Performance and economic evaluation of a porous PVA floating wick in a solar still under concentrated solar energy

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Abstract

Solar still is becoming a promising solution for people in remote areas to convert brackish and saline water into potable water through distillation process. However the solar still's performance is still low. In order to improve the performance, various approaches are implemented by researchers. In the present study, solar interfacial evaporation technique is proposed. A porous PVA floating cloth is used to enhance solar-heat conversion and water absorption by capillarity action under concentrated solar energy. The concentrated solar energy is produced by beam down reflector installed at Stellenbosch University. The maximum evaporation rate observed in one of the clear days is found to be approximately 2.3 kg/m^{2}hr with efficiency of 71% under average concentrated solar beam of 2 kW/m^2. A mathematical model is developed by using the energy balance equations on the evaporation structure in the solar still. Fair agreement was seen between the model and experimental results. An estimated economic analysis based on the evaporation rate was also performed for the proposed solar still on a 10-year life cycle. Despite the high costing of the concentrating solar system, the proposed solar still is still economical.
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Keywords: Solar still, concentrated sunlight, interfacial evaporation.

1. Introduction

Many people in Asia and Africa living in rural areas are of low income class. About 900 million of these people do not have access to clean water supply that result in human health, high living costs and gender and other societal inequalities. The majority of the population in these areas are elderly, women and children who are illiterate and unskilled hence unable to cope with natural variability and its effects (Rural water development, 2022).

Rural water and sanitation support is more difficult due to development models characterized by varied cultural values and low economic conditions. Omarova et al. (2019) showcased that many villagers entirely rely on brackish water or free water sources due to scheduled water supply to rural areas. Moreover, acute shortage of water supply compelled residents to consume brackish water, water from open sources, and rain water.

To solve the aforementioned problem, traditional distillation methods were considered the best ways for purification of brackish water. Traditional technologies include reverse osmosis, multistage flash distillation, multi effect distillation and vapor compression distillation (Liu, Mishra & Wang, 2020). However, these technologies are still inadequate to meet the increasing demand for freshwater due to its high energy consumption which are not feasible in off-grid areas.

Solar energy as an alternative source has a vital role in enhancing the efficiency of the desalination process. South Africa receives significant solar irradiation with estimate annual average of 220 W/m^2 accounting to be one of the highest in the world (Department of Energy, 2021). Therefore, harnessing solar irradiation through concentrated solar system creates a great potential to reduce on the electricity generation through carbonization in South Africa. Furthermore, reduction of greenhouse gas emissions is required by Paris agreement where South Africa is a signatory. The agreement has committed the country to become carbon neutral by 2050 (Department Of Energy, 2021).

The solar distillation method uses solar energy to provide thermal energy, which allows water to be purified at a significantly reduced cost. When impure water is exposed to sunlight, it evaporates, causing water vapor to separate from the dissolved materials and condense as pure water. Because solar energy is free of pollution and charges, it is a well-established method for purifying brackish water.

A solar still is a device that uses the solar distillation process to produce drinkable water at a relatively low cost in rural areas. Solar stills can be fabricated using materials that are readily available locally. Solar stills are rectangular boxes with impure water inside that are firmly covered by glass cover. The heat from the sun causes the water in the basin box to evaporate and collected as pure water in the condensate form. Solar still is an effective tool for obtaining potable water in remote lands because they require minimum maintenance hence inexpensive.

The solar still's output and efficiency are significantly lower than those of other traditional distillation devices. The performance of solar stills was improved in a number of research studies. These includes, the researchers developing modified designs for various climatic and operational factors.

Dunkle *et al.* (V. 1961) provided mass and heat transfer equations to solve heat transfer coefficients of conventional solar still. The primary drawback of the solar still is its low productivity. Therefore, much has been published on the adjustments, such as increasing the evaporation surface area by using sponges, jute cloth, wick and various heat storage materials. Sodha *et al.* (1981) designed a multiple-wick solar still and used a black wet jute cloth to increase the evaporation rate. Al-Karaghouli & Minasian *et al.* (1995) compared the experimental distillate outputs of conventional basin-type solar stills and floating blackened jute wick. The floating blackened jute wick solar still was found to produce a higher amount of distillate than conventional still. He reported 10.5kg/m^{2}day under the same external environmental conditions. On winter days in Delhi, he obtained efficiency and distillate output of 34% and 2.5 kg/m^{2}day, respectively. Charcoal particles were used by Naim *et al.* (2003) to modify the conventional solar still. The particles acted as a heat-absorbing medium on the wick surface. An improvement of approximate 15% productivity was reported as compared to wick-type stills.

A new corrugated floating cum tilted-wick solar still with a flowing water effect above the condensing cover was analysed by Janarthanan *et al.* (2006). A thermal model of the solar still was developed, and heat balance equations were derived. The conclusion reached was that the experimental results were close to the theoretical results. The water flowing over the condensing cover also had a considerable impact on the thermal. Shukla & Sorayan *et al.* (2005) conducted theoretical and experimental performances of single and double slopes wick-type solar stills. For the proposed solar stills, he formulated analytical equations and a computer model. The results of the theoretical and experimental studies were found to be fairly in agreement. Black steel cubes, yellow and black sponge cubes, as well as coal were used by Abu-Hijleh *et al.* (2003) to boost the distillate yield in basin water, but it was discovered that sponge cubes were more efficient. When compared to a conventional still, the distillate yield of the cube-equipped still increased from 18% to 27.3%.

Sakthivel *et al.* (2010) used jute cloths that were attached to the middle and back wall of a conventional solar still. It was discovered that the still's daily productivity was 20% higher than conventional still. This modification improved the still's efficiency from 44% to 52%. Agrawal *et al.* (2013) performed experimental and theoretical investigations and altered the design of a conventional solar still by incorporating porous absorbers with low thermal inertia; strips of blackened jute cloth were used as the porous absorbers. On clear days, the modified still produced 68% while cloudy days, the distillate yield was about 35% higher than convention still. Srithar *et al.* (2011) looked into the effectiveness of a double-slope basin-type solar still using a variety of wick materials, including sponge sheet, waste cotton, light jute cloth, light black cotton cloth, and coir mat. Investigations were also conducted on various arrangements of rectangular aluminium fins wrapped in various wick materials. The light black cotton fabric tested outperformed the other materials in terms of daily distillate yield. It was discovered that the longitudinal configuration of rectangular aluminium fins with cotton cloth was more efficient.

Samuel *et al.* (2016) performed theoretical and experimental research on how to use various energy storage materials to increase distillate output. The maximum distillate output reported to be 3.7 kg/m^{2}day in the solar still with spherical salt balls, compared to 2.7 kg/m^{2}day with sponge and 2.2 kg/m^{2}day without any storage material. The productivity and heat transfer coefficients of conventional stills were compared experimentally and theoretically in Indian conditions for different basin water depths by Agrawal *et al.* (2017). It was observed that the distillate output reduces as the basin's water depth increases. The theoretical and experimental daily efficiency for 2-cm and 10-cm basin water depths were approximately 52.83% and 41.75%, and 41.49% and 32.42%, respectively. Modified versions of basin-type solar stills were modelled and tested by Matrawy *et al.* (2015). In his model, he submerged the black corrugated cloths on the porous material in water. The capillary effect caused the black cloths to absorb the water. When compared to conventional stills, the modified solar still's distillate output increased by about 34%.

Shalaby *et al.* (2016) provided the experimental performance assessment of the V-corrugated absorber solar still with and without phase-change material (PCM; in this example, paraffin wax). The daily productivity values of the PCM-equipped V-corrugated absorber solar still were inferred to be 12% and 11.7% higher than those of the PCM-free V-corrugated absorber solar still and the PCM-equipped V-corrugated absorber solar still, respectively. In a review of different wick-type solar still designs, Manikandan *et al.* (2013) found that the floating wick-type solar still had the best performance. Other types of wick-type solar stills included multi-wick and floating cum tilted-wick stills. Omara *et al.* (2016) investigated the performance of stacked wick materials and reflectors in conventional solar stills and corrugated solar stills. According to the findings, the modified solar still was 145.5% more productive than the conventional solar still for brine depths of 1 cm. The modified and conventional solar stills achieved daily efficiencies of about 59% and 33%, respectively.

Panchal and Mohan *et al.* (2017) examined a variety of strategies to boost the distillate output in a solar still. Numerous strategies used by earlier researchers were described, and the outcomes of various finned still designs, different energy storage materials, and multiple basins were evaluated. In addition to doing theoretical and experimental research on solar stills using sandstone and marble fragments as heat energy storage materials. Panchal *et al*. (2018) also looked at the effects of cooling and dripping techniques. It was discovered that the distillate yield of the solar still with sandstones and marbles improved by 30% and 14%, respectively, when compared to that of the conventional still. With the additional use of cooling and dripping provisions, the distillate production increased by 12%.A single-basin solar still's performance was increased by Sellami *et al.* (2017) by using blackened sponge sheets of varying thicknesses glued over the heat-absorbing surface. For the 5-mm and 10-mm thick sponge sheets, the performance of solar still improved by 57.77% and 23.03% respectively and for 15-mm thick sponge sheet, the output was 29.5% lower than that of conventional still.

Vala *et al.* (2017) conducted experiments to compare the performance characteristics of a pyramid-shaped still and a single-slope conventional still with and without jute cloth. The pyramid-shaped still's distillate output value was 26% higher in a shallow basin of water than the single-slope still, and both stills' efficiency was improved by the use of jute cloth. Sharon *et al.* (2017) assessed the performance of a tilting solar still with a wick and basin, they discovered that the daily distillate yield were 4.99 and 4.54 kg/m^{2}day, respectively. Kaushal *et al.* (2017) investigated the experimental efficiency of a single-basin vertical multiple-effect diffusion solar still using a floating cotton wick and heat recovery system. According to the study, the modified still's daily productivity was 21% higher than that without floating wick and heat recovery system. In order to enhance the performance of basin-type solar stills, Haddad *et al.* (2017) devised a vertical rotating wick. In winter, the daily distillate output was 5.03 kg/m^{2}day, whereas in summer 7.17 kg/m^{2}day was reported. Modi *et al.* (2019) used jute and black cotton cloths piled in a small pile over the absorber plate of solar stills to test the effectiveness of single-slope double-basin stills. According to the experimental findings, the distillate yields of the solar still with a with a small pile of jute fabric was 18.03% and 21.46% better that of a solar still with a small pile of black cotton cloth, respectively, at basin water depths of 0.01 and 0.02 m. The knitted jute cloths that are wrapped over the sand heat energy storage were used by Kabeel *et al.* (2018) to increase the productivity of conventional basin solar stills. At a 20-kg basin water mass, it was discovered that the modified solar still's distillate output was 18% than the conventional still

Arunkumar *et al.* (2018) improved the single-basin single-slope solar still by utilizing a porous absorber and bubble-wrap insulation. The daily productivity values of the solar still with bubble-wrap insulation, without bubble-wrap insulation, with both bubble-wrap insulation and a porous absorber, and with wooden insulation alone, were determined to be 2.3, 1.9, 3.1, and 2.2 kg/m^{2}day, respectively. Incorporating PCMs, nanoparticles, and various basin wick materials improved the thermal performance of a single basin solar still by Shanmugan *et al*. (2018). In a single basin solar still containing PCMs and nanoparticles, it was found that the distillate output values were 7.460 kg/m^{2}day during the summer and 4.120 kg/m^{2}day during the winter, respectively. Six-wick solar stills with humidification and dehumidification units were designed, fabricated, and their performance was examined by *Abdullah et al*. In addition to using various packing materials in the humidifier, the experiment was carried out in the inclined solar still at various water flow rates. 4 kg/min flow rate produced a higher distillate output value than 2 kg/min flow rate.

Rashidi *et al*. (2018) experimented black sponge rubber in a solar still to improve thermal performance. It was found that the modified still's productivity was 17.35% higher than the output of the conventional solar still. Manokar *et al.* (2018) examined the thermal efficiency of an angled solar panel basin solar still with active and passive modes. The daily productivity achieved in the active mode was found to be 44.63% better than that in the passive state. In the active and passive modes of solar still, the productivity values were 7.91 and 4.38 kg/m^{2}day respectively.

To the best of our knowledge, all experiments in the reviewed literature were done under natural sunlight and therefore no testing was done with concentrated sunlight. Moreover, the absorber plays a major role in the performance of the closed/semi-closed solar still. According to the literature, most researchers were investigating the overall performance of the solar still without knowing the effectiveness of the absorber in the solar still. This poses a need for exploration.

In the present work, experimental analyses are conducted to evaluate the performances of conventional (CSS) and modified semi-closed (MSS) solar stills. The MSS is incorporated with black-coated PVA cloth to enhance light absorption and evaporation. The experimentations are conducted to obtain various parameters such as evaporation rate, temperatures and solar flux in both stills. Moreover, the mathematical heat transfer model is developed and use measured temperatures in the experiment to predict evaporation rate on the absorber. The model results are then validated by experimental evaporation rate results. Finally, this study carried out an estimated economic viability of the proposed solar still.

2. Mathematical model

A mathematical model is formulated for the MSS by using energy balance equations on the evaporation structure. Control volume was created around the evaporation structure in the solar still for analysis as shown in Fig 2.The aim of the model was to calculate the mass flow rate through the structure. For simple analysis, the following assumptions were made

1. Steady state conditions
2. Air cavity region is dominated by water vapor
3. The water vapor in the domain participates in radiation
4. The absorber and the water vapor are grey bodies.
5. No heat loss or gain in the water basin and air cavity region from external conditions.
6. Water is considered as the wick since its thermal conductivity is higher than the PVA wick material

7. The physical property of EPS, , glass and water vapour absorptivity's are constant
8. The mass of water absorbed through capillary action is equal to mass of water vapour leaving the system.
9. Uniform temperature distribution in the underlying water, absorber surface and water vapour.
10. The water is heated up from a hot horizontal surface facing upwards so as to apply *Equation 8* for Nusselt number (Ganesan & Mills, 2009).
11. Capillary action by absorber on the sides is equal.

The energy balance on the evaporation structure

$$Q_{sol} + mh_l = Q_{conv} + Q_{rad} + Q_{cond} + mh_v \quad (1)$$

For mass conservation equation 1 becomes;

$$m = \frac{Q_{sol} - Q_{conv} - Q_{rad} - Q_{cond}}{(h_v - h_l)} \quad (2)$$

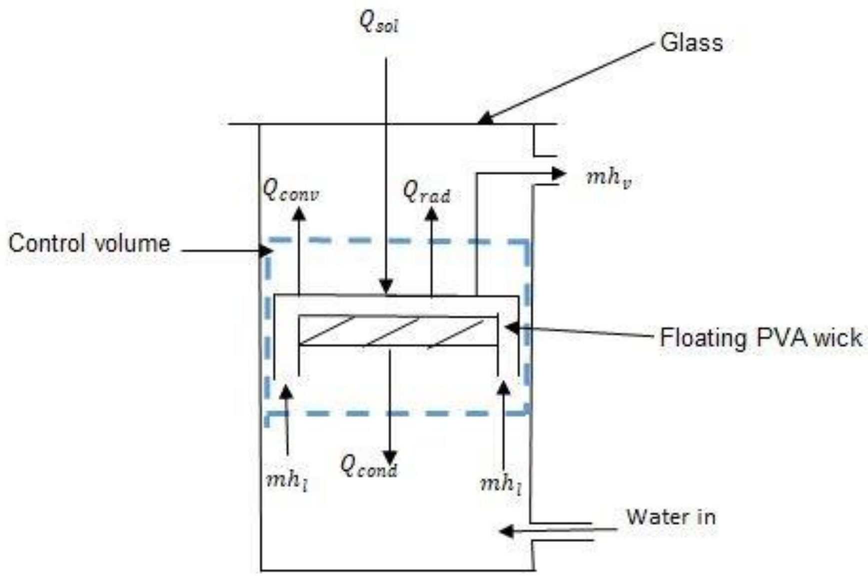

Fig. 1-Schematic diagram showing control volume and energy balance on the evaporation structure.

The solar energy received transmitted through the glass to the participating medium is calculated using Beer's law as follows

$$Q_{solg\to m} = e^{-\alpha_g l_g} \times q_i \times A_g \quad (3)$$

The solar energy absorbed by the absorber is determined as;

$$Q_{sol} = e^{-\alpha_m l_m} \times Q_{solg\to m} \times \alpha_{abs} \quad (4)$$

Where $A_g = A_{abs}$

The convection energy loss from the absorber surface to vapour is calculated using Newton's law of cooling as;

$$Q_{conv} = h_{avg} A_{abs} (T_{abs} - T_v) \quad (5)$$

$$h_{avg} = \frac{Nu \times K_v}{L_c} \quad (6)$$

$$L_c = \frac{A_{abs}}{2(l_{abs} + w_{abs})} \quad (7)$$

$$Nu = 0.58Ra^{\frac{1}{5}} \quad (8)$$

$$Ra = \frac{\beta g {L_c}^3 (T_{abs} - T_v)}{{\nu_v}^2} \quad (9)$$

$$\nu_v = \frac{\mu_v}{\rho_v} \quad (10)$$

$$\beta = \frac{1}{T_v} \quad (11)$$

The conduction energy loss from the absorber into the underlying water is evaluated using Fourier's law. Effective thermal conductivity is calculated using analogy of parallel thermal resistances (Ni et al., 2018).

$$Q_{cond} = \frac{k_{eff}}{h_{abs}} A_{abs}(T_{abs} - T_w) \quad (12)$$

$$k_{eff} = \frac{k_{pol}A_{pol} + k_w A_w}{A_{pol} + A_w} \quad (13)$$

The radiation energy from the absorber to vapour domain is determined using Stefan-Boltzmann law as follows;

$$Q_{rad} = \sigma A_{abs} \varepsilon ({T_{abs}}^4 - {T_v}^4) \quad (14)$$

The difference between the enthalpy of water vapor and water liquid is referred to as latent heat of vaporization and is calculated as (Agrawal & Rana, 2019);

$$(h_v - h_l) = (2501.67 - \ 2.389 \times T_{abs}) \times 10^3 \ \frac{J}{kg} \quad (15)$$

Therefore the evaporation rate and efficiency of the evaporation structure is calculated as follows respectively.

$$Evap.rate = \frac{m}{A_{abs}} \quad (16)$$

$$Eff = \frac{Evap.rate}{3600 \times Q_{sol}} \times (h_v - h_l) \quad (17)$$

3. Experimental

3.1 Experimental set up

The setup comprises two identical basin-type solar stills. The first still unit is used as a CSS, whereas the second as MSS. Both basins and air cavity cap are in the shape of a rectangular boxes each measuring (0.25 × 0.25 × 0.15 m^2). The basins are made of 2mm thick rustproof galvanized iron sheets whereas air cavity are made up of 0.01m thick wood. Each of the basins are covered by thick polyethylene sheet insulation to reduce heat losses/gain of the bulk water. The basin is connected with a 0.025m diameter hose pipe of 0.15m length to an external bucket. The external bucket acts as a temporary storage of impure water and supplies water to the basin still to replace the evaporated water. In the CSS, the inside of the metallic basin was painted black to enhance absorption of solar radiation. Each solar still is covered with a 0.004m thick transparent glass that is fixed on the top edges of the wooden cap. Putty is fitted at the edges and ensure the transparent region is equivalent to the evaporation area. All the gaps and openings between the basin and the wooden cap are sealed with silicone rubber to prevent inflow of external air. A 0.025m diameter hole at a height of 0.05m from the glass cover is drilled on one side of the wooden cap to allow vapor generated to escape to the atmosphere and therefore reduce condensation of the vapor inside the glass.

In the MSS, the floating PVA wrapped on extended polystyrene foam (EPS) was used. EPS reduces heat dissipation to the underlying bulk water. The evaporation surface area of the PVA (0.244 x 0.244) m2 was coated black with a normal. The uncoated sides of the PVA cloth wrapping the EPS remain under the water to absorb water to the evaporation surface by capillary action. The experiment was performed at the roof top of mechanical engineering department. The roof top has solar tower that provide concentrated solar beam (Fig 1(a)).Heliostats concentrate sunlight to the beam down reflector that provides concentrated sunlight to the solar still. In this experiment a maximum of 3 heliostats were used. The calibrated T-type thermocouple wires were inserted through small holes on the side wall of the still as shown in Fig 1(b). For MSS, the temperature of the underlying water, black coated PVA surface and moist air in the cavity were measured as demonstrated in Fig 1(c). For the CSS the water temperature was measured. Simultaneously, water mass flow rate and solar flux in both stills were measured using electronic weighing balance and solar flux metre.

3.2 Experimental procedure

The experiment was conducted for three clear days. Among the three days, the best observations were made on the second day. The orientation of the still is such that the concentrated solar beam is normal to the glass cover. Both the still were filled up with water. For the MSS, the water was filled to level that it can accommodate the evaporation structure where the evaporation surface was at same level with the brim of the basin. For the CSS, the water was filled to the brim of the basin. The synchronization tests were carried before the days of experiments were to be conducted. The results showed good synchronization. The experiments were conducted and all the required parameters were measured. Due to technical limitations of the concentrating solar system, each experiment was performed separately for one hour according to the number of heliostats. Each day consisted of three experiments i.e. 1st experiment using 1 heliostat, 2nd experiment using 2 heliostats and 3rd experiment using 3 heliostats. Due to varying weather conditions, solar flux was measured after every 20minutes to and the average was used to reduce on the fluctuation error for the analysis. The temperatures and amount of water loss were measured after one hour. The MSS experiment were performed for the first three days and the CSS on the fourth day for benchmarking. All the experiments were conducted between 11am and 3pm every day.

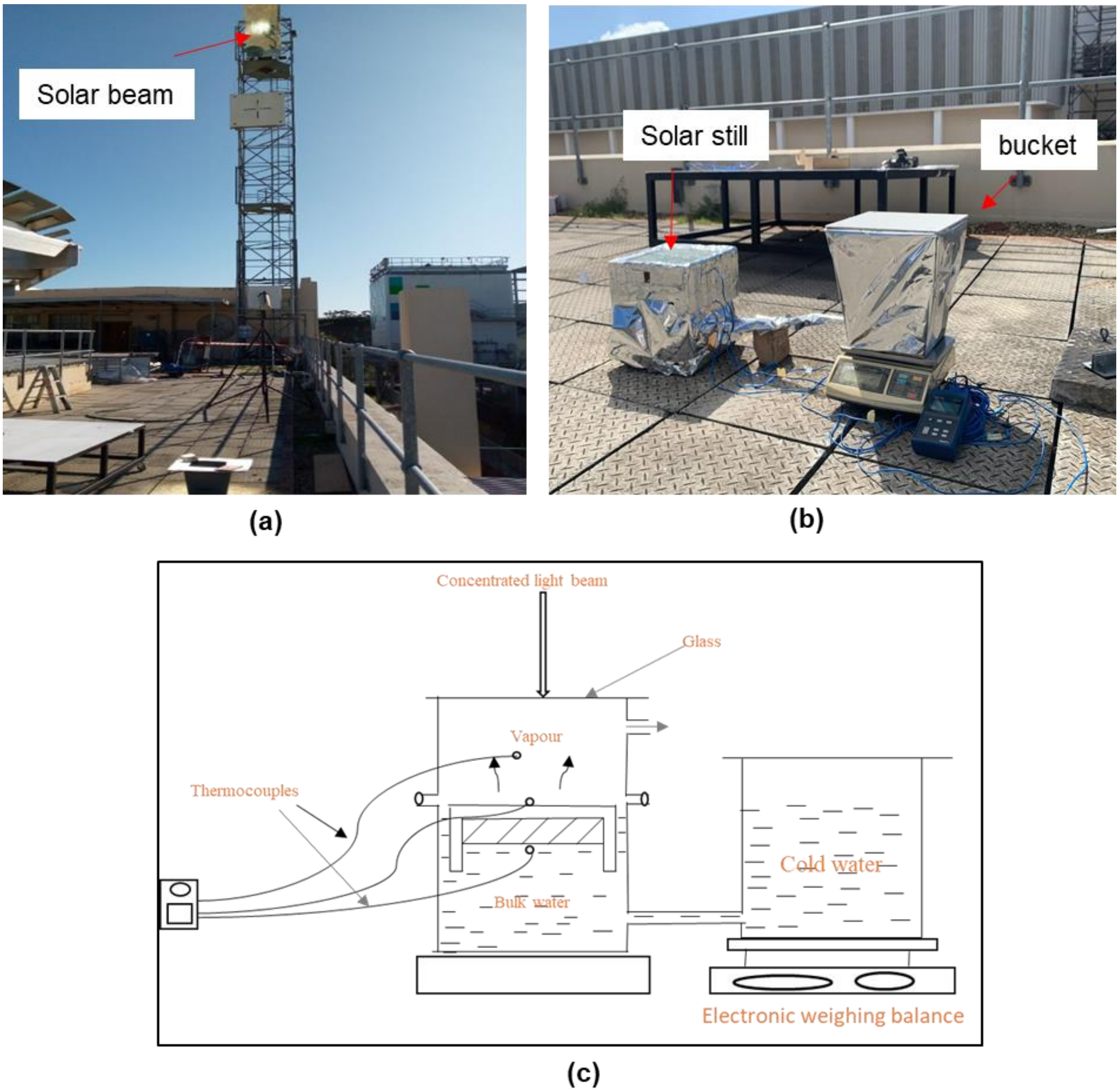

Fig. 2-Photograph of (a) Rooftop solar beam tower (b) Experimental set up and (c) Schematic diagram showing locations of temperature and mass water loss measurement.

3.3 Uncertainty analysis

The uncertainty analysis technique analyses a derived quantity regarding the errors in the experimentally measured quantities. It determines the possible errors and integrate the results to obtain the overall uncertainty of the experiment. The associated percentage standard errors of each instrument is calculated according to Agrawal (2017) and summarised in table. The total uncertainty were calculated using the fractional change approximation approach in this work (Rajaseenivasan, Nelson Raja & Srithar, 2014). The main outcomes in this study are evaporation rate and efficiency. The total uncertainty of the evaporation rate was $\pm 3.8\%$ and efficiency$\pm 4.1\%$.

Table 1-Accuracy, Range and percentage error of measuring instruments

Sl. No	Instrument	Accuracy	Range	% standard error
1	Thermocouple	$\pm 0.8\,^{\circ}C$	$0 - 100\,^{\circ}C$	0.46
2	Solar flux metre	$\pm 6\%$	$0 - 3000\ W/m^2$	3.4
3	Weighing balance	$\pm 0.1\ g$	$0 - 30000\ g$	0.058

4 Results

During the experiments, the readings were accurately taken to obtain correct results for analysis. The results of the MSS for the three days and CSS for one day are presented and discussed.

4.1 Variation of evaporation rate with solar flux

Evaporation rate of all the solar stills increased with increase in solar flux as illustrated in Fig 3. This is because the evaporation rate in the solar stills is directly proportional to the net heat flux according to *equation 2*. The heat energy generated is used for water-vapour phase change hence increasing water evaporation at the air-water interface. Maximum predicted evaporation rate using 3 heliostats for Day 1, 2 and 3 were 2.50, 2.42 and 2.49 kg/m^{2}hr respectively. On the other hand, highest evaporation observed was 1.59 kg/m^{2}hr.The CSS evaporation rate was lower than all the MSSs. This is attributed to high heat capacity of bulk water in the basin. The takes time before reaching its saturation point (Agrawal, Rana & Srivastava, 2017) unlike in MSS where small amount of water on the surface of the absorber requires little time to evaporate due to interfacial heating. Evaporation rate in Day 1 and Day 2 tends to slows down. This may be attributed to limited water flow through the PVA wick

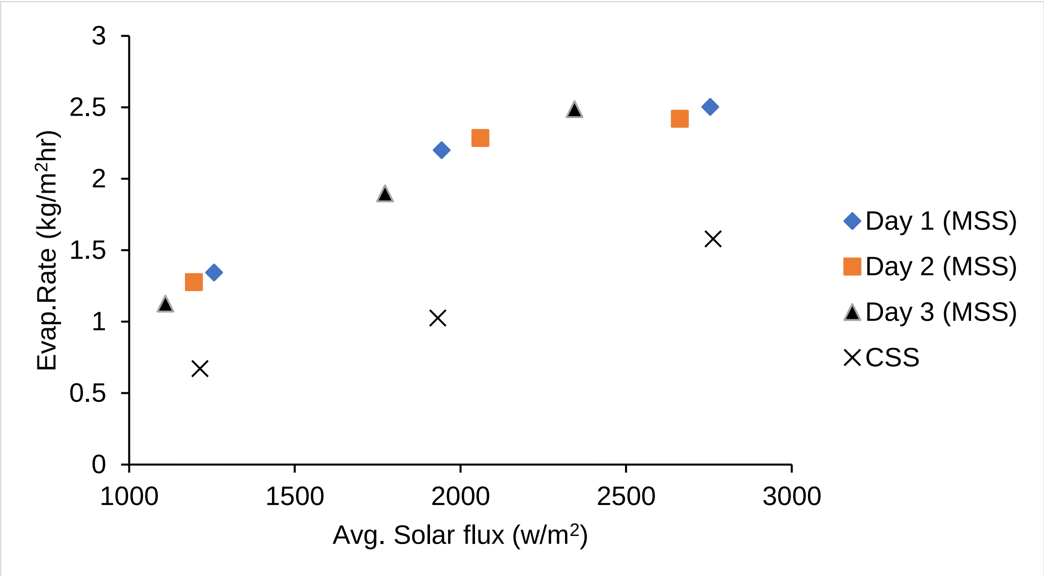

Fig 3-Variation of Evaporation rate with solar flux for MSS and CSS

4.2 Variation of efficiency with solar flux.

The efficiency of the MSSs and CSS were determined using measured temperatures of the absorber and basin water to calculate the latent heat of vaporization in *equation 15.* The results are displayed in *Fig 4*. It is observed that the efficiency of MSSs are higher than the CSS. The maximum efficiency attained by MSS in Day 1, 2 and 3 were 72.5%, 71.2% and 69.0% respectively whereas the highest efficiency achieved by the CSS was 37.0%. This is attributed to heat losses to the sides and bottom of the basin still (Agrawal & Rana, 2019).. For the MSSs the heat energy is only used to evaporate the water at the surface hence it experience less heat losses as compared to bulk heating in CSS. MSSs in day 2 and 3 decreases above average solar flux of 2500 W/m^2. This may be attributed to the steady state condition of the evaporation rate as seen in *Fig 3* hence increase in energy input on the absorber has no influence on evaporation rate.

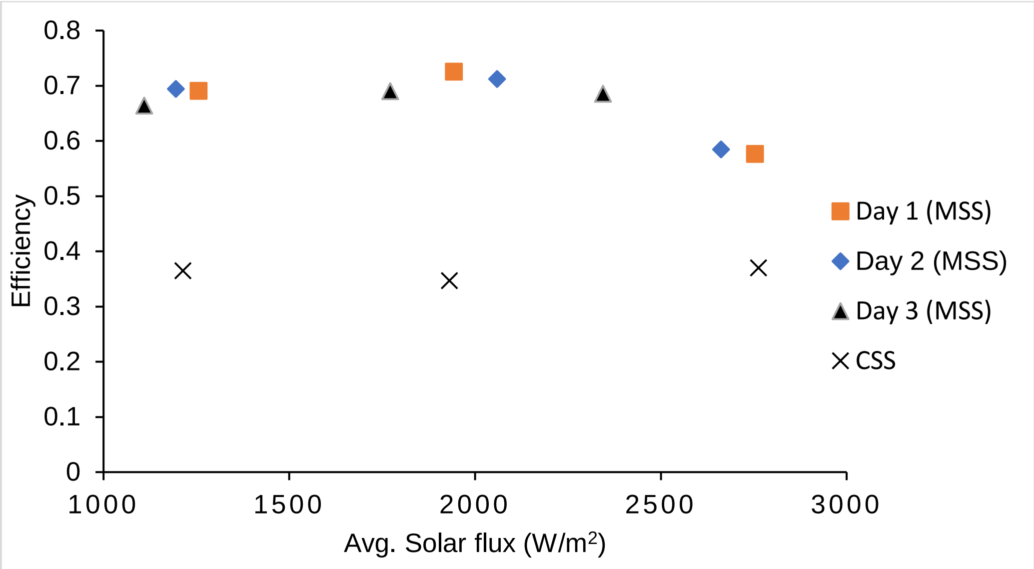

Fig 4- Variation of efficiency with solar flux for MSS and CSS

4.3 Model validation

The evaporation rates for all the days were compared with the model results. The model equations were used to calculate evaporation rates using MATLAB code. The required design parameters are summarized in *Appendix Table 4*. Moreover, the measured temperatures and instantaneous average solar flux for each experiment were used as inputs in the model

From *Fig 5*, an average percentage deviation of 16% of theoretical results from the experimental results was obtained. The theoretical results predicted the experimental results at initial stages but limited to predict the experimental results above 2500 W/m^2. This implies that at initial stages the absorber was fully wetted and the air cavity domain was dominated with water vapour as assumed by the model. The inability of the model results not to predict the experimental results was attributed to the behaviour response of the PVA material at high flux. This maybe attributed PVA capillary action not matching up with high flux above 2500 W/m^2 (Qiu et al., 2021). This may be due to microstructure disorder of the material at high light intensity that can affect the capillary action dependant factors such as pore size, pore geometry and porosity (Liu, Mishra & Wang, 2020).

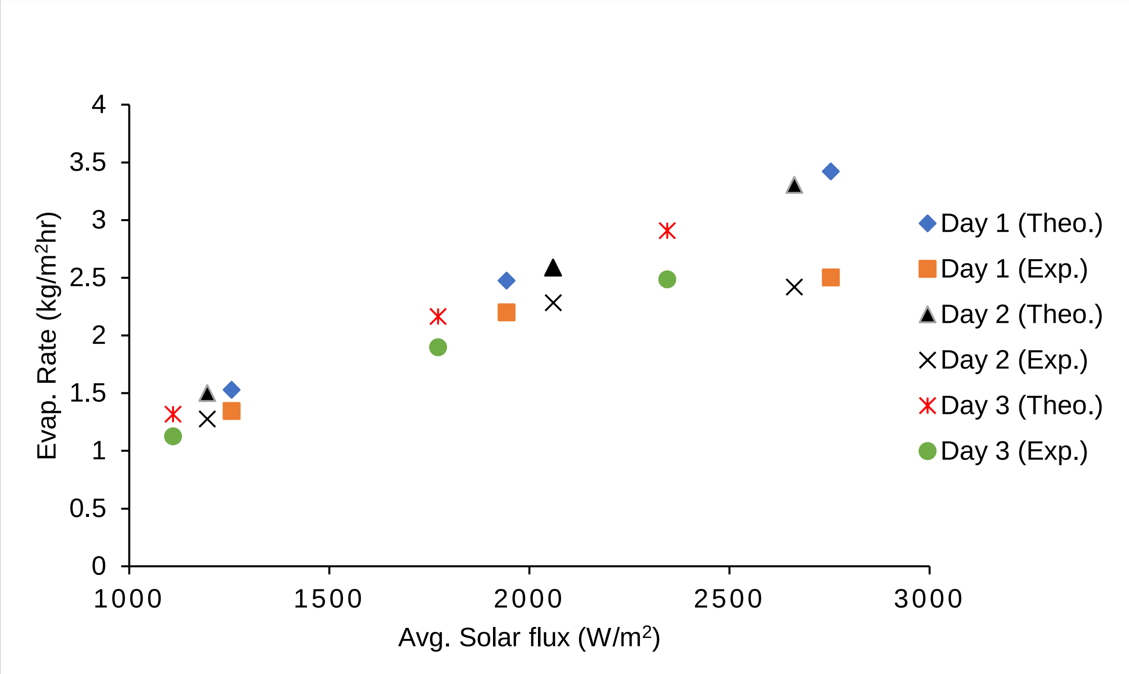

Fig 5- Comparison of Theoretical and experimental evaporation rates against solar flux

4.4 Comparison between the present and previous works

Most previous works were majorly daily distillate output as in the introduction. For comparison purposes, the present work assumed that the proposed still works daytime to a maximum of eight hours on a clear day. Locally external passive condenser of efficiency 0.87 fabricated by Sivaram *et al.* (2021) in the literature was considered to estimate the daily output and compared with few previous works as summarised in table. The present still performed well at an average solar flux of 2 kW/m^2 with maximum evaporation rate 2.3 kg/m^{2}hr with an efficiency of 71% in day 2.

$$Estimated\ daily\ distillate\ output\ MSS = 2.3 \times 8 \times 0.87 = 16.01\ kg/m^2 \qquad (18)$$

Based on the experiment for the proposed solar still found was comparable and higher than those achieved by the previous works. This is attributed to the incorporation of concentrated sunlight in our work. Optical concentration multiplies the available sunlight energy which increases evaporation rate in the solar still thus contributing to higher yield unlike the previous works where they used natural sunlight.

Table 2-Display of previous works' results with the present results

Sl	**Solar still floating material**	**Daily distillate output (kg/m^2)**	**Reference**
1	Vertical rotating wick	7.17	(Haddad., 2017)
2	Bubble wrap with porous absorber	3.10	(Arunkumar., 2018)
3	PCMs and nanoparticles	7.46	(Shanmugan., 2018)
5	V-shaped floating wick	7.19	(Agrawal.,2019)
6	Spherical salt balls	6.20	(Harris., 2016)
7	**Black-coated PVA**	**16.01**	**Present work**

4.5 Economic Analysis

The economic analysis of the present still is conducted according to economic analyses relations of Govind and Rashidi *et al*. *(Govind & Tiwari, 1984; Rashidi et al., 2018)*. The major goal of this study is to evaluate the economic viability of the water purification method under concentrated solar system i.e. if the production of the solar still can offset the initial investment in one year. The total output for the year was calculated using the maximum evaporation rate of 2.3 kg/m^{2}hr, 87% condenser efficiency (Sivaram et al., 2021) with annual average sun hours of 3100 received in Stellenbosch (SAURA 2021) following is a description of the economic analysis. Let *P* be the capital invested in the implementation of the present solar still at an interest rate "i" per year and "n" be the number of years the solar still can effectively perform

$$Capital\ Recovery\ Factor, CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (19)$$

$$First\ annual\ cost\ (FAC) = CRF\ \times P \quad (20)$$

$$Sinking\ fund\ factor\ (SFF) = \frac{i}{(1+i)^n - 1} \quad (21)$$

$$Annual\ salvage\ value\ (ASV) = SFF\ \times S \quad (22)$$

Where S represents salvage value of the solar still system.
Therefore, the total annual cost (TAC) of the proposed still can be determined by annual operation costs (AOC) and ASV as follows;

$$TAC = FAC + AOC - ASV \quad (23)$$

The annual cost of yield per kilogram (ACY) is calculated as;

$$ACY = \frac{TAC}{T.Y} \quad (24)$$

The annual market cost of yield (AMC) as follows;

$$AMC = T.Y \times market\ cost\ per\ kg. \quad (25)$$

Net earnings per year is determined as follows;

$$Annual\ net\ earnings = AMC - AOC \quad (26)$$

Hence payback period will be calculated as;

$$Payback\ period = \frac{P}{Net\ earnings\ per\ day} \quad (27)$$

The annual cost calculations are summarized in Table. The payback days found were 168 days which are less than the days in one year. This implies that the cost implication of the present still can be offset by the annual output of the system. This implication is attributed to high capital investment on the concentrating solar system such as heliostats and reflective mirror as observed in the material costing in the *Appendix Table 4*.

Table 3-Summary of Annual cost calculation of estimated distillate output for the proposed still

S.I	Particular	solar still	Reference
1	P	R 12900	*Appendix Table 5*
2	i	12%	(Agrawal & Rana, 2019)
3	n	10 years	(Agrawal & Rana, 2019)
4	CRF	0.177	
5	FAC	R 2708	

6	SFF	0.0569	
7	ASV =20% of P	174	(Kabeel, Hamed & El-Agouz, 2010)
8	AOC= 15% of (FAC)	R 406	(Kabeel, Hamed & El-Agouz, 2010)
9	TAC	R 2940	
10	T.Y	6203 kg/m^2/year	
11	A.C.Y	R 0.5/kg	
12	Market cost of yield	R 10/kg	Water purification station Stellenbosch
13	AMC	R 62,030	
14	Net earnings per year	R 61,624	
15	Payback period	168 days	

5 Conclusions and recommendations

The main aim of this study was to evaluate the performance a black-coated PVA floating wick in the conventional-type solar still by incorporating concentrated solar system. The MSS was fabricated and experiments conducted at Stellenbosch University. Moreover, mathematical model on the performance of the floating wick. It was observed that the performance of MSS was better than CSS due to interfacial evaporation initiated by the floating wick. The best evaporation rate of the wick and CSS realized was 2.3 kg/m^2hr with efficiency of 71% and 1.59 kg/m^2hr with efficiency of 71% respectively under average solar flux of 2 kW/m^2. Moreover the estimated performance of the MSS was found to be higher than the previous works. This was attributed to incorporated concentrating solar system that multiplies available energy hence increasing production unlike in previous works where most researchers used natural sunlight. The model developed fairly predicted the experimental results at initial stages but limited to predict at high flux above 2500 W/m^2hr.Economic analysis was done and found that the proposed solar still is still economical despite the high costing of solar concentrating components.

We recommend in future the experiment to be conducted with an indoor and controlled concentrating solar flux away from external interference such as cloud covering to get accurate solar flux. This study relied on average solar flux due to fluctuation of measured flux during the experiment. We also recommend to get properties of the wick floating wick used such as porosity, pore size, microstructure orientation, absorptance and emissivity. Finally, we suggest for simulation of the process to get insight of the capillary action of the wick at high solar flux.

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Appendices

Nomenclature

Q_{sol} Solar energy (W)
Q_{conv} Convection heat energy (W)
Q_{rad} Radiation heat energy (W)
Q_{cond} Conduction heat energy (W)
q_i Solar heat flux (W/m^2)
mh_l Energy of water liquid (W)
mh_v Energy of water vapour (W)
Ra Rayleigh number
l_{abs} Absorber's length
w_{abs} Absorber's width (m)
β Volumetric expansion (K^{-1})
ν_v Kinematic viscosity (m^2/s)
μ_v Dynamic viscosity (m^2/s)
ρ_v Density (kg/m^3)
k_{eff} Effective thermal conductivity (W/m K)
h_{abs} Height of the absorber (m)
k_{pol} Thermal conductivity of polystyrene foam (W/m K)
A_{pol} Polystyrene foam surface area (m^2)
α_g Glass absorptance
α_m Water vapour absorptance
α_{abs} Absorber absorptance
A_{abs} Absorber surface area (m^2)
A_g Glass surface area (m^2)
T_{abs} Absorber surface temperature (K)
T_v Water vapour temperature (K)
T_w Bulk water temperature (K)
σ Stephan-Boltzmann constant
m Mass flow rate (kg/s)

Table 4-Design constants of solar still

SI. No	Design parameters	Numeric values
1	Area of absorber	(0.244 x 0.244) m^2
2	Thickness of evaporation structure	0.022 m
3	Area of the wick	0.0049 m^2
4	Thermal conductivity of EPS	0.028 W/m K
5	Gravity constant	9.81
6	Area of the glass	(0.244 x 0.244) m^2
7	Absorber and water vapor emissivity	1
9	Glass absorptivity	0.013
10	Water vapor absorptivity	1
11	Height of the air cavity	0.15 m
12	Stefan-Boltzmann constant	5.67 x 10^{-8} W/m^2 K^4
13	Absorber absorptivity	1
14	Glass thickness	0.004 m

Table 5-Summary costs of the materials for the proposed solar still.

S.I	Name of the material	quantity	Cost (Rands)	Reference/source
1	Fabrication of Galvanized tank	I still	1000	Mechanical depart.
2	Wooden box	1 unit	200	Mechanical depart.
3	Plain glass cover (4 mm thick)	1 m^2	200	Builders Exp. Hardware
4	Expanded Polystyrene foam	8 m^2	200	Builders Exp. Hardware
5	PVA cloth	8 m^2	400	Online pack Capetown
6	Paint, sealant, putty, reflectors	1 still	200	Personal estimation
7	Passive condenser	I unit	550	(Mohaisen, Esfahani & Ayani, 2021)
8	heliostats	2/m^2	3000	(Kurup et al., 2022)
9	Reflector mirror	1m^2	5000	Builders Exp. Hardware
10	Labour charges & miscellaneous		2550	(Agrawal & Rana, 2019)
	Total cost		**12900**	