Modified Active solar distillation system employing directly absorbing Therminol 55 –Al_2O_3 nano heat transfer fluid and Fresnel lens concentrator

M.Muraleedharan[1], H. Singh[2], M.Udayakumar[1], S. Suresh[1 *],

[1]Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli, 620015, India

[2] Brunel University London, Kingston Lane Uxbridge, UK

[*] (corresponding author) Email: ssuresh@nitt.edu

Dr. S. Suresh
Assistant Professor
Department of Mechanical Engineering
National Institute of Technology
Tiruchirappalli – 620 015
India.
E-Mail: ssuresh@nitt.edu
Phone: +91 431 2503422

Dr. M. Udayakumar
Professor
Department of Mechanical Engineering
National Institute of Technology
Tiruchirappalli – 620 015
India.
E-Mail: muday@nitt.edu
Phone: +91 9487257871

Dr. Harjit Singh
Senior Lecturer,
Brunel University London
Uxbridge UB8 3PH
UK
E-Mail: harjit.singh@brunel.ac.uk
Phone: +44 (0)1895 265468

Mr. Manoop Muraleedharan

Research Scholar
Department of Mechanical Engineering
National Institute of Technology
Tiruchirappalli – 620 015
India.
E Mail: manoop86@gmail.com
Phone: +9496468536

Abstract

This paper reports ~~the development and the measured performance of a modified active solar distillation system (MSDS) against that of a conventional solar still (CSS~~) reports the design and construction of a modified active solar distillation system (MSDS) and comparison of its performance parameters with that of a conventional solar still (CSS). MSDS consists of a solar still, a Fresnel lens concentrator with an evacuated receiver tube and a serpentine loop type heat exchanger ~~to supply heat energy from the solar concentrator to the basin water~~. Al_2O_3 –Therminol-55 nanofluid is used as heat transfer fluid in the solar collector loop. Various performance parameters of MSDS and CSS such as saline water temperature, hourly yield, total yield, and efficiency have been compared under the ambient and solar conditions prevailing at Trichy (Tamilnadu, India). ~~It can be observed from the experimental results that~~ The experimental results indicate, the hourly yield of MSDS with 0.1% nHTF is 45-250.27% more than CSS and the total yield of MSDS with 0.1% nHTF is 12.190 L/m^2 day compared to 3.48 L/m^{2}day for CSS. ~~The MSDS recorded a daily efficiency of approx. 53.55 %, against 26.74 % for CSS.~~ The daily efficiency of MSDS is found to vary with the volumetric concentration of nanofluid, and maximum efficiency of 53.55 % is obtained for 0.1% nHTF. The estimated cost for production of one little-distilled water is approximately 1.54 INR for CSS and 1.41 INR for MSDS The modified solar desalination system developed in this study is found to be a better alternative to the conventional solar still due to its high productivity and ~~thermal efficiency.~~ cost effectiveness

Keywords: Solar still; Fresnel lens concentrator; nanofluid; heat exchanger

1.Introduction

In several developing countries, water is either economically scarce i.e. finding a reliable source of water is time-consuming and expensive or physically scarce where ~~simply~~ just enough water is not available. Desalination of the sea and brackish water can be a better solution ~~to meet the increasing demand for fresh water~~ to the scarcity potable water. However, desalination techniques employing fossil fuel reserves to supply their huge energy requirement are quite expensive. ~~The exploitation of fossil fuels can lead to their depletion and also environmental instability in the long run~~. and fossil fuels have been linked to environmental degradation. ~~Hence~~

The utilization of ~~renewable energies~~ solar energy for powering desalination plants could be a sustainable solution. ~~A tubular solar still integrated~~ Integration of Tubular solar still~~-~~with compound parabolic concentrator was reported to have productivity higher by 3.7 L/dal compared to that of a conventional solar still, Arunkumar et.al(2016). ~~Integrating cylindrical parabolic concentrator and phase change material~~ Integration of phase change material and cylindrical parabolic concentrator (Kabeel and Abdelgaied,2017, Voropoulos,2001) photovoltaic-thermal collectors (Singh et.al., 2016), parabolic trough concentrators (Abel Rahim and Lasheen, 2007), flat plate solar collectors (Badran et.al., 2005) and the use of hot air injection and PCM (Kabeel et.al., 2016; Tabrizi et.al., 2010) ~~can~~ could overcome the low productivity ~~problem~~ of conventional solar still ~~with varying degree of success~~ to some extent . ~~Experiments were done by~~ Singh and Tiwari (2017) and Singh et.al (2016) used with N identical PVT collectors and compound parabolic collector(CPC) ~~on the solar still have concluded that integration of PVT collectors overcomes the low productivity problem of conventional solar still~~ to enhance the daily yield of conventional solar still. To the best of author's knowledge ~~The solar thermal collectors employed~~ in all previously reported studies were the surface absorbing solar thermal collectors ~~type~~, which suffers from higher radiative loss from the hot receiver area (A. Toppin-Hector, H. Singh, 2013). ~~To enhance the utilizability of the collected solar energy~~ For the efficient utilisation of the collected solar energy nanoparticles can be introduced either directly to the saline water (Sahota and Tiwari, 2016 a, 2016b, 2017) or ~~to~~ the solar collector heat transfer fluid (Mahian et.al, 2017; Omara.et.al., 2015). The studies conducted by Rashidi et.al (2018a,2018b) with nanofluid on solar still indicated that a marginal increase in productivity is obtained while using nanofluid. However, the conventional method of adding the nano-additives to heat transfer fluid still needs a selectively absorbing metallic surface, which adds to the cost of fresh water produced ~~and is a cause of decreased~~ Also, the performance as the coating degrades due to weathering or prolonged exposure to enhanced temperatures. The coating can be irreversibly damaged in the case of leakage of the heat transfer fluid.

This study focus to improve on improving the daily productivity of conventional solar still by a novel Modified solar distillation system (MSDS) comprising of a linear Fresnel lens based optical concentrator using directly absorbing Al_2O_3-Therminol-55 nanofluid as a heat transfer fluid and a serpentine heat exchanger in the still basin. To the best of the knowledge of the authors, this is the first study reporting the use of such solar concentrator in a solar still.

2. Experimental setup

A conventional solar still (CSS) and modified solar distillation system (MSDS) ~~were~~ are fabricated and tested under the ambient and solar conditions of Trichy (Tamilnadu, India) during the summer of 2018; see Fig. 1-3. The CSS consisted of a basin, a rectangular cross-section mild steel container (1.5 mm thick), whose inner surface (1m^2 area) was painted black to act as the solar radiation absorber. For minimizing the heat loss the outer box of solar still being designed a ~~different way~~ specially to provide sufficient thermal insulation. It consists of two layers of mild steel separated by a wooden block. The total thickness of outer box is about 20 mm ~~from the basin~~, Apart from this the basin is well insulated using a 50mm thick glass wool insulation (thermal conductivity 0.035 W/mK) ~~was applied between the basin and outer box~~.

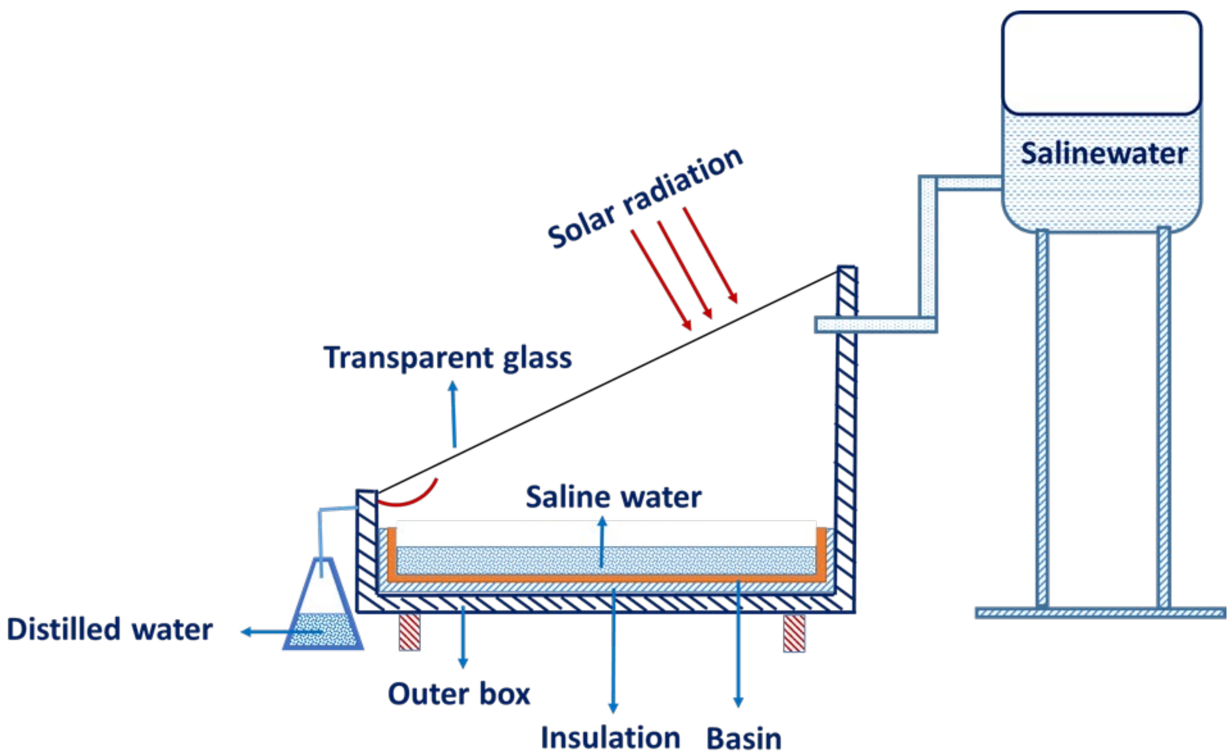


Fig.1. Schematic diagram of Conventional Solar Still (CSS)

A transparent glass cover (4 mm thick) ~~provided~~ acts as the condensation surface located at the top of the outer box. The slope of the condensation surface is an important factor affecting the productivity of solar still. Hashim et.al (2010), and Tiwari and Tiwari (2005) reported that the condensation surface should be inclined at the latitude angle of the location to get maximum desalinated water yield. In this study, glass cover was tilted at 15°, the latitude of Trichy.

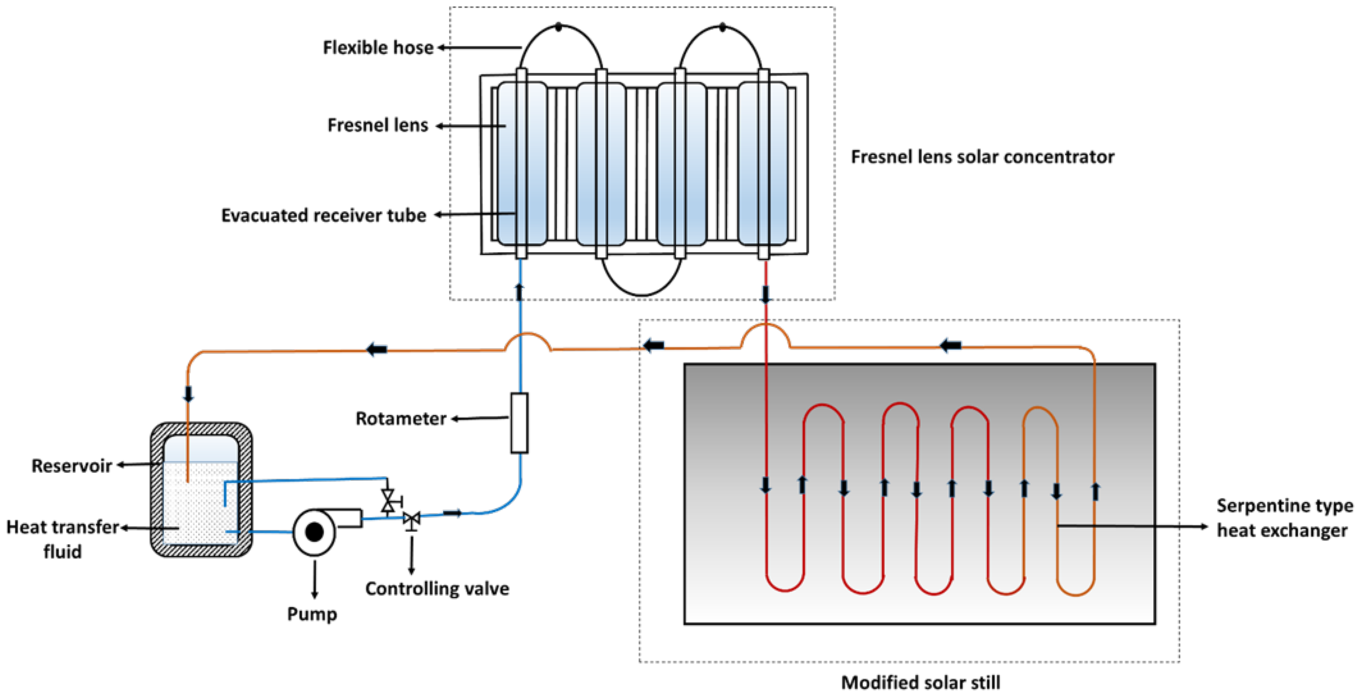


Fig.2. Schematic diagram of the Modified Solar Distillation System (MSDS)

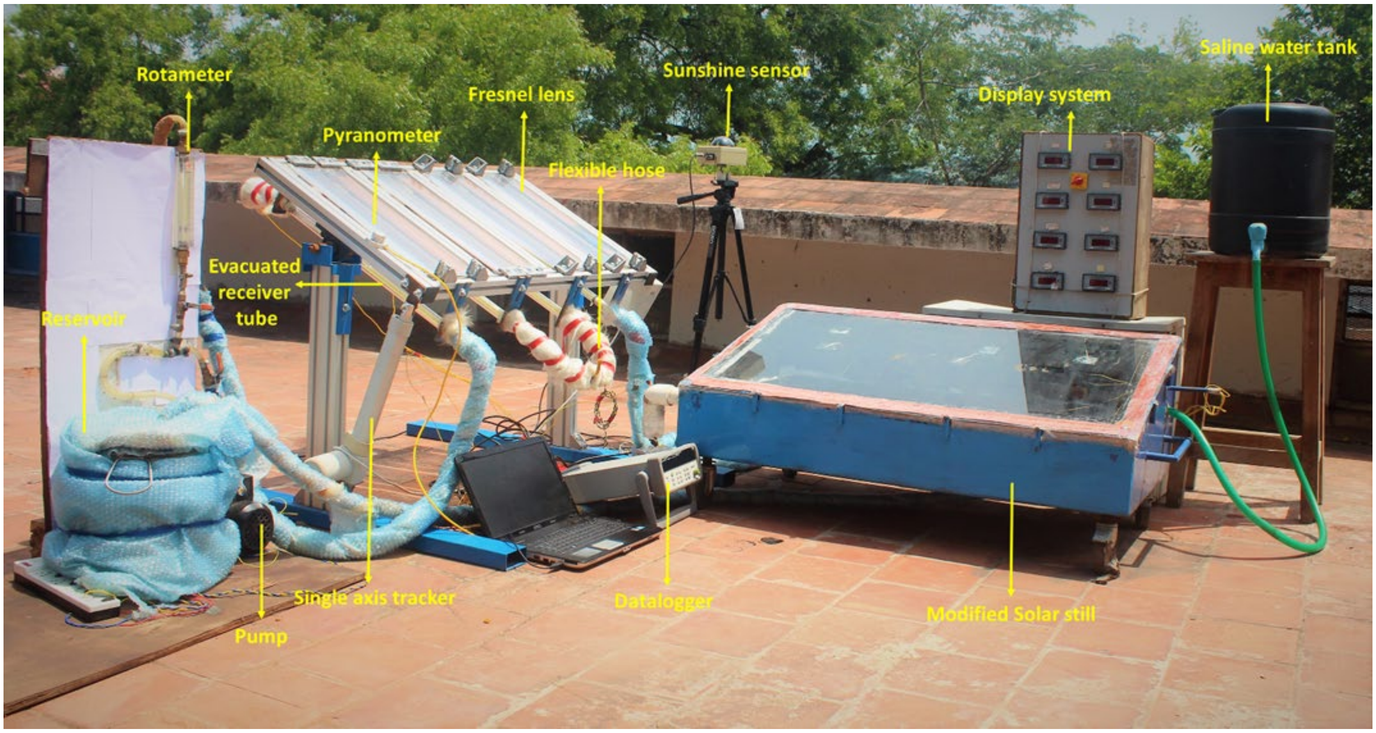


Fig.3. Experimental setup containing the MSDS

The **MSDS, see** Fig. 2-3, comprised of a modified solar still (MSS) with a serpentine heat exchanger and a single axis tracked linear Fresnel lens concentrator.

2.1 Modified Solar still (MSS)

The modified solar still (MSS) tough had the similar geometrical specifications and condensing surface tilt of 15° as the CSS, ~~but it differed from the later in basin construction~~. but the basin construction of MSS differs from the latter.Copper sheet was used to fabricate the basin to achieve a higher heat transfer ~~coefficient~~ between the absorbing surface and saline water. ~~In addition~~, Also, a serpentine shape heat exchanger made of copper tube (diameter 10 mm) was located in the basin. The heat exchanger was mounted on Teflon blocks to ~~stop it from directly touching~~ prevent direct contact with the basin surface. ~~The net height of the heat exchanger is the sum of the diameter of the heat exchanger tube (15mm) and the spacing from the bottom of the basin (5mm). To enhance the amount of heat transferred to the saline water and to ensure heat exchanger was always immersed in water, the water depth in the basin was maintained at 25 mm~~

using a floating valve system. The water depth in the basin is maintained at 25 mm using a floating valve system to ensure that the heat exchanger is always immersed in water

The MSDS harnessed (i) direct energy from the sun and (ii) that energy supplied by the line-focusing Fresnel lens-based solar collector concentrating light on directly absorbing Al_2O_3-Therminol 55 nanofluid. Further details of the solar concentrator and the nanofluid can be had from Muraleedharan et al. (2016). A detailed description of the solar concentrator and the nanofluid is presented in the author's previous paper (Muraleedharan et al. 2016)).

3.Error analysis

Inorder to analyze the overall performance of the distillation system, several parameters have been taken into account Several parameters are taken into consideration to analyse the overall performance of the distillation system. The temperatures at unique points (Atmospheric temperature, Temperature of glass, the temperature of saline water) have been is measured using K-type thermocouples which are incorporated with data logger and laptop. Total solar radiation intensity measurements have been measurements are obtained using two pyranometers. The linearity accuracy and range and of the measuring instruments are depicted in table 1

Table.1 Accuracy Specification of measuring instruments

Sl.No.	Device	Accuracy	Range
1	Thermocouple	$\pm 1^0$C	-270^0C– 500^0C
2	Pyranometer	$\pm$ 1 W/m^2	0 -5000W/m^2
3	Calibrated flask	$\pm$ 1mL	0-2000 mL

The approach described by Barford(1990) has been used to estimate uncertainty in the hourly thermal efficiency. It is calculated as the root sum square of fixed error of the instrument and random error in the measurement. Accordingly, the uncertainty in calculated of hourly thermal efficiency is 0.8%

4. Hourly efficiency of solar still

The hourly efficiency of a conventional solar still is defined as the ratio of the actual amount of heat consumed in producing distilled water in a specific time interval to the amount of solar energy incident on the still aperture during that time interval. Mathematically, it can be expressed by equation (1). The daily average efficiency of the system is the sum of hourly efficiency to a number of working hours

$$\eta_{h(css)} = \frac{m_h \times L_w}{A \times [I(t) \times 3600]} \times 100 \quad (1)$$

$$\eta_{D(css)} = \frac{\sum \eta_{h(css)}}{n} \quad (2)$$

Where η is the hourly efficiency of CSS, $\eta_{D(css)}$ is the daily efficiency of CSS,n is the number of working hours , m_h is the water distilled in one hour (kg), $L_w$is the latent heat of saline water (J/kg) and it is given by the equation (2), A is the area of the basin (m^2), $I(t)$ is the average solar irradiation received in one hour (J/m^2)

$$L_w = 10^3 \, [2501.9 - 2.4076 T_w + 1.192217 \times 10^{-3} T_w^2 - 1.5863 \times 10^{-5} T_w^3 \quad (3)$$

In the case of the MSDS, in addition to direct solar energy, thermal energy received from the solar concentrator is also used to evaporate the saline water. Its hourly($\eta_{h(MSDS)}$) and daily ($\eta_{D(MSDS)}$)efficiency can be described as shown in Equation (4).and (6)

$$\eta_{h(MSDS)} = \frac{m_h \times L_w}{[A \times (I(t) \times 3600)] + q_{ex}} \times 100 \quad (4)$$

$$q_{ex} = mc(T_{in} - T_{out}) \times 3600 \quad (5)$$

$$\eta_{D(MSDS)} = \frac{\sum \eta_{h(MSDS)}}{n} \quad (6)$$

Where q_{ex} is the energy supplied by the nHTF circulated in serpentine heat exachanger to saline water (J/hr), m is the mass flow rate of nHTF (kg/s), c is the specific heat of nHTF (J/kg.K), T_{in} , T_{out} are the average inlet and outlet temperature (^oC) of nHTF in modified solar still in one hour

5. Cost evaluation

Cost required to produce of producing one liter of desalinated water is estimated in this section. With respect to climatic conditions of Tamilnadu, India assume that It is determined under the assumption that both CSS and MSDS is functional 300 days in a year under the climatic conditions of Tamilnadu, India. The total cost for producing one liter of desalinated water per year(TAC/L) is the ratio of total annual cost(TAC) to total quantity(Q) of distilled water produced.

According to Faithetal 2003 TAC involves the cost of so many factors such as fixed annual cost(FAC), annual operating and maintenance cost($AOMC$) and annual salvage value (ASV). It is given by Eqn. 7

$$TAC = AOMC + FAC - ASV \tag{7}$$

$$FAC = P \times CRF \tag{8}$$

Where P is the capital cost

Capital recovery factor(CRF) can be found through

$$CRF = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{9}$$

The number years(n) in The period during which the system operates and annual The period during which the system operates (n) and interest(i) of capital cost are assumed to be 5 years and 7% respectively. The period during which the system operates (n) and annual interest (i) of capital cost are assumed to be five years and 7% respectively From the table, AOMC is taken as 40% of FAC and salvage value (s) of the system taken as 20% of capital cost

$$ASV = S \times SFF \tag{10}$$

The sinking fund factor is(SFF) can be stated as

$$SFF = \frac{i}{(1+i)^n - 1} \tag{11}$$

Therefore total cost for producing one liter of desalinated water can be estimated using the eqn. 12

$$\frac{TAC}{L} = \frac{TAC}{Q} \tag{12}$$

Where Q is the total quantity of desalinated water collected in a year in litters

4. Experimental

The experimental set up shown in Fig 3 ~~was~~ is ~~fabricated~~ constructed to study the performance of MSDS in producing desalinated water under realistic outdoor conditions at Tiruchirapalli (India). Water productivity performances of the CSS and MSDS ~~were~~ are measured. Sixteen K-type thermocouples ~~were~~ are employed to measure hourly temperatures of nano heat transfer fluid (nHTF), saline water, inner glass surface, and ambient temperature . The flow rate ~~was~~ is maintained at 0.5 L/min whilst saline water depth at 25mm for both base fluid and nHTF. Two pyranometers ~~were~~ are used; one located in shade to measure diffuse radiation and the other directly attached to the concentrator plane to measure global radiation. Working fluid, pure Therminol 55 or nHTF ~~returned to~~ recycled to the reservoir after transferring heat to saline water.

5. Results and discussion

The study was conducted at an outdoor test facility at NIT Trichy during summer of 2018. The following sections take into ~~account~~ consideration only the best results obtained from several experiments conducted during this period. The intensity of solar radiation and the ambient temperature play a vital role in the ~~desalination~~ distilation process. Fig.4 shows the daily averages of solar radiation intensity chosen for the comparison of the performance of the system. It is clear from the figure that the comparison of various concentrations has been made for solar intensity exposures in the range of 764 W/m2 to 770 w/m2, which indicates more or less the same atmospheric conditions

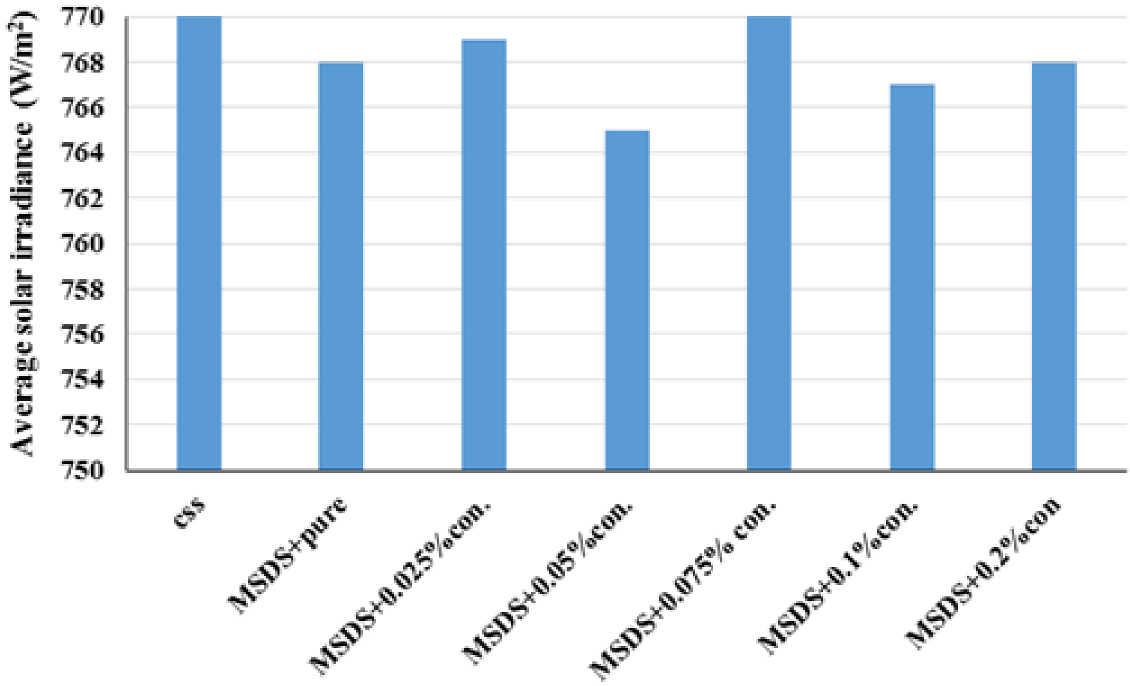


Fig.4.Irradiance during experiments

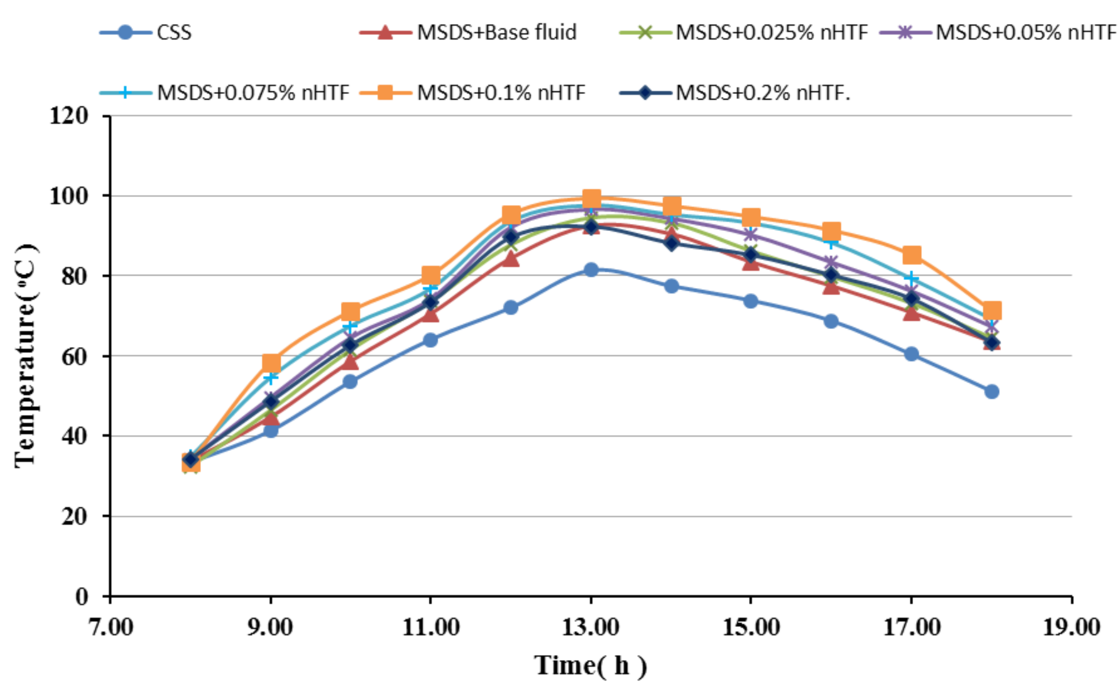


Fig.5. Temperature variation of saline water in CSS and MSDS basins

The hourly saline water temperatures of CSS and ~~in~~ MSDS at different concentrations of Al2O3 in the nHTF (0, 0.025, 0.05, 0.075, 0.1 and 0.2%) ~~and CSS~~ are shown in Fig.5. Although the trend is similar, quantitatively the temperature of saline water in MSDS is on an average of 1-18 °C greater than that of CSS. This is clearly due to additional thermal energy supplied by the solar concentrator. Temperatures of nHTF different concentrations measured on are detailed in Table 2.

Table 2. Hourly base fluid and nHTF temperatures measured on experimental days

Time	**nHTF temperature (°C)**					
	Base fluid	**0.025%**	**0.05%**	**0.075%**	**0.1%**	**0.2%**
8:00	**35.2**	**36.2**	**36.4**	**37.2**	**37.8**	**35.4**
9:00	**49.5**	**50.8**	**55.6**	**60.2**	**65.7**	**54.6**
10:00	**64.2**	**67.8**	**71.3**	**76.4**	**86.4**	**68.4**
11:00	**77.6**	**81.7**	**84.5**	**86.8**	**92.6**	**82.3**
12:00	**93.7**	**99.4**	**104.5**	**108.7**	**115.7**	**98.7**
13:00	**102.6**	**107.6**	**110.6**	**116.7**	**126.6**	**105.4**
14:00	**99.7**	**102.4**	**104.7**	**113.5**	**120.5**	**101.5**
15:00	**91.4**	**95.4**	**99.8**	**106.3**	**112**	**94.4**
16:00	**83.4**	**85.4**	**93.1**	**97.5**	**102**	**87.7**
17:00	**76.4**	**79.4**	**85.4**	**87.7**	**94.5**	**81.6**
18:00	**67.2**	**68.4**	**72.8**	**74.6**	**79.6**	**66.4**

As indicated in Fig. 5 and Table 2 the temperature of nHTF and saline water increases with increase in the concentration of nanoparticle up to 0.1% after that it decreases. ~~The cause of the decrease can be had from Muraleedharan et al. (2016)~~ The reason for the decrease is detailed in the author's previous paper (Muraleedharan et al.,2016). ~~The~~ A maximum saline water temperature of 99.4 °C was reported for 0.1% nHTF, which is 8°C more than when MSDS used the base fluid as heat transfer fluid.

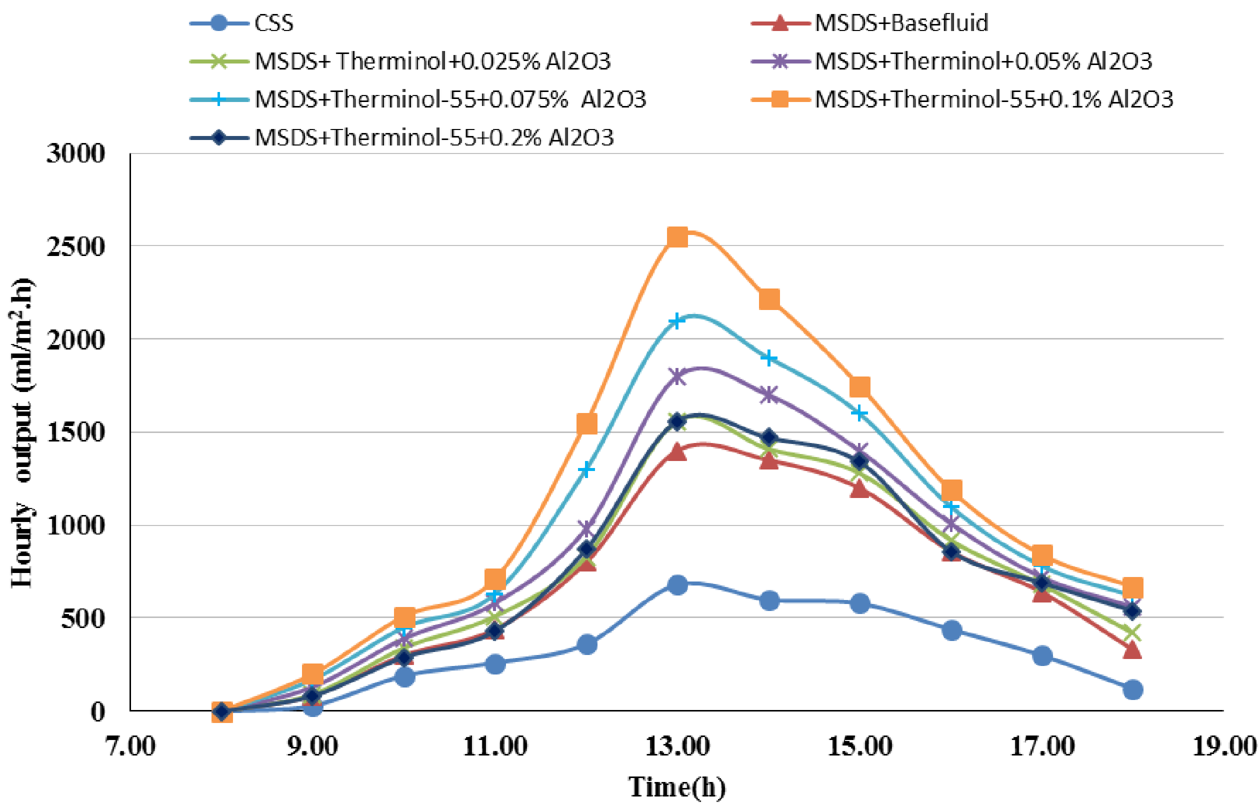


Fig.6. Hourly discharge of CSS and MSDS

The hourly freshwater discharge for both CSS and MSDS is shown in Fig.6. The total yield for the MSDS and CSS are shown in Fig.7. The figure indicates that throughout the observation period the accumulated freshwater productivity was higher for MSDS than CSS. The final accumulated freshwater productivity for CSS, MSDS+base fluid and MSDS+0.1%nHTF are respectively 3480 ml/m^2 , 7404 ml/m^2 and 12190 ml/m^2. An overall increase in accumulated freshwater productivity of about 250.27% can be seen for MSDS+0.1% nHTF compared to CSS.

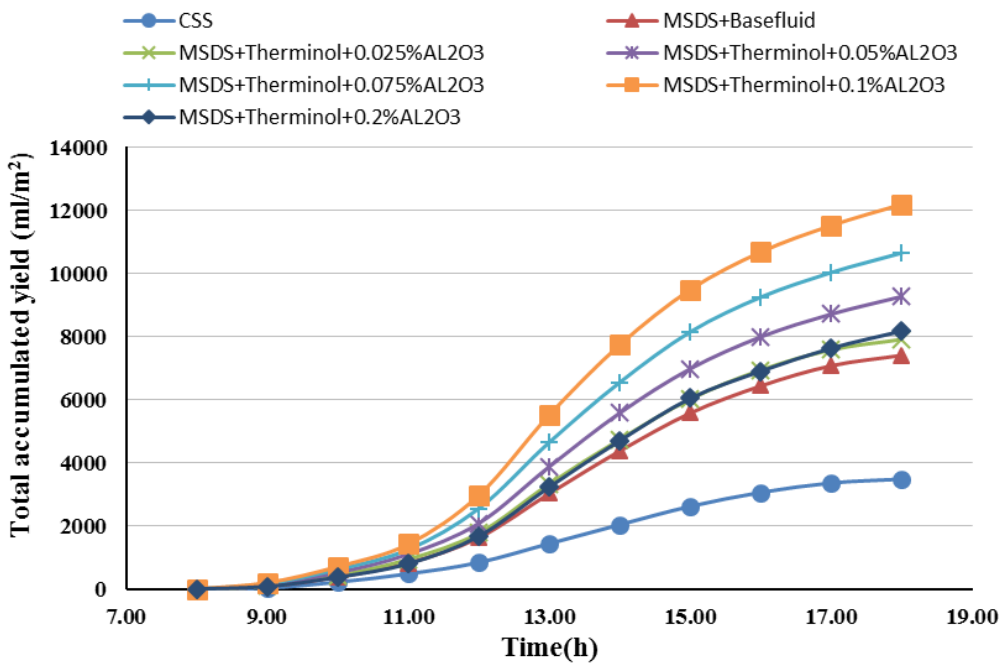


Fig.7. Total accumulated yield of MSDS and CSS

The hourly yield, total discharge and nocturnal yield in the 24-hour cycle for MSDS with 0.1% concentration are depicted in Fig.8 and table 3. The result shows that as the saline water depth is increased above an optimum depth of 25 mm, the hourly yield during day time decreases steadily, while the nocturnal yield increases up to a water depth of 35 mm and then decreases. This is due to the fact that because as the water depth increases the saline water stores more thermal ~~energy due to the specific heat of water~~. ~~Due to the cooler~~ ~~The colder atmosphere in the night, the stored energy is released and this, in turn, produces nocturnal yield~~ The colder atmosphere in the night results in the release of stored energy and this, in turn, produces nocturnal yield. As far as total yield in the 24-hour cycle is concerned a brine depth of 25 mm is 9% more yielding than a brine depth of 35 mm. Hence it can conclude that a brine depth of 25 mm is optimum for maximum yield.

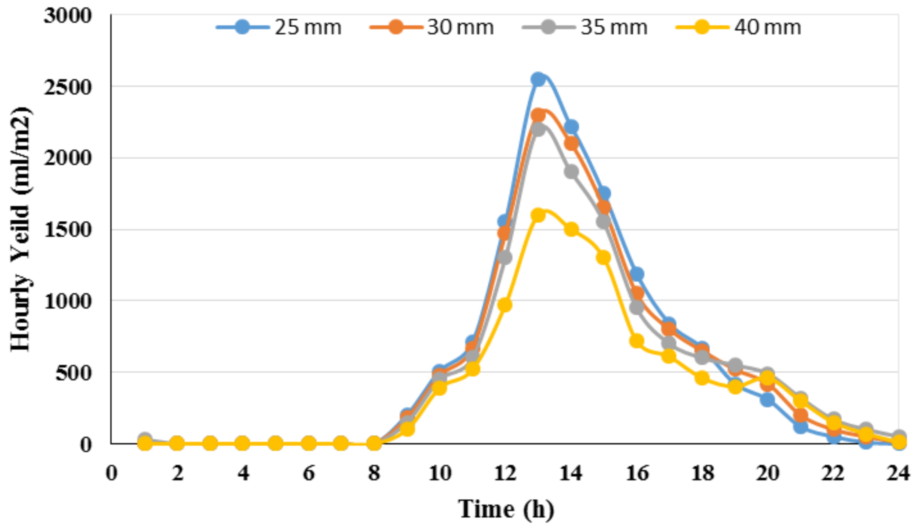
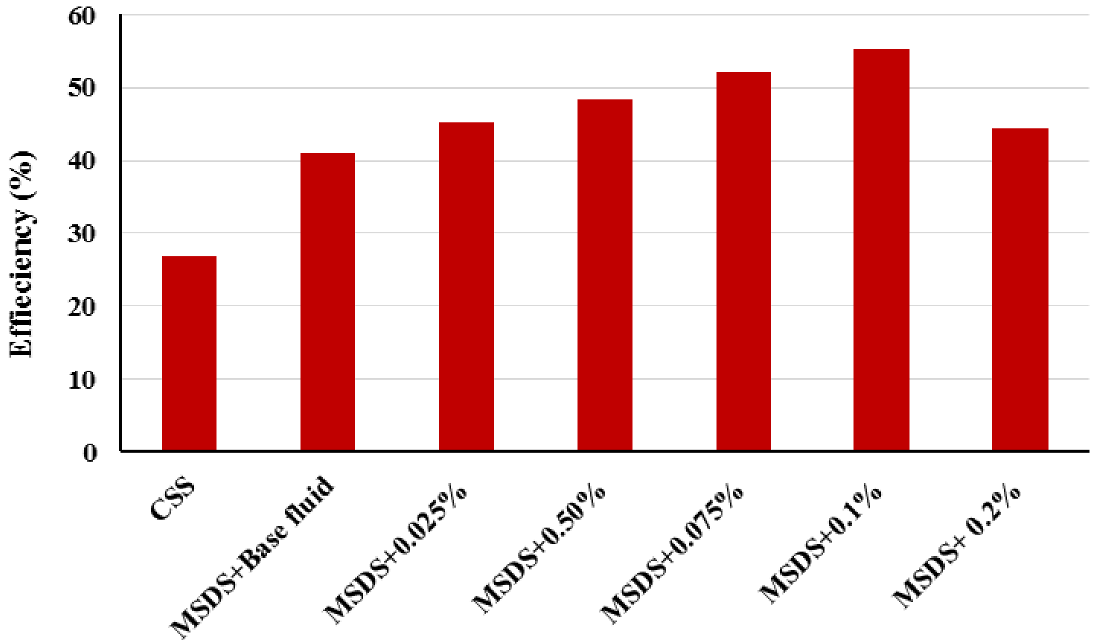


Fig.8 Hourly yield during a 24-hour cycle

Table.3. Comparison of Nocturnal and total yield at a different water depth

Sl No	Water depth (mm)	Nocturnal yield (ml/m^2)	Total yield Ml/m^2
1	25	910	13100
2	30	1300	12650
3	35	1680	12080
4	40	1390	9560

Daily average efficiencies of MSDS and CSS are calculated based on equations (2) and (6) is shown in Fig. 9. The calculated daily average efficiency for CSS was found to be lower than that of MSDS. The average daily efficiencies for CSS, MSDS+base fluid and MSDS+0.1%nHTF were calculated to be respectively 26.7%, 41 %, and 53.6 %. Daily average efficiencies of MSDS calculated at different concentrations of nHTF based on equation (6) are shown in Fig. 9. The estimated daily average efficiency for MSDS is found to vary with the volumetric concentration of nanofluid, and maximum efficiency of 53.55 % is obtained for 0.1% nHTF.



~~**Fig.9.** Daily average efficiencies of MSDS and CSS~~

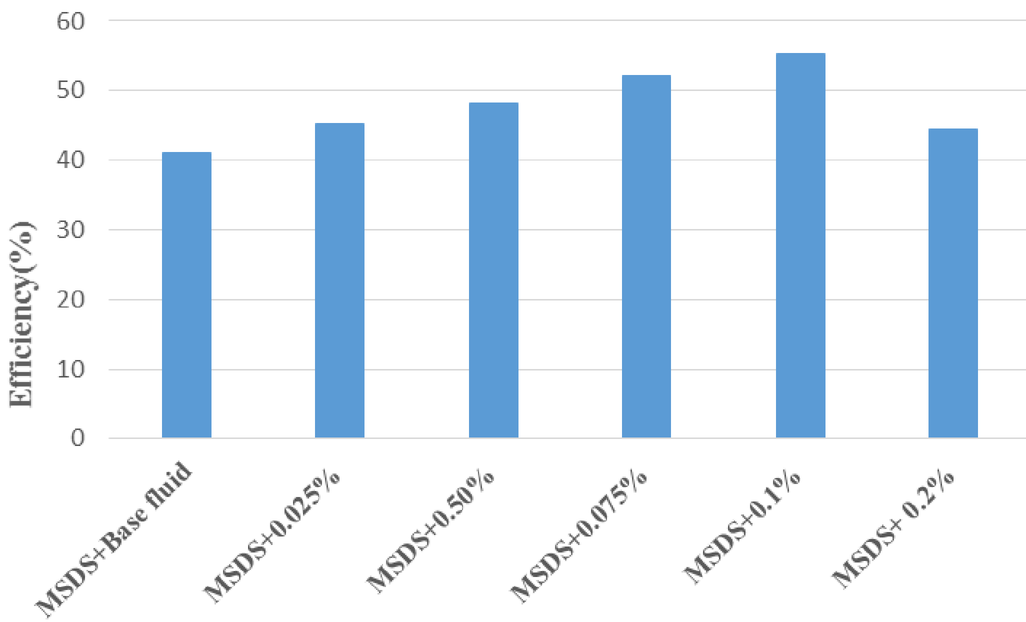


Fig.9. Daily average efficiencies at different nanofluid concentrations of MSDS

Table.4 Cost analysis

Sl No	Particulars	CSS	MSDS
1	Capital cost(P) in INR	5000	20000
2	Operational period(n) in years	5	5
3	Interst per year (i)	7%	7%
4	AOMC in INR	487.8	1951.2
5	FAC in INR	1219.5	4878
6	ASV in INR	86.9	347.6
7	TAC in INR	1620.4	6481.6
8	Annual desalinated water production(Q) in litters	1050	4140
9	The cost for one little-distilled water production in INR	1.54	1.41

The ~~details of the~~ cost evaluation of both CSS and MSDS is given in Table 4. It indicates that the estimated cost for one little-distilled water productions reaches approximately 1.54 INR for CSS and 1.41 for MSDS ~~respectively~~. That is an expenditure of producing 1 liter distilled water in MSDS is less than that of CSS. Therefore MSDS is economical.

The experimental results signify that integration of a Fresnel lens solar concentrator with Therminol-55+ 0.1% Al_2O_3 nHTF and a serpentine shaped heat exchanger to CSS has resulted in a significant improvement of daily fresh water productivity without compromising on the instantaneous efficiency of the system.

6. Conclusion

Performance parameters such as total fresh water productivity, temperatures of saline water and efficiencies have been experimentally measured under the same ambient conditions of Trichy

(India) for CSS and MSDS in conjunction with a range of nHTF variants. The MSDS was found to be a better alternative to the conventional solar stills due to its high productivity (by 250.27%) and daily average efficiency (by 26.81 %) for nHTF containing 0.1% vol concentration of Al_2O_3 and cost-effectiveness. Clearly, solar concentrator based solar distillation system investigated in this study has a significant potential.

Acknowledgment

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