [4] Also as climate change intensifies more and more countries will be dealing with rising sea levels and rapid depletion of fresh water resources. Hence better and easier desalination is needed for the future.

Our system aims to improve on the current design [2] to provide a compact, completely self-sufficient solar powered desalination device, to be used in such situations by amplifying the passive system's operational efficiency, while keeping it independent by the use of solar powered electronic control system and Fresnel lens. Our design acts as an auxiliary system to focus more solar radiation on the solar absorber/intensifier to make it more efficient.

3. Materials and Methods

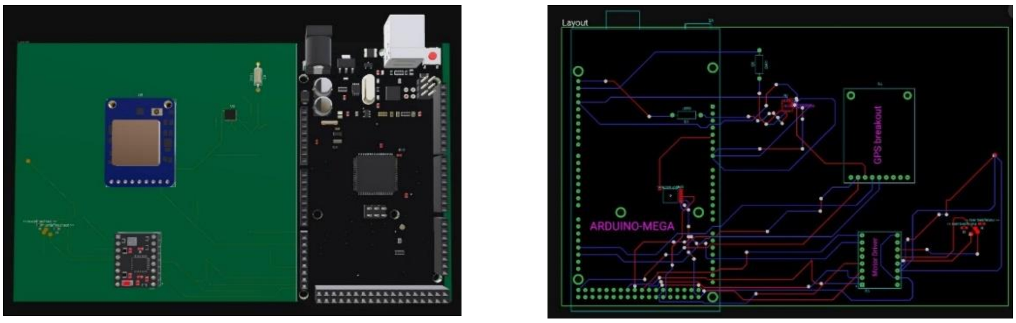
The objective of this paper is to develop a system to focus available sunlight on the solar absorber using a solar powered electronic system to control a Fresnel lens set on a dynamically adjustable platform which will orient itself for maximum convergence of sunlight throughout the day.

[7] Blackened chromium is chosen as the solar heat accumulator for the auxiliary system due to its high solar absorptance coefficient (0.95) and tolerance to temperatures higher than 300°C. [10] Implementation of solar tracking algorithm is undertaken due to an established observation of at least 24% rise in efficiency of photovoltaic cells, a similar effect was expected to enhance operational efficiency of the auxiliary system as well.

3.1. Electronic Architecture

i. The electronics architecture was designed to achieve a robust modular PCB as output, which could be reproduced easily for the specified auxiliary system. It is compact and two-layered for simplicity and allowing for scalability when increased workloads are to be encountered. It comprises of the following components:
ii. Two generic bipolar stepper motors with two coils; one for rotation step angle of distillation device and another for controlling tilt angle of Fresnel lens platform.
iii. Arduino Mega 2560 - MPN as the microcontroller and the logic unit for establishing sensor-actuator control flow mechanism.
iv. Two A4988 motor drivers for PWM signal based control of stepper motors.
v. 12-bit Motion sensing rotary encoder module for accurate monitoring and correction of step-angle output of the motors
vi. GPS breakout board for providing input to solar tracking algorithm uploaded into the microcontroller memory.
vii. 2 x 10k ohm resistors for pulling down voltage levels between non-compatible PWM channels
viii. Integrated solar cell charger circuit for recharging the power supply system of the auxiliary system.
ix. Li-Po/Li-ion battery packs for rechargeable power supply.

Figures 1.a, 1.b illustrate the PCB design and 3d Render of components used for the electronics architecture.



a. 3D render b. PCB layout

Figure 1. Electronics architecture illustration

3.2. Support Structure

The support structure was designed to perform the task of providing adequate maneuverability, flexibility and strength along requisite points for maintaining functionality of the device while enhancing its efficiency. It is provided with a large cylindrical reservoir to store freshwater produced, the reservoir has a tube passing through its center, the base of which houses the stepper motor control PCB. The reservoir has hydraulic piston jointed tubes attached to it which provide support for the Fresnel lens platform. A wedge of base angle 30 degrees is kept fixed on top of the reservoir. The wedge allows the desalination device to remain at its required angular alignment. Figure 2 illustrates a 3D render of the support structure with the Fresnel lens in position.

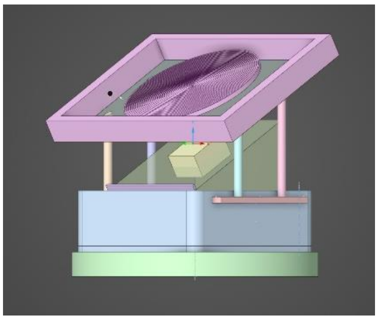


Figure 2. Support structure

3.3. Fresnel Lens Analysis

The analysis and viability check of Fresnel lens was carried out using Ansys Speos, a commercial optical system design software.

The lens area is calculated using Equations (3.1) through (3.3)

$$W_{L1} = \frac{V_{FW} \times k_{L1}}{\sum_{i=1}^{i=n} k_{Li}} \times \rho_{SW} \tag{3.1}$$

$$E_{req} = W_{L1} \times (c.\Delta t + 2260) \tag{3.2}$$

$$Area_{req} = \frac{E_{req}}{E_{abs}} \tag{3.3}$$

Where, W_{L1} is Sea water input weight in Layer 1; V_{FW} is Volume of required fresh water; k_{Li} is coefficient of proportionality of the layer(i); E_{req} is Energy required for evaporation; c is specific heat of water; E_{abs} is Energy absorbed per unit area. For a given value of V_{FW}, applying the formulas (5.1 through 5.3) we obtain the required area of the Fresnel lens corresponding to it.

Lens specifications for analysis:

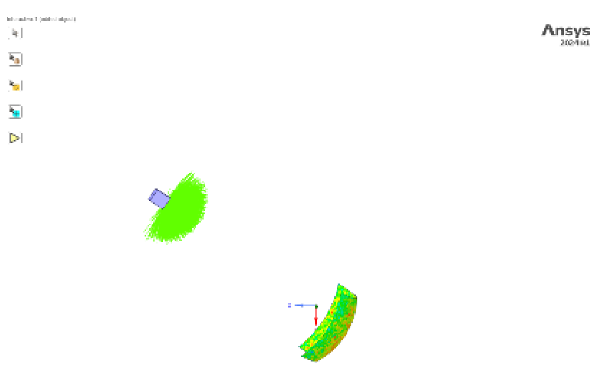
- a. Shape: Circular
- b. Diameter: 588.72mm
- c. Steps: 72
- d. Step Height: 2.32mm
- e. Step Angle: 16.4 degree
- f. Refractive index: 1.71

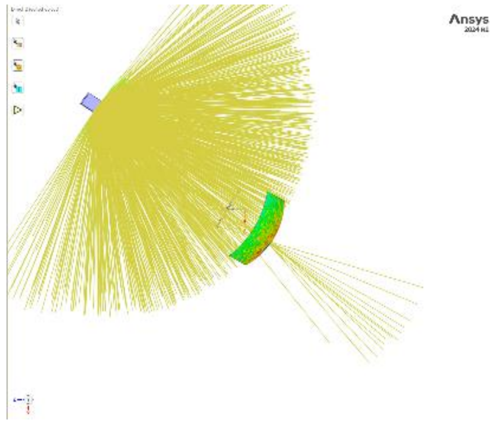
Source specifications:

- a. Surface- Luminous intensity (cd): 125600 cd (Daylight)

Setup specifications:

- a. Length b/w source and lens: 2186.47mm
- b. Length b/w lens and intensity sensor: 727.35mm

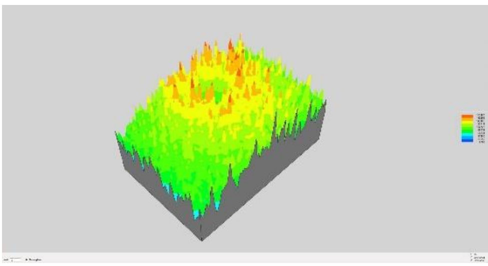


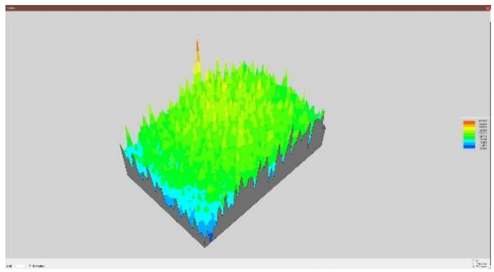


a. Interactive + direct render win

b. Interactive + direct render without lens

Figure 3 iIllustrates the outcome of test for light collimating properties of Fresnel lens.





c. Intensity 3d graph with Lens

d. Intensity 3D graph without Lens

Figure 3. Ansys simulation of Fresnel lens impact

Hence, we can observe converging characteristics of the Fresnel lens selected and we can determine that the focal length of the lens is about 730mm from the source. Hence the power of the 1.367 Diopter.

It is indicated conclusively in past designs of the passive solar distillation devices(which have a freshwater production rate of 4 to 6 liters per hour)[2] that a higher number of semi-permeable membrane separated desalination layers leads to a higher freshwater volume output. Due to transfer of heat via conduction between layers. Here we had assumed 4 layers for distribution of the total input volume of seawater. All estimates and calculations for arriving at various demonstrated results have been inferred from the first layer (LAYER 1) from (Table 1) since it is in direct contact with the solar heat accumulator of the auxiliary system provided and is therefore directly affected by oncoming solar radiation.

Table 1. Multi-Layer distillation setup

	Proportions	Volume of sea water per Layer (L)	
LAYER 1	2.2	1.354	2.030
LAYER 2	1.8	1.110	1.661
LAYER 3	1.4	0.861	1.292
LAYER 4	1.1	0.677	1.015
Total	6.5	4	6

[14] The average solar irradiance on the surface of the earth on an area of one meter square is 1360 watts hence the energy received per hour is 4896 kJ. We have demonstrated the analysis for the same in Final_Calc_IAMU.xlsx (6.2), where the energy received is obtained as the product of the actual energy received and the product of absorptance factor of black chromium.

Density of seawater (1.025 kg/L), Latent heat of vaporization (2260kJ/kg) and specific heat of water (4.168 kJ/kg℃) are assumed as constant values for operating on values of (LAYER 1), we find that, average energy required to desalinate 1.44-2.15 kg of seawater, we require 4651.98 kJ of heat which is sufficiently provided by the oncoming irradiance (4896 kJ).

Upon implementation of the proposed auxiliary system which involves the use of [13] a solar tracker algorithm the estimated rise in efficiency of the system proposed, is found to 11.11% to 19.44%.

4. Results and Discussions

The estimations for rise in efficiency are extremely conservative and do not take into consideration the fact that water starts evaporating at a much lower temperature than its boiling point (100℃), Thereby in Final_Calc_IAMU.xlsx (6.2), we perform all operations over an 80℃ range. A median yearly temperature of 18.8℃ (for Dew point) [6] by operating on relative humidity values of the discussed region [6] for a year is obtained, this temperature is sufficient for water to start evaporating into the air at normal atmospheric pressure, however the estimates of this thesis are intentionally conservative in order to demonstrate the clear advantage the adaptation of such auxiliary systems might bring about for passive solar distillation devices.

The estimated increase in efficiency is as follows (Table 2):

Table 2. Estimated efficiency enhancement

	Absorbed Energy (KJ)	Average water (Kg)	Efficiency Increase (%)
With 5% Loss	5348.88	2.06	11.11
With 0% Loss	5581.44	2.15	19.44

5. Conclusion

In conclusion we find that even with an extremely conservative estimate, the proposed auxiliary system provides an increase in efficiency in the range of (11.11% to 19.44%). The auxiliary system is designed to be scalable over a large range of volume of seawater to be desalinated. The two-layer PCB, simple-easily reproducible support structure and easy availability of Fresnel lenses of varying sizes commercially are made while taking into consideration the aim of providing a self-sufficient system that can tend to varying freshwater requirements [1]. Hence, we have attempted to arrive at a formula for estimating the scalability of similar auxiliary systems. We consider the freshwater volume requirement on a per hour basis for the particular use case and provide the requisite area of Fresnel lens to be used for the setup. However an upper limit of redundancy is observed whereby upon providing increasingly large freshwater volume requirements, the effectivity of the auxiliary system stagnates and an overall loss of self-sufficiency occurs. To avoid this, it is recommended to split the volume into multiple smaller subsystems.

6. Instructions for access:

6.1. The PCB layout design, Ansys simulation files and the 3D model for the auxiliary structures can be found at https://github.com/Nidus11857/IAMUC-2024-PAPER

6.2. The estimations for the analysis mentioned are to be found in Final_Calc_IAMU.xlsx

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