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ORIGINAL ARTICLE

Performance enhancement of a single slope solar still with single basin using Fresnel lens

Parimal S. Bhambare[1], Dinesh K. Kaithari[1], Said Abdullah Rashid Al Hosni[1]

[1] Mechanical and Industrial Engineering Department, College of Engineering, National University of Science and Technology, Muscat, Oman

ABSTRACT – This paper presents an experimental study using Fresnel lens to increase the overall efficiency of the conventional Single Slope Solar Still (SSSS) with single basin. The work aims to increase the performance of single basin conventional SSSS while maintaining the simplicity and usability of the system. Especially in the rural parts of Oman, the device is very simple to use. For the present unit, the conventional single basin SSSS has been fitted with an adjustable Fresnel lens. The adjustment enables the carrying out the experiments with and without the Fresnel lens at our Institute. The equipment was constructed from simple available materials and was placed north-south during the experimentation. The Fresnel lens fitted frame once adjusted in the morning was kept at same position for the entire day without tracking. The depth of water in the basin was maintained constant at 0.02 m during the study. The distillate yield for single basin SSSS fitted with Fresnel lens is observed 3 to 3.5 times higher than the conventional. The overall efficiency of the system has also increased almost 32.19 percent over the conventional. The quality of the distillate was assessed, which was estimated to be within limits in compliance with international standards. In conclusion, Fresnel lens has significantly improved the distillate production output and overall efficiency of conventional single basin SSSS.

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Single slope solar still; distillation; Fresnel lens; solar energy

INTRODUCTION

Water is one of the fundamental primary elements needed for life to occur on any part of the Universe. The survival of earthly life is because of the availability of water. Just 0.33 per cent of the total water available in this world is suitable for practical use as fresh water [1]. Regardless of the rapid industrial developments worldwide, most water bodies get polluted [2]. Pure and clean water is the right of every citizen. Various methods and procedures are used to produce safe, drinking water for use [3]. Water distillation is one of the different processes that are used for industrial and domestic applications to obtain safe and potable water. This process is an energy intensive process which requires electrical and/or thermal energy obtained from fossil fuels that are not renewable.

Solar stills are the simplest devices used to obtain distilled water and are used in nearly all locations where solar energy is available. In the process of solar distillation, water is vaporized, separating the water vapors from the dissolved salts / impurities, which are condensed as pure and clean water. In remote locations, fresh drinking water has to be brought from a long distance away. Solar desalination is important in this regard and is therefore used to convert salt / brackish / dirty water into distilled water. Moreover, the design of the system is simple and user-friendly.

Figure 1 shows the schematic diagram of a simple single slope, single basin type solar still with its components. Solar radiations entering through the transparent glazing (glass) is absorbed [4] by the glazing (5%), water (5%) and absorber plate (90%). The heat absorbed by saline or the brackish water and the absorber plate, in turn, evaporates, leaving the impurities behind. The water vapors further condenses on the inside surface of the glazing (glass) in the form water droplets and glides over it to be collected as the distillate.

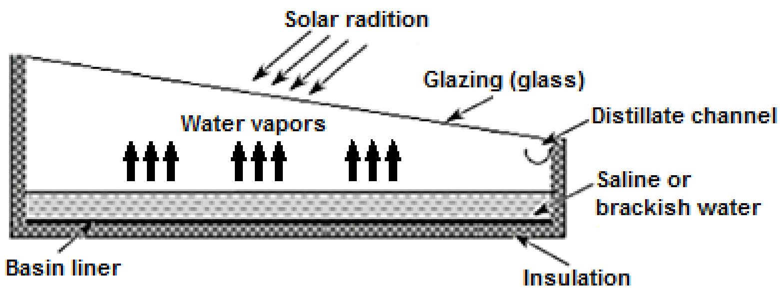

Figure 1. Components of single slope type Solar Still [5]

*CORRESPONDING AUTHOR | Parimal S. Bhambare | ✉ parimalbhambare@nu.edu.om

Apart from climatic conditions and solar insolation at the location, the efficiency of the solar stills is affected by various parameters such as: thermo-physical properties of glazing, the temperature and the inclination of the glazing, the insulation material and its thickness, the material of the basin liner and its absorptivity, the depth of the water in the basin, the number of basins, the temperature of the inlet water and the basin water, etc.

Several researchers have made efforts to improve the performance of the single slope type solar still by varying one or more parameters. Abhay Agarwal and Rana [6] used multiple V-shaped floating wicks in conventional single basin SSSS, which increased the surface area of the conventional still by 26%. This increased the annual output of the distillate by 47.08%. Rees, et.al [7] investigated the effect of nano Al_2O_3 mixed with basin fluid along with jute cloth. Overall, an increase of 15% in distillate output was observed during the study. Amey Pednekar, et.al [8] used an additional reflector mirror and a water cooled condenser in a conventional single basin SSSS. The distillate output could be increased from 2.2 lit/m^2 for the basic still to maximum of 4.6 lit/m^2 with the modified still. Deshpande et.al, [9] used internal, external reflector and black granite gravel to improve SSSS performance. A total improvement in distillate output of 29 - 80% output has been observed with the system. Granite gravel produced the highest output in the basin compared to the other two arrangements. Assari et.al [10] presented an innovative single basin SSSS with external rotating mirrors. The modified system increased the distillate output by 64% over the conventional system. Kabeel et.al [11] provided a comparison between single basin inclined solar still (ISS) with baffles, conventional solar still (CSS) and conventional – inclined solar still (CSS- ISS). Productivity and overall efficiency increased by almost 200% with the CSS-ISS and was the highest of all arrangements. Although many researchers have used different methods to maximize daily water distillation in a single basin solar system, the efficiency could be increased to a maximum of 60% with an overall yield of 2-11 lit/m^2/day [12,3,13,14].

Fresnel-based non-imaging refractive lenses are distinguished by light weight, small size, lower cost, wide opening and short focal length, when compared to conventional lenses. These are used for various solar energy applications. Rajesh et. al [15], used a Fresnel lens in a direct active single basin SSSS connected to a solar heater tank. The system improved overall system efficiency to 55%. Ravishankar et. al [16] investigated the modified solar still with convex lenses on the cover of glass and blue stones as an energy storage material. The total output of the distillate has increased by 35.55% over the conventional type. Sriram et.al [17], used a Fresnel lens on a double / multi-slope pyramid, a single basin solar still. The distillate output of 1.99 L/m^2/day was reported. Ana et. al [18] presented a theoretical model for simulating the performance of a single SSSS basin with external solar enhancement. Experiments with a Fresnel lens fitted single basin SSSS system from the literature, to validate the model showed 638% improvement in the performance of the system. Lei Mu et.al [19], discussed the performance improvement analysis of a single SSSS basin using a manually tracked Fresnel lens. The overall system configuration is complex for the number of parts involved and the operation. Nucleate boiling significantly increased the coefficient of heat transfer, which improved the overall system productivity by 467% over the traditional SSSS.

From the literature review, it could be concluded that very few studies have been reported on solar still distillation using Fresnel lens. The present work aims to improve the performance of conventional SSSS while maintaining its simplicity and usability. For its construction, simple available materials have been used. Moreover, as it does not require tracking similar to conventional single basin SSSS, it can be easily operated with minimal skills in the rural settings of Oman.

MATERIALS AND METHODOLOGY

Experimental Set Up

The basin (79 cm x 54 cm x 50 cm) of the fabricated single basin SSSS was made from galvanized iron sheet of thickness 3 mm in the form of a box.

The bottom surface of the basin exposed to sunlight is coated with black board paint for enhancing the absorptivity of the surface [20]. The basin is contained in the wooden box constructed using plywood of thickness 12 mm, with shorter side of 80 cm height and longer side 105 cm height from ground. The gap between the two is filled with glass-wool insulation of thickness 50 mm.

The inclination of the glass cover equal to the Muscat latitude ($23.588^o \sim 24^o$), has been used. This ensures the beam radiation strikes normal to the plane of the glass [21,22] for the maximum annual energy availability. Non corrosive PVC channels have been used for collecting the distillate. Toughened glass of 6 mm thickness and size 1168.4 mm x 914.4 mm is used as the normal glass for the system.

The toughened glass is fitted in a frame made up of 1.5 inch wooden bottom patti. The frame rests on rubber seal placed on the inclined surface. Silicone has been used to seal all the gaps between the toughened glass and frame. This part serves as the conventional single basin SSSS unit for the testing and analysis.

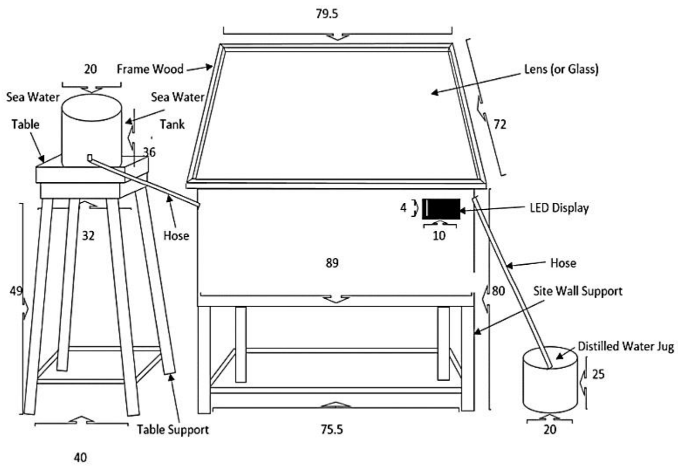

Figure 2. Front view of the system layout

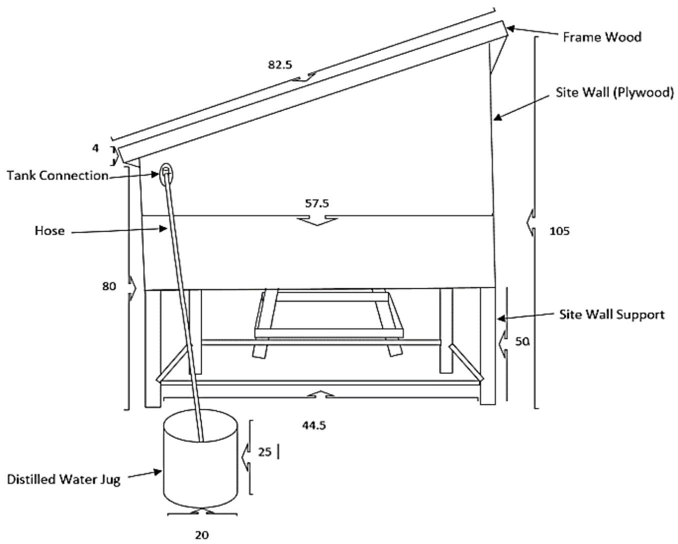

Figure 3. Side view of the system layout

Fresnel lens of size 1168.4 mm x 914.4 mm fitted in a frame of wooden bottom patti of size 1.5 inch is fitted over the normal glass with two hinges at the front side. The Fresnel glass can be lifted and either held in a position over the toughened glass while adjusting the focal point at the bottom of basin or can be kept aside by turning down. This facilitates to test the SSSS with or without the Fresnel lens. Front view and side view of the system with dimensions in centimetre is shown in Figures 2 and 3. The photographs of the actual system are shown in Figure 4.

J-type thermocouples with an accuracy of 0.75 % were used to measure the glass, sea water and ambient temperatures. These thermocouples were connected to the LED display placed at the front side of the solar still. The selector switch allows measuring the respective temperatures. The solar pyranometer of Kipp and Zonen installed in the weather station at our institute was used to measure the solar insolation. The accuracy of pyranometer taken from the manufacturer's catalogue is ± 1 W/m^2. The basin was filled with sea water at a depth of 0.02 m. The productivity at this depth has been observed highest from the literature [11,21,19]. The depth of sea water was maintained constant during the study using a small sea water tank and float kept inside the basin. The solar still was placed North - South (N-S) during the entire testing.

Each experiment was performed for 8 hours in a day from 8 am to 4 pm during summer in May 2019 at our institute. The solar still was tested for a complete day alternatively with and without the Fresnel lens. For experimentation with Fresnel lens, the lens was adjusted once in the morning for its focal point at the bottom of the basin. The position of the lens was then kept constant throughout the day. For this position, the solar radiations are received at the bottom of the basin after passing through the Fresnel lens and the normal glass. For testing the still as conventional single basin SSSS, the Fresnel lens was turned down about the hinges exposing the normal glass to the direct solar radiations. Temperatures were recorded hourly from the LED display using the selector switch. The distillate output was hourly collected and measured using a measuring jar connected to the PVC channel from the solar still. Solar radiation data on hourly basis for the day were obtained from the weather station installed at our institute. TDS, thermal conductivity and turbidity of the water has been measured using the available equipment at the institute laboratory for assessing the quality of the water before and after the experimentation.

Figure 4. Photographs of the fabricated system

Thermal Efficiency Calculation

The overall thermal efficiency of the basic still with toughened glass is calculated using the following relation,

$$\eta_g = \frac{m_w \ x \ h_{fg} \ x \ 1000}{\left[\sum_{i=8\ am}^{4\ pm} I_{bi}\right] x \left(\tau_g \ x \ \tau_w \ x \ \alpha_b \ + \ \alpha_w \ x \ \tau_g\right) \ x \ A_s \ x \ 3600} \tag{1}$$

where, m_w and h_{fg} are the mass of distillate in kg collected at the end of the experimentation and latent heat of evaporation in kJ/kg for water at average basin temperature respectively. A_s and I_b are the basin surface area in m^2 and beam radiation in W/m^2 respectively. Table 1 show the radiative properties of toughened glass, water and Fresnel lens used during the analysis.

Table 1. Radiative properties [5]

Property	Value
Transmissivity of the glass, τ_g	0.9
Transmissivity of the water, τ_w	0.67
Transmissivity of the Fresnel lens, τ_F	0.9
Absorptivity of basin liner material, α_b	0.9
Absorptivity of water, α_w	0.3
Absorptivity of glass, α_g	0.05

When the Fresnel lens is used along with the normal toughened glass the overall thermal efficiency of the system is calculated using the following relation,

$$\eta_F = \frac{m_w \: x \: h_{fg} \: x \: 1000}{\left[\sum_{i=8\,am}^{4\,pm} I_{bi}\right] x \left(\tau_g \: x \: \tau_F \: x \: \tau_w \: x \: \alpha_b \: + \: \alpha_w \: x \: \tau_g \: x \: \tau_F\right) x \: A_s \: x \: 3600} \tag{2}$$

The latent heat of evaporation, h_{fg} at given basin water temperature, T_w in °C, is calculated in kJ/kg, using the following relation [23],

$$h_{fg} = 2503.3 - 2.398 \: x \: T_w \tag{3}$$

The partial pressures P_w and P_g in Pascal at the basin water temperature, T_w and the glass temperature, T_g respectively, are calculated using the following relation [24,25],

$$P(T) = \exp\left[25.317 + \frac{5144}{T + 273}\right] \tag{4}$$

The evaporative heat transfer coefficient, $h_{e,w-g}$ in W/m^{2}K between water and the internal surface of glass cover is calculated using following relation [5,25,22,26],

$$h_{e,w-g} = 16.273 \: x \: 10^{-3} \: x \: h_{c,w-g} \: x \left[\frac{P_w - P_g}{T_w - T_g}\right] \tag{5}$$

The convective heat transfer coefficient, $h_{c,w-g}$ in W/m^{2}K, between water and the internal surface of the glass cover is calculated as [11,25,26],

$$h_{c,w-g} = 0.884 \: x \left[(T_w - T_g) + \frac{(P_w - P_g) \: x \: (T_w + 273)}{268.9 \: x \: 10^3 - P_w}\right]^{\frac{1}{3}} \tag{6}$$

The heat transfer by evaporation, Q_{e-w} and the theoretical distillate output, m_{ew} in kg per hour is calculated using the following relation,

$$m_{ew} = \frac{Q_{e-w}}{h_{fg}} \: x \: 3600 \tag{7}$$

$$Q_{e-w} = A_s \: x \: h_{e,w-g} \: x \: (T_w - T_g) \tag{8}$$

RESULTS AND DISCUSSION

Basin water and glass temperature comparison

The hourly changes in basin water, glass and ambient temperatures for SSSS with and without Fresnel lens along with daytime solar insolation are shown in figures 5 to 8 below. From Figures 5 and 6 it can be seen that the difference in solar radiation and ambient temperatures for both the days of experiment used for comparison is small. Thus the results for both these days can be compared with each other without much error. From Figures 5, 6 and 7 it can be observed that the basin water temperature for SSSS with Fresnel lens is higher than that of conventional SSSS.

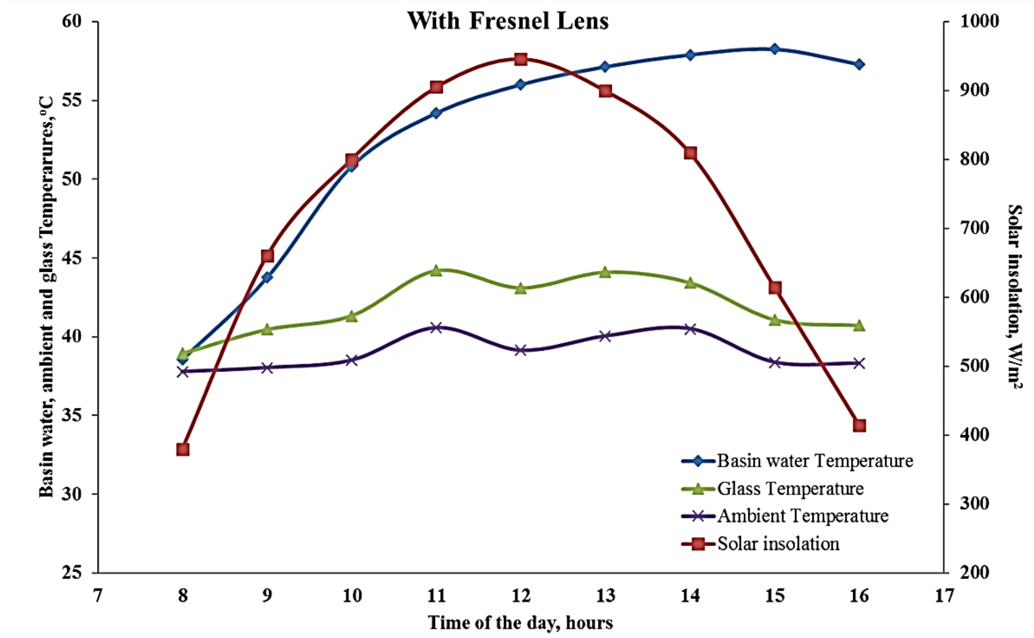

Figure 5. Hourly variations of temperatures – basin water, glass & ambient temperatures and solar insolation conventional SSSS with Fresnel lens

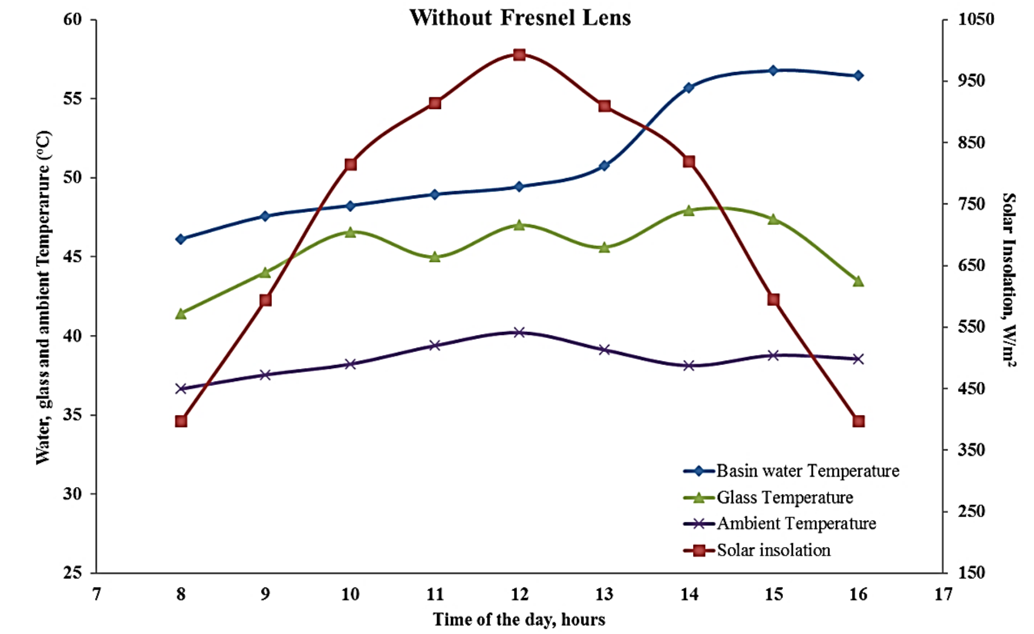

Figure 6. Hourly variations of temperatures – basin water, glass & ambient temperatures and solar insolation for conventional SSSS without Fresnel lens

For SSSS with Fresnel lens, the difference in basin water (Tw) and ambient (Tamb) temperature is 25 to 30 per cent higher on average than conventional SSSS. The Fresnel lens concentrate the solar radiation on the receiver, thus in turn increases the heat transferred and the heat gained by the water in the basin. Eventually when the heat gained by the water is higher over the losses, the temperature and the rate of evaporation of water at the basin increases [19]. This in effect has increased the distillate yield from the single basin SSSS fitted with Fresnel lens.

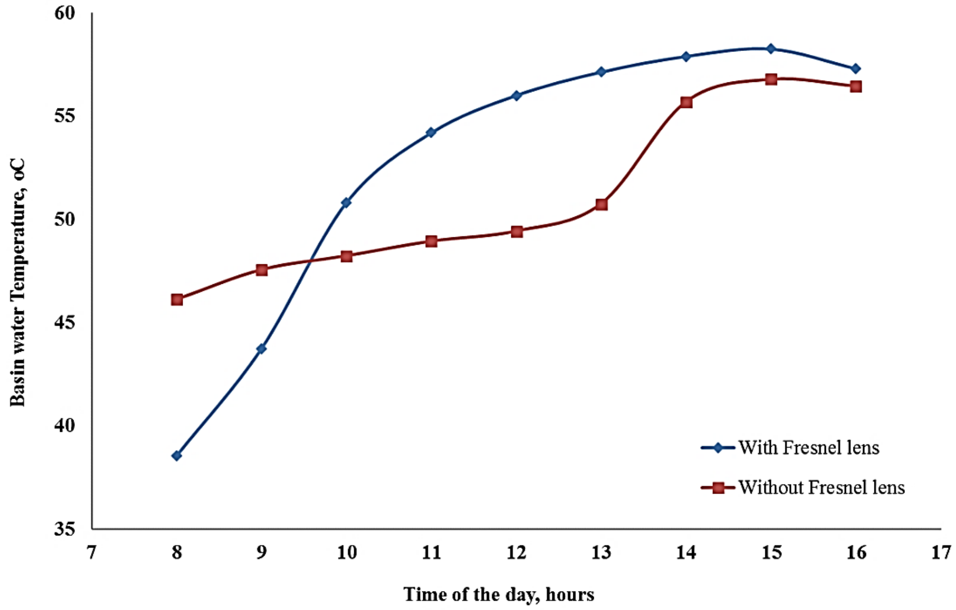

Figure 7. Basin water temperature comparison

Also, Figures 5, 6 and 7 demonstrate the comparison between glass temperatures for the conventional and Fresnel lens-fitted single basin SSSS. The inner toughened glass cover has very low absorptivity, and with the addition of Fresnel lens, it gets covered from direct sunlight. Moreover, the focus of the Fresnel lens is adjusted at the bottom of the solar still. Due to this, the glass temperature for SSSS fitted with Fresnel lens is observed lower than the conventional SSSS. It appears in Figures 5, 6, and 8. With the addition of Fresnel lens, the increased evaporation rate from the basin and the reduced glass cover temperature, increases the condensation rate over the inner surface of the glass cover and in turn helps to increase the distillate output from the SSSS fitted with Fresnel lens.

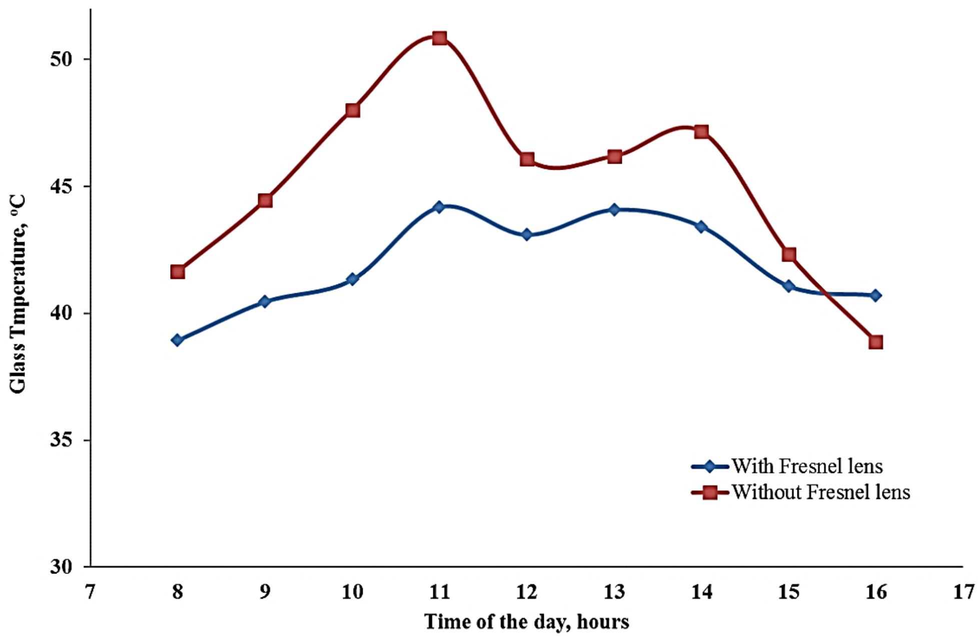

Figure 8. Glass temperature comparison

Evaporative Heat Transfer Coefficient (EHTC) and Distillate Yield Comparison

Figures 9 and 10 for both arrangements compare the distillate output and the Evaporative Heat Transfer Coefficient (EHTC). As contrasted with conventional SSSS the EHTC for SSSS with Fresnel lens is observed higher. The decreased glass temperature decreases the partial pressure at the glass while the elevated water temperature in the basin raises the partial pressure at the basin. That increases the EHTC for the Fresnel lens-fitted SSSS.

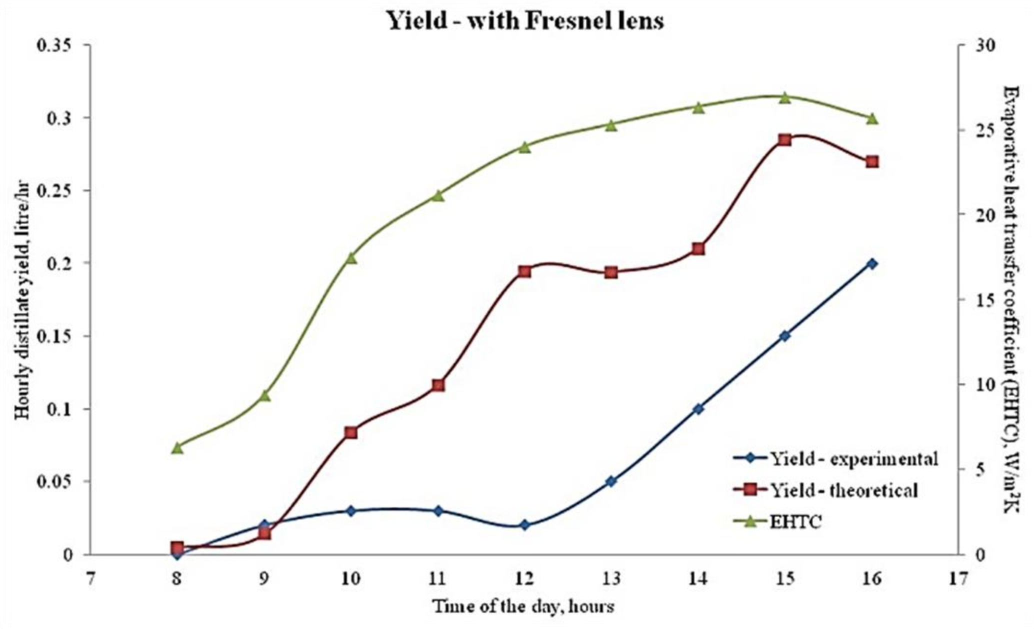

Figure 9. Hourly distillate yield and EHTC with Fresnel lens

The hourly distillate yield from SSSS fitted with Fresnel lens is always observed higher than the conventional SSSS. Figures 9 and 10 also complement this. For SSSS fitted with a Fresnel lens, the highest yield was collected as 0.2 L/day versus 0.05 L/day for conventional SSSS.

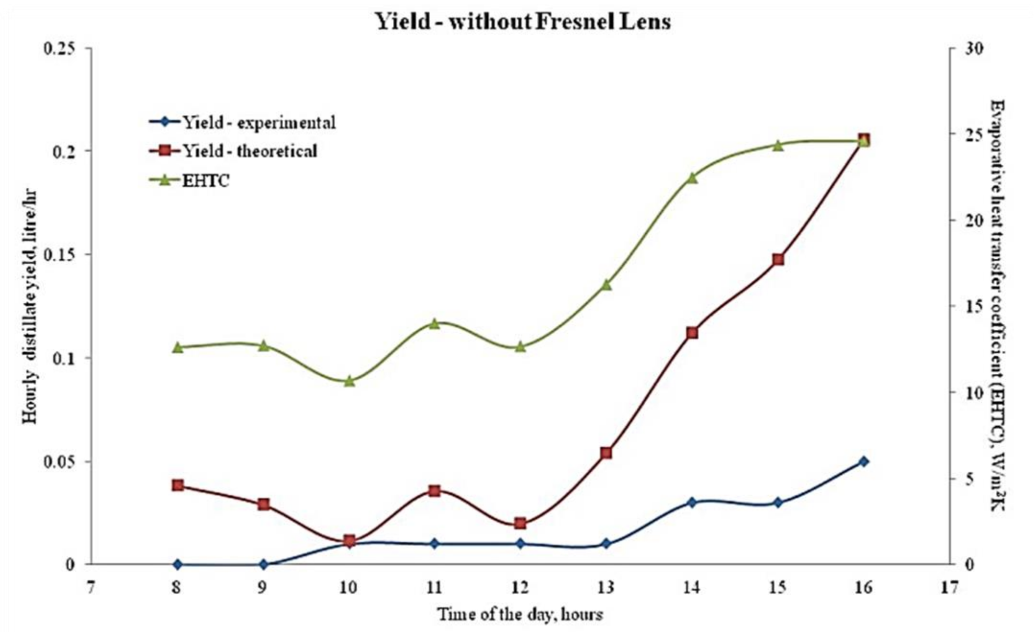

Figure 10. Hourly distillate yield and EHTC conventional SSSS without Fresnel lens

Experimental distillate outputs for SSSS with Fresnel lens are reasonably closer to theoretical output than those for conventional SSSS. Figure 11 compares the output of the distillate for SSSS with and without the Fresnel lens. The distillate yield is observed to be higher for the SSSS equipped with Fresnel lens throughout the day. The distillate yield of SSSS with Fresnel lens is on average 3-3.5 times higher than the conventional SSSS without Fresnel lens.

Figure 12 shows the graph for the cumulative output of the distillate collected for both SSSS arrangements. The cumulative distillate output collected from SSSS fitted with Fresnel lens is approximately 3.5 to 4 times the distillate output of conventional SSSS. This could also be seen from Table 2.

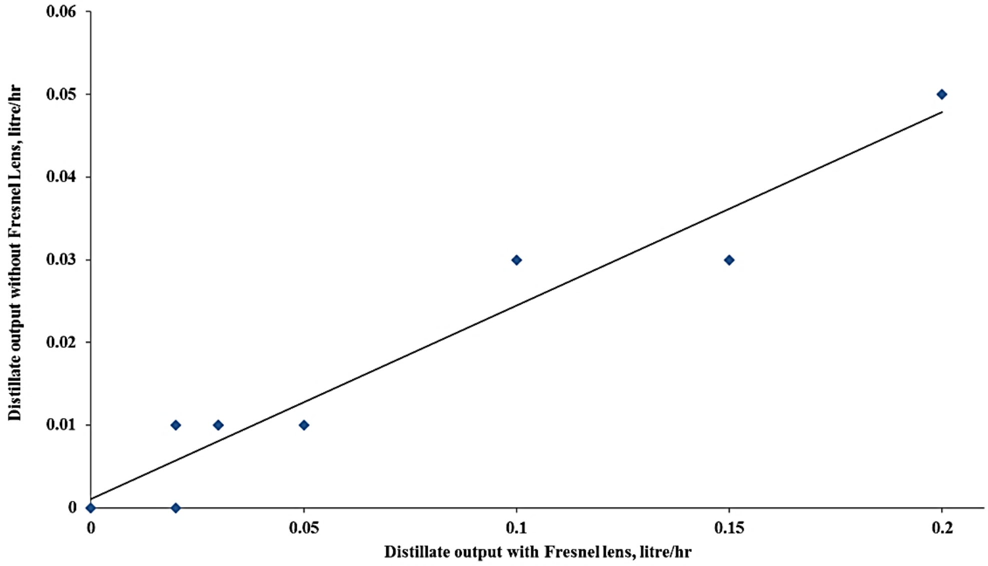

Figure 11. Hourly distillate yield comparison with and without Fresnel lens

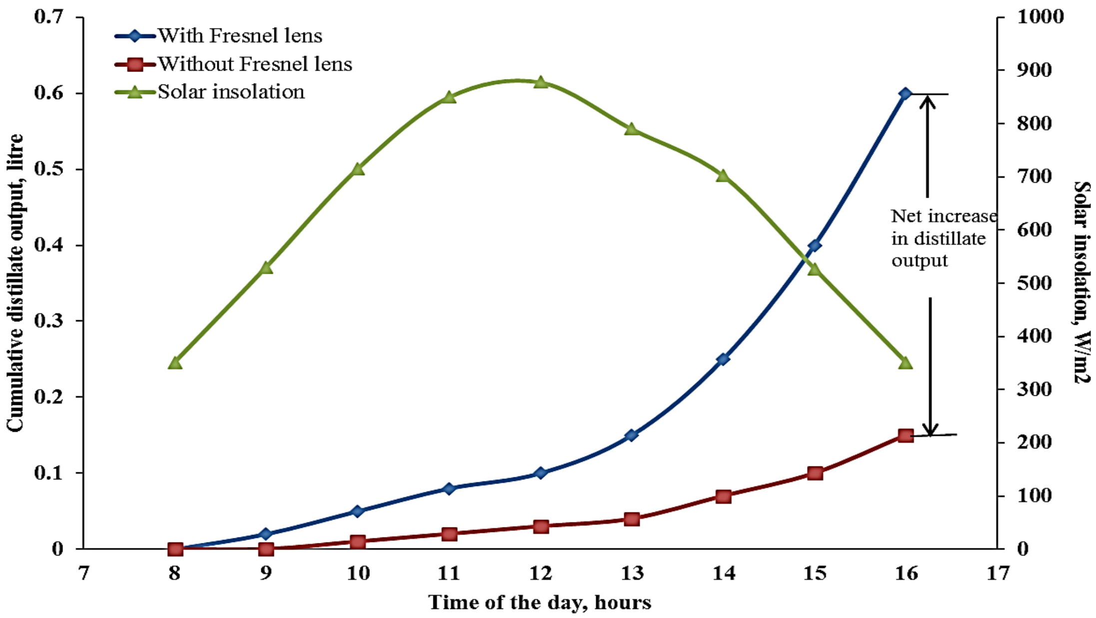

Figure 12. Cumulative distillate output comparison with and without Fresnel lens

Overall Thermal Efficiency

The overall thermal efficiency has been calculated using the equations 1 and 2 for both the arrangements. The overall thermal efficiency calculations for both the SSSS showed an average improvement of 32.19% in overall efficiency with the introduction of Fresnel lens for traditional SSSS. This can be seen from Table 2.

Table 2. Cumulative yield and average thermal efficiency comparison

	Average cumulative distillate yield, litre	Overall Thermal Efficiency
SSSS without Fresnel lens	0.165	11.76%
SSSS fitted with Fresnel lens	0.55	43.95%

Water Quality Testing

TDS, thermal conductivity and turbidity of the water are measured for the initial characterization of sea water sample used for the experimentation and noted. Further, these quality parameters are also measured for the distillate collected at the end of experimentation. The results are then compared with the international quality standards for drinking water. Table 3 shows the results of the characterization with the international quality standards for the drinking water.

Table 3. Comparative analysis of water samples before and after the experimentation

Parameter	Sea water	Distillate output	WHO standards [27-29]
TDS (mg/l)	33829	34.95	500
Electrical conductivity, mS/cm	59.59	0.06	NA
Turbity, NTU	6.73	1.17	5
pH	8.07	6.44	6.5-9.5

CONCLUSIONS

This paper has analyzed the performance improvement of conventional single slope solar still (SSSS) with single basin when integrated with the Fresnel lens. The modified solar still with Fresnel lens was built with simple materials and it inherits the conventional still's simplicity and usability. This is of particular benefit to Oman's remote and rural areas. With the addition of the Fresnel lens, the increased temperature of the basin water has enhanced the rate of evaporation of the water in the basin, which in effect increased the production of distillate from the single basin SSSS. An improvement of 3.5 to 4 times has been recorded during the study in the cumulative distillate output from the solar still fitted with the Fresnel lens. The overall thermal efficiency of the single SSSS basin has also increased from 11.76% to 43.95%. The collected distillate's qualitative analysis showed that its consistency matches the international standards. In conclusion, the experimental results showed that the incorporation of Fresnel lens significantly improves the distillate yield and the overall performance of the conventional single basin SSSS. For better results, the use of automatic tracking for Fresnel lens along with methods for improvising condensation rates over glass glazing, are recommended.

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