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RESEARCH ARTICLE

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Experimental and numerical analysis of solar still using Pyrex glass quantum dot in tropical climate

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Summary

This study investigates the effect of using quantum dots (QDs) on the performance of solar still in the tropical climate of India. This article presents a new way to use QDs, which on absorbing solar energy increases water evaporation rate. Pyrex glass powder QDs are used in the solar still due to its high absorptivity value. An experimental setup of solar still with QD and without QD was developed, and a comparative analysis was conducted under the real outdoor environment in a tropical climate. The experimental results were also validated through mathematical modeling. The experiment was carried out by mixing Pyrex glass powder QDs with black paint and was coated on the basin and sidewalls of the solar still. Experiments were conducted for a depth of 0.02 m for solar still with QDs and without QDs. The results revealed that for 0.02 m of water depth and 1 m^2 of basin area, the percentage increase in distillate output using Pyrex glass powder QDs is 29.36% experimentally and 29.94% theoretically. Furthermore, the net percentage increase in solar still efficiency by using Pyrex glass QDs is 74.74% experimentally and 61.03% theoretically. The study analyzed that all the experimental results are in good agreement with the theoretical analysis. The addition of Pyrex glass powder QDs and black paint mixture in the basin of solar still caused significant enhancement in the distillate output and solar still efficiency.

KEYWORDS

distillate output, evaporation, quantum dot, solar still

1 | INTRODUCTION

Due to the population explosion in the 21st century, the whole world is facing the problem of water scarcity. Water is abundant in nature, but drinkable water is approximately 2% of total water present on Earth. It is one of the most important contentions among regions, states, and communities. So, the evaluation on the proper use and conservation of water has now become important for sustainable development. The availability of fresh water varies from location to location on earth. According to the world water development report, there are more than 2.2 billion people who do not have the accessibility of safe drinking water.[1] A study revealed that almost 4 billion people live under water crisis at least 1 month of the year.[2] To mitigate these challenges in a sustainable and cleaner way, the United Nations set "clean water and sanitation" as their one of the important goals.

On Earth's surface, oceans are the largest water bodies. However, seawater is saline and is not fit for drinking. The

seawater has the highest amount of total dissolved solids (TDS), which is in the range of 35 000 to 45 000 ppm, while for land water, the TDS is up to 10 000 ppm. The TDS in water for drinking purpose should not exceed more than 500 ppm (ppm).[3-5] The excess amount of TDS along with impurities in the drinking water causes health problems like stomach problems, bad taste, etc. The distillation process is used for the cleaning and purification of saline water, which have total dissolved solids TDS upto 500 ppm or less. Seawater desalination is the most widely used technology for water purification,[6-8] but it is very costly process and not affordable by everyone. Generally, the technologies that are used for waste water treatment are thermal evaporation, ion water exchange, and osmosis.[9,10] However, these technologies are also expensive and have complex configuration and covers large area for their operation and management. Wastewater treatment technology to remove pollutants like metal ion, detergents, and organic contaminants is also not cost-effective.[11,12] One of the sustainable technologies that have gained much hype in recent years is solar-enabled purification, called solar distillation.[13,14] Solar distillation is one of the techniques which use solar thermal energy to distillate the water with the help of a component known as solar still. Since, solar radiation for thermal applications is available in abundant quantity throughout the year in tropical countries like India, and because of various merits associated with solar energy, it can be easily and effectively used for solar distillation.[15] However, the low productivity of solar still limits its applicability for distillation. Many studies have been carried out to evaluate and enhance the productivity of solar still.

A study shows experiment with transparent side walls and honeycomb structure in the basin on single slope solar still (SSSS) so that there is an increase in evaporation rate, which increases yield up to 2.61 L/m^{2}day.[16] A study shows an experiment with a baffled absorber plate that was put in the basin of solar still; the productivity is 20% higher than conventional still.[17] A different study investigated the impact of using side mirrors and sun tracking in active and passive modes. In passive mode, the maximum fresh water with only sun tracking was 1.90 L compared to conventional passive solar still, which has productivity of 1.53 L. The maximum quantity of freshwater with sun tracking and mirror was found to be 2.19 L.[18] One study conducted the experiment with inclined solar still with wick material on different absorber configurations (stepped wire mesh plate, stepped plate, and flat plate). The maximum yield obtained is upto 4.28 L/day. The main drawback with wick type solar still is that it does not work at night.[19] An experiment was performed by taking corrugated sheets (CSs) as absorber material and granite gravel as a sensible heat storage material (SHSM) on conventional solar still with triple basin, which has evacuated heat pipes. The productivity of solar still is around 19 L/m^2/day.[20] A comparative analysis between conventional solar still, conventional pyramidal solar still, and modified pyramidal solar still (using CuO and carbon black nanofluids and evacuated tube) was conducted. This study found that the improvement in distillate output increased by 27.75% when CuO nanofluid is used while there is 33.59% increase in output by using carbon black nanofluid. The maximum solar still efficiency is 64.5 for modified pyramidal solar still with carbon black nanoparticles.[21] An experiment was performed by using phase change material along with solar concentrating unit under desert condition. The concentrator unit is used to heat the brakish water, which then goes to conical distiller where they have used paraffin wax as a PCM to absorb heat from brakish water. They found that with the addition of PCM, the increase in system productivity, system efficiency, and concentrating efficiency was 783%, 157.8%, and 157.8%, respectively, and also increase in working hour of distillation system.[22]

Researchers have used different types of materials to enhance the distillate output of still. A study used nanofluid in the basin. The distilled output is 5.25 L, while by using nanofluid in the basin and nano paint on the glass, the yield is 5.56 L.[23] Another experiment used Al_2O_3 nanoparticle of varying concentration in the basin of solar still. They observed that by using nanoparticle, the distilled output is increased by 2.6%,7.2%, 12.3%, and 17.6% for weight concentrations of 0.2%, 0.10%, 0.05%, and 0.01%, respectively, in comparison with solar still without nanoparticles.[24] Single-basin dual-slope solar still along with Al_2O_3 with varying depth of 0.010, 0.020, and 0.030 m was used for experiment. Enhanced productivity of 1.252, 1.220, and 1.120 L was observed in comparison to conventional solar still, which has distillate output 0.989, 0.950, and 0.938 L with a depth of 0.010, 0.020, and 0.030 m, respectively.[25] An investigation on SSSS by adding nanofluid of Al_2O_3/water with varying concentrations (0.05% and 0.1% volume fraction) and integrated with parabolic trough collector was conducted. The study reveals that the maximum yield is 1.741 L with 0.1% volume fraction of Al_2O_3/water nanofluid with a basin area of 1 m^2 and water depth of 0.025 m. There is 66% increase in distillate output and solar still efficiency is increased by 70% with this modification.[26] TiO_2 nanoparticles mixed with Cr_2O_3 along with different combinations of hybrid bond absorption were used to enhance the performance of solar still. The average daily distillate output of still is 7.89 and 5.39 L/m^2 during summer and winter, respectively.[27] An experiment was conducted on solar still in which CuO nanoparticle was implanted with paraffin on V-corrugated plate and the distillate output of different nanoparticles of 0.3%, 0.2%,

and 0.1% by weight was 0.510, 0.455, and 0.440 L/0.25 m^2/day, respectively.[28] A study has performed with weir-type solar still in which PCM material is used. They used paraffin as PCM material due to which 4.35% of increment in annual productivity compared to conventional solar still was achieved.[29] A study did the experiment to analyze the performance of solar still using Kanchey marble, which acts as a sensible storage material in the solar still. They found out that the yield with Kanchey material was 4.094 L/m^2/day, which is 16.32% more than conventional solar still.[30] A study did the experiment on pyramidal solar still by using TiO_2 nano black paint on the absorber plate, the yield is 6.6 kg/m^2.[31] The author has performed the experiment with SSSS by perturbation of water surface. Perturbation is achieved by injecting air bubbles in the water basin, which produces surface ripple, which enhances evaporative surface area and also helps to increase mass transfer coefficient. The total distillate yield was 6.137 L/m^2.[32] A study investigates the performance of solar still with different heat storage material in upper basin of double slope solar still with vacuum tubes. The productivity with pebbles was 9.34 kg, with granite gravel the productivity was 9.86 kg, and with calcium stones, it was 10.42 kg in summer days.[33] A study presents several experiments using different material to enhance the performance of solar still. One experiment used black dye in which the distillate output was 3.7 L/m^2/day. In another experiment, black rubber mat was used where the distillate output was 3.3 L/m^2/day. Black ink was also used in which the distilled output was 3 L/m^2day.[34] Similar experiment was performed by using black dye in conventional solar still (CSS); the productivity was 3.4 L/m^2/day, and in other experiment, he used black dye with regenerative solar still, the yields was 4.2 L/m^2day.[35] A study presents the analysis by using Paraffin wax as a phase change material in the concentrating solar heater. They have performed following experiments: (a) Using water as an absorber material and without solar tracker, (b) using water as an absorber material and with solar tracking, (c) using PCM as a thermal storage material without solar tracker, and (d) using PCM as thermal storage material and with solar tracker. They found that the system working time is increased by 3 hours by adding PCM without solar tracker, and the system productivity is enhanced by 180% while when they used both PCM and solar tracker then the system working time is enhanced by 3 hours, and the system productivity is enhanced by 307.54%.[36] A study shows comparative analysis of SSSS in three different ways that is, (i) simple solar still with thermoelectric heating (TEH) in basin, (ii) simple solar still with TEH and silver nanofluid with 0.03% by weight in the basin, (iii) simple solar still with TEH, silver nanofluid, and double slope symmetrical external condenser. They found that the maximum yield of 7.760 L/m^2/day when TEH, silver nanofluid, and double slope symmetrical external condenser is incorporated simultaneously.[37] An experiment was performed on single slope solar distiller. They have analyzed (a) conventional solar still without any modification, (b) using paraffin as a PCM in the solar still, and (c) using combination of paraffin wax with nano-Al_2O_3. They found that by adding Paraffin wax the productivity is increased up to 10.38% while when the combination of paraffin wax with nano-Al_2O_3 is used then the productivity of the system is increased by 60.53% in comparison to conventional solar still.[38]

It has been found that various studies have analyzed the effect on distillate output and efficiency of solar still by using nano-particles and heat storage techniques. Currently, nano-technology is emerging as a new field, and researchers are trying to use nano-material for enhancing the performance of solar still. QDs is also part of nano-material. QDs are semiconductor crystals with a diameter of 1 to 10 nm. The most important characteristics of QDs polymer and composites are their size, photo bleaching stability, luminance, bio compatibility, low toxicity, and optical property. Due to its various properties, researchers are trying to use it for various applications like in biomedical, light emitting diodes, photovoltaic, catalysis, photodetector, and photoconductor.[39] However, a limited amount of work has been reported by using QD for solar thermal applications. Most work on the use of quantum dots for harnessing solar energy is carried out by PV cells for conversion of solar energy into electrical energy. Furthermore, no study was carried out on evaluating the effect of QD on the performance of solar still. In this study, a novel approach of enhancing the performance of solar still in the tropical environment is presented. Two solar still was developed to conduct this study. The basin of one solar still was coated with Pyrex glass QD, while the basin of another solar still is without QDs. A comparative investigation of both the solar still in terms of distillate output, temperature of glass, and efficiency of solar still was conducted in real outdoor tropical climate of India. Additionally, a mathematical model was also developed to validate the experimental findings. The research work on the solar still with QDs provides a new way to enhance the performance of passive type solar still.

2 | METHODOLOGY

This study consists of experimental work and mathematical modeling to evaluate the effect of QDs on the performance of solar still. Two similar solar still, one with QDs and the other without QDs, was fabricated at the roof of

the CERD (Centre for energy and resource development) lab of Mechanical engineering Department, IIT (BHU), Varanasi (25.3176°N, 82.9739°E). The location has typical tropical-type environment having plenty of solar radiation throughout the year. The experiment was conducted, and data were collected for 28 Oct, 2020, from 9:30 AM to 5:30 PM and. For the calculation purpose 1-day data are easier to analyze and validate with experimental results. The solar still was tilted at around 25° to collect maximum solar radiation, and the depth of water was taken as 0.02 m. Since we are analyzing and comparing the distillate output, we can take any value for depth of water as per suitability of given set-up. So, we have taken the same depth of water for both the setups.

As shown in Figure 1, when the solar radiation incident on the basin water, the evaporation of water takes place. The evaporated vapor from the basin is condensed to liquid. The condensation of liquid water takes place on the surface of the glass cover, which was exposed toward the side of basin water. Because of the slope of the glass cover, the condensed water moves to the channel and a passage having diameter of 0.01 m was drilled in the middle of the channel in the front of the basin through which fresh water is collected in the flask. We have coated Pyrex glass QDs in the basin, which results in an increase of the absorptivity of the basin due to which there is increase in the water temperature in the basin. Increase in water temperature results in the increase of the evaporation rate. Because of the increase in evaporation rate, the distillate output also increases. Pyrex glass QDs has the ability to absorb heat and we are taking advantage of this absorption property. In present work, QD paint has been prepared by mixing Pyrex glass QDs and black paint. This mixture was then coated onto the surface of the basin, which improves the energy absorbing capacity of solar still. During the experiment, various parameters like temperature of basin water, temperature of glass cover, and output of solar still are measured and recorded for every 1 hour from 9:30 AM to 5:30 PM. The recorded data of both the solar still were analyzed, and a comparative performance evaluation was presented.

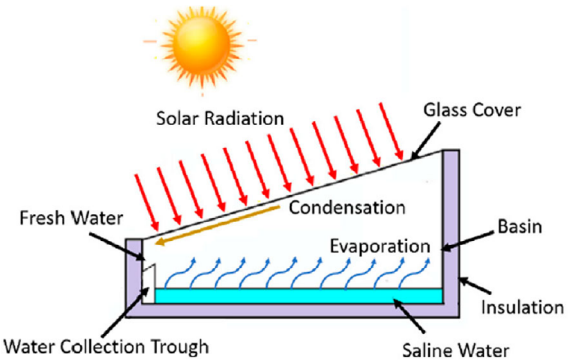

FIGURE 1 Schematic diagram of solar still[40]

3 | MATHEMATICAL MODELING

The assumptions for mathematical analysis of solar still are following:

1. The specific heat capacity of plain glass cover is very small, so we can neglect its effect for our calculation.
2. Whole set-up is leakage proof.
3. The heat transfer through side wall and back wall is assumed to be negligible, so only one directional heat transfer takes place which is from cover to basin
4. There is no heat loss through side walls
5. The intensity is taken as the average intensity value for 1 step hour.

Applying energy balance on glass surface, we get

$$h_{gw}\left(T_w - T_g\right) = h_{ga}\left(T_g - T_a\right) \tag{1}$$

Applying energy balance on water, we get

$$\alpha_w I(t) + h_{bw}(T_b - T_w) = (MC)_w \, d/dt(T_w) + h_{gw}\left(T_w - T_g\right) \tag{2}$$

Applying energy balance on basin, we get

$$\alpha_b I(t) = h_{bw}\left(T_b - T_w\right) + h_{ba}\left(T_b - T_a\right) \tag{3}$$

By rearranging Equation (1), we get

$$T_g = \left[h_{gw}{}^{*} T_w + h_{ga}{}^{*} T_a\right] / \left(h_{gw+} h_{ga}\right) \tag{4}$$

By rearranging Equation (3),we get

$$T_b = \alpha_b I(t) + h_{bw} * T_w + \left[h_{ba} * T_a / \left(h_{bw} + h_{ba}\right)\right] \tag{5}$$

By rearranging Equation (2) and putting value of T_g and T_b in terms of T_w and T_a, we get

$$\begin{aligned} &(MC)_w \, d/dt(T_w) \\ &+ \left(h_{bw}{}^{*} h_{ba}/h_{bw} + h_{ba} + h_{gw}{}^{*} h_{ga}/h_{gw} + h_{ga}\right) * T_w \\ &= \alpha_w I(t) + h_{bw}/h_{bw} + h_{ba}\left(\alpha_b I(t) + h_{ba} T_a\right) \\ &+ \left(h_{gw} h_{ga}/h_{gw} + h_{ga}\right) * T_a \end{aligned} \tag{6}$$

Calculation of h_{gw} between glass and water,

$$h_{gw} = h_{radiation,g-w} + h_{convection,g-w} + h_{evaporation,w-g}$$

The co-efficient of radiative heat transfer ($h_{radiation,g\text{-}w}$) is given by Duffie and Beckman.[41]

$$h_{radiation,g-w} = \varepsilon_{effective}\,\sigma\left(T_w{}^2 + T_g{}^2\right)\left(T_w + T_g\right) \quad (7)$$

where, $\varepsilon_{effective}$ is the emmisivity computed as follows

$$\varepsilon_{effective} = 1/\varepsilon_w + 1/\varepsilon_g - 1 \quad (8)$$

As the process of evaporation–condensation is taking place simultaneously, Dunkle's equation is used[42]:

$$h_{convection,w-g} = 0.884\left[T_w - T_g + \left(P_w - P_g\right)*T_w/\left(268.9*10^3 - P_w\right)\right]^{1/3} \quad (9)$$

$$h_{evaporation,w-g} = 16.276*10^{-3}*h_{convection,w-g}*P_w - P_g/T_w - T_g \quad (10)$$

P_w denotes the value of vapor pressure corresponding to basin water temperature, and P_g denotes the value of vapor pressure corresponding to the glass temperature, and we can find out their value by using following relation:

$$\text{where, } P_w\ (\text{water vapor pressure corresponding to } T_w) = e^{(25.317 - 5144/T_w)}, \quad (11)$$

$$P_g\ (\text{water vapor pressure corresponding to } T_g) = e^{(25.317 - 5144/T_g)} \quad (12)$$

$$h_{ga} = h_{radiation,g-sky} + h_{convection,g-air}$$

By using Duffie–Beckman relation which gives the co-efficient of radiative heat transfer $h_{radiative,g\text{-}sky}$, between the sky and the cover.[41]

$$h_{radiation,g\text{-}sky} = \varepsilon_g{}^*\sigma^*\left(T_g{}^2 + T_{sky}{}^2\right)\left(T_g + T_{sky}\right) \quad (13)$$

where the temperature of sky (T_{sky}) is given by following.[43]

$$T_{sky} = 0.0552\,T_a{}^{1.5} \quad (14)$$

The co-efficient of the convective heat transfer $h_{convection,g\text{-}air}$ is a function of wind velocity and is obtained by following relation:

$$h_{convection,g-air} = 2.8 + 3V, \text{where } V \text{ is average velocity of wind which is in m/s} \quad (15)$$

$$h_{bw} = C^*k^*[Gr^*Pr]^{1/n} \quad (16)$$

For free convection the heat transfer correlation is given by.[44]

$$C = 0.54, n = 1/4, for\ 10^4 < Ra_L < 10^7; \quad (17)$$

$$C = 0.15, n = 1/3, for\ 10^7 < Ra_L < 10^{10}; \quad (18)$$

L = area/perimeter;

The Grashof number is given by.[45]

$$Gr = g^*\beta_w{}^*\Delta T^*L_c{}^3/\nu_w{}^2 \quad (19)$$

$$Pr = c_{pw}{}^*\mu_w/k_w \quad (20)$$

where, $\Delta T = T_w - T_b$; L_c = area/perimeter.

The heat transfer coefficient between basin and air is computed as Fourier equation of conduction:

$$h_{ba} = k_b/L_b + \left[L_{in}/k_{in} + 1/h_{air}\right]^{-1} \quad (21)$$

For our case, we have taken,

ε_w(Emissivity of water) = 0.9,[46]

ε_g (Emissivity of window glass) = 0.9,[47]

M_w (mass of water) = 20 kg (we maintain the same level of water in the basin),

$C_w = 4.18*10^3$ J/kg K,[48]

$\sigma = 5.67*10^8\ \text{W/m}^2\,\text{T}^4, \text{g} = 10\ \text{m/s}^2, \text{L} = L_c = A_s/P_s = 0.25\ \text{m}, V$ (average velocity of wind) = 7.6 m/s,

A_s (area of basin) = 1 m^2 (1m length and 1 m breadth)

$\beta_w = 385*10^{-6}$ 1/K,[49] it depends on temperature but variation is not much for a range of temperature, so we can assume it as constant for our analysis.

$\nu_w = 0.615*10^{-6}$ m^2/s,[50] as kinematic viscosity depends on temperature, but it does not vary much, so we can assume it as constant for our analysis.

$k_w = 0.62$[51] Thermal conductivity of water depends on temperature, but we can assume it constant for our analysis.

$\Delta T > 0$,

k_b (Thermal conductivity of basin) = 0.8 (FRP without quantum dot).

k_b (Thermal conductivity of basin) = 0.82 (FRP with quantum dot coating).

k_{in} (thermal conductivity of wool) = 0.03 w/m K,[52]

L_{in} = 0.07 m,α_w = 0.85,

α_b (Absorptivity of basin or fraction of solar energy absorbed by basin) = 0.68 (FRP without QD).

α_b (Absorptivity of basin or fraction of solar energy absorbed by basin) = 0.98 (FRP with QD).

h_{air} = 13.75 W/m^2 K. These data are shown in Table 1.

TABLE 1 Different data that are used for mathematical modeling of solar still

A_s = area of basin (in m^2)	1
P_s = perimeter of basin (in m)	4
L_c = Characteristic length of basin (in m)	0.25
L_b = Thickness of basin (in m)	0.01
L_{in} = Thickness of insulation material (in m)	0.07
M_w = Mass of water (in kg)	20
C_w = Specific heat capacity of water (in J/kg-K)	4.18*10^3
h_{air} = Average heat transfer co-efficient of air (free convection in W/m^2·K)	13.75
$(MC)_w$ = Product of mass of water and specific heat of water (J/K)	83.6*10^3
V = Average velocity of air used for calculation (m/s)	7.6
k_b = Thermal conductivity of basin (W/m K)[for FRP in SS]	0.8
k_b = Thermal conductivity of basin (W/m K)[for QD]	0.82
k_w = Thermal conductivity of water (W/m K)	0.62
k_{in} = Thermal conductivity of wool (W/m K)	0.03
ν_w = Kinematic viscosity of water	0.615*10^{-6}
α_w = Absorptivity value of water or fraction of solar energy absorbed by water (dimensionless)	0.85
ε_w = Emissivity value of water (dimensionless)	0.9
ε_g = Emissivity value of glass (dimensionless)	0.9
α_b = Absorptivity of basin or fraction of solar energy absorbed by basin (dimensionless) [for FRP]	0.68
α_b = Absorptivity value of basin or fraction of solar energy absorbed by basin (dimensionless) [for QD]	0.99
β_w = Coefficient of volumetric thermal expansion (K^{-1})	385*10^{-6}
σ = Stefan–Boltzman constant (W/m^2 K^4)	5.67*10^8

FRP, fiber-reinforced plastics; QD, quantum dots.

So by calculation, Ra_L is in range of (10^7-10^{10}), so we use Equation (18) for our analysis of heat transfer coefficient between basin and water.

We can take an average value of intensity in 1 step hour period for our analysis.

Since $h_{b\text{-}w}$ is not changing much so we can assume it to be constant for our whole analysis.

So our Equation (6) will look like,

$$d/dt\,(T_w) + a\,T_w = c \tag{22}$$

where $a = 1/(MC)_w[h_{bw}{*}h_{ba}/h_{bw} + h_{ba} + h_{gw}{*}h_{ga}/h_{gw} + h_{ga}]$;

$$c = 1/(MC)_w[[\alpha_w + (h_{bw}{*}\alpha_b/h_{bw} + h_{ba})]I(t) + [h_{bw}{*}h_{ba}/h_{bw} + h_{ba} + h_{gw}{*}h_{ga}/h_{gw} + h_{ga}]T_a]$$

so a and c are constant value for 1step hour and the solution of the Equation (22) is

$$T_w^{\,i+1} = T_w^{\,i}\,e^{-3600a} + c{*}\left[1 - e^{-3600a}\right]/a \tag{23}$$

$$T_g^{\,i+1} = h_{gw}{*}T_w^{\,i+1} + h_{ga}{*}T_a^{\,i+1}/\left(h_{gw} + h_{ga}\right) \tag{24}$$

$$T_b^{\,i+1} = \alpha_b\,I(t)_{average}^{\,i} + h_{bw}\,T_w + h_{ba}\,T_a/(h_{bw} + h_{ba}) \tag{25}$$

$I(t)_{average}^{\,i}$ = average intensity for ith period.

The evaporative heat transfer rate and distillate output (hourly basis) are given by Equations (26) and (27) respectively:

$$Q_{evaporative} = h_{evaporation,g-w}{*}\left(T_w - T_g\right)A_s \tag{26}$$

$$m_{evaporation}\ (\text{theorectical output of water in ml}) = \left[h_{evaporation,g-w}{*}\left(T_w - T_g\right){*}A_s{*}3600/\text{Latent Heat}\right]{*}10^3 \tag{27}$$

The Solar still efficiency can be determined by:

$$\eta_i = h_{evaporation,g-w}\left(T_w - T_g\right)/I(t) \tag{28}$$

4 | SOLUTION TO MATHEMATICAL MODEL

As we have observed that T_w, T_g, T_a, N_i value changes with time. In the above calculation, a numerical method has been used. For our numerical analysis, we have used the time interval Δt as 1 hour. The following steps have followed for numerical analysis:

1. First, we initialize the value of T_w, T_g, and T_a solar still specifications and other climatic parameters, and then we calculate various heat transfer coefficients value.
2. After calculating various heat transfer coefficient values, we predict the next value of T_w and T_g using previous heat transfer coefficients by using Equations (23) and (24) and distillate output is calculated using Equations (26) and (27).
3. When we get new values of T_w and T_g, the new value of heat transfer coefficients is calculated, and step 2 is repeated for next time interval.
4. For a given time interval Δt, the value of T_g, T_w, and T_a and heat transfer coefficient values are assumed to be constant for each interval of time, and as a result, the total distillate output is calculated.
5. For a given time interval Δt, the solar still efficiency for ith period (ηi) is obtained by using Equation (28).

5 | EXPERIMENTAL SET-UP

The solar still with a basin, which is of square shape with an area of $1m^2$ (1 m × 1 m) and thickness of 0.01 m is used. Side walls which are of triangular shape having base, height, and thickness of 1, 0.45, and 0.01 mm, respectively, and back wall, which is of rectangular shape having length, height, and thickness of 1, 0.45, and 0.01 m, respectively. The basin side wall and back wall are made up of fiber-reinforced plastics (FRP), which has thermal conductivity value of 0.8 W/m·K and absorptivity value in the range of 0.6 to 0.7. In one setup, only FRP is used as basin material, and in the second setup, black paint with glass powder quantum dot, as shown in Figure 2, was coated on FRP. The detailed dimensional view of the solar still developed to conduct the experiment is shown in Figure 3.

Glass powder QDs were procured from Center for Material for Electronics Technology (C-MET), Pune, Ministry of Electronics and Information Technology, India, as shown in Figure 4. The value of its thermal conductivity is around 0.82 W/m·K, and absorptivity value is in the range of 0.95 to 0.99, respectively. Plain window glass is used as a glass cover, which has transmissivity of 0.9 and length, breadth, and thickness of 1.10, 1, and 0.005 m, respectively. Insulation, by using glass wool, was done around the side wall, back wall, and bottom of basin to minimize the heat loss to the surrounding. Glass wool has thermal conductivity of 0.03 W/m·K, and thickness of 0.07 m is used as insulating material.

The four iron rods each of height 0.15 m, which were welded below the basin of solar still, act as support for still. The whole set-up was put on a cement foundation with some part of the iron stand in the cement. The length, breadth, and height of cement foundation are 1.30, 0.22, and 0.30 m respectively. The productivity of solar still is a function of the temperatures of basin water and the inner glass temperature. So, thermocouple is fixed on cover glass and on glass basin to record the value of temperature. The glass cover temperature, basin temperature, water temperature, and surrounding temperature were measured by K-type thermocouple. Pyranometer was used to measure the solar intensity, which was coming from the sun. Pyranometer has accuracy of $\pm 25\ W/m^2$, and its working range is between 0 and 1750 W/m^2. The comparative analysis of productivity and efficiency of simple solar still and solar still with quantum dot has been analyzed at the water depth of 0.02 m. Wind velocity is measured by an instrument named anemometer. The intensity and wind velocity data with time on Oct 28, 2020, are shown in Figure 5. We can also say from Figure 3 that the variation of intensity and wind velocity depends on the external environment. Wind velocity is more uniform than intensity on Oct 28, 2020. There is a sudden drop in intensity from 856 to 300 W/m^2 at 13:30 hours due to sudden clouds formation in the sky. However, soon clouds disappear, and solar intensity increases from 300 to 499 W/m^2. The specifications of measuring instrument are shown in Table 2.

FIGURE 2 Experimental set up of solar still A, without Quantum Dot B, with glass powder Quantum dot

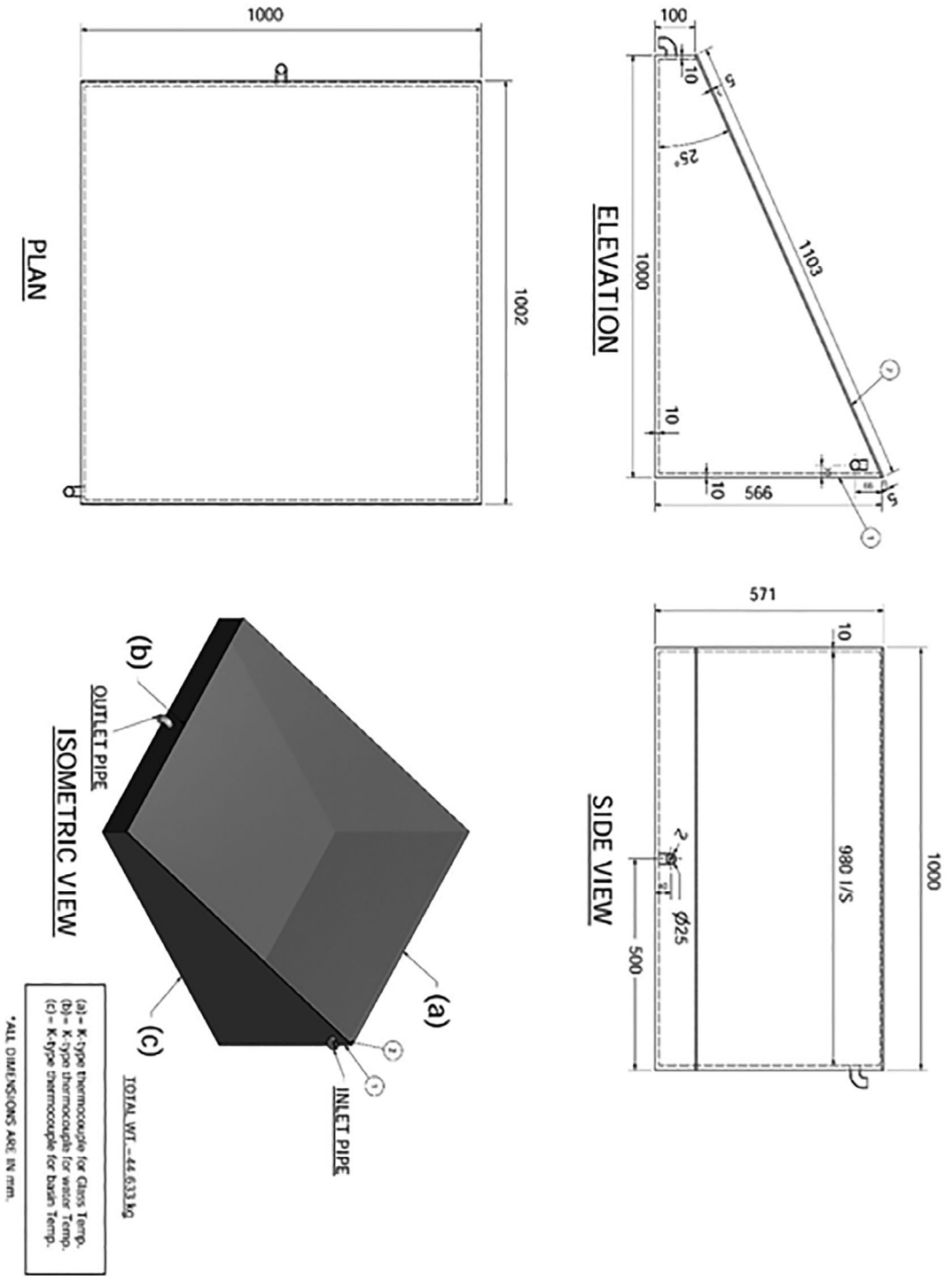

FIGURE 3 Dimensional view and isometric view of the solar still

6 | RESULT AND DISCUSSION

The temperature distribution of water, which is measured by thermocouple and also theoretical temperature prediction in SSSS and SSSS with QD, is shown in Figure 6. From the graph, we can say that for a depth of 0.02 m when simple solar still is used, the absorber plate has reached the highest temperature around 51°C at 13:30 hours and theoretically highest around 50°C at 12:30 hours. When Pyrex glass QD with black paint is used in the basin of solar still for depth of 0.02 m, then the highest temperature experimentally was around 54°C at 12:30 hours, and theoretically the highest temperature was around 52°C. The temperature of water recorded in

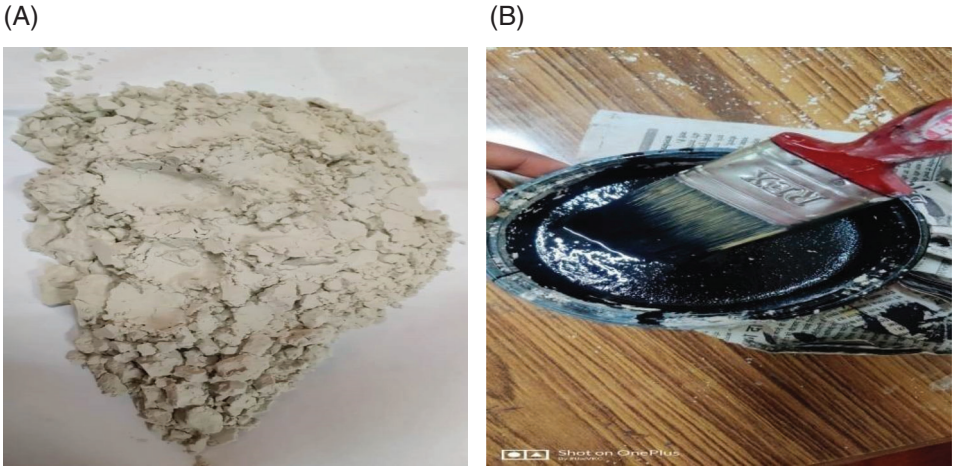

FIGURE 4 A, Pyrex glass powder quantum dots (QD) and B, black paint with Pyrex glass powder QD

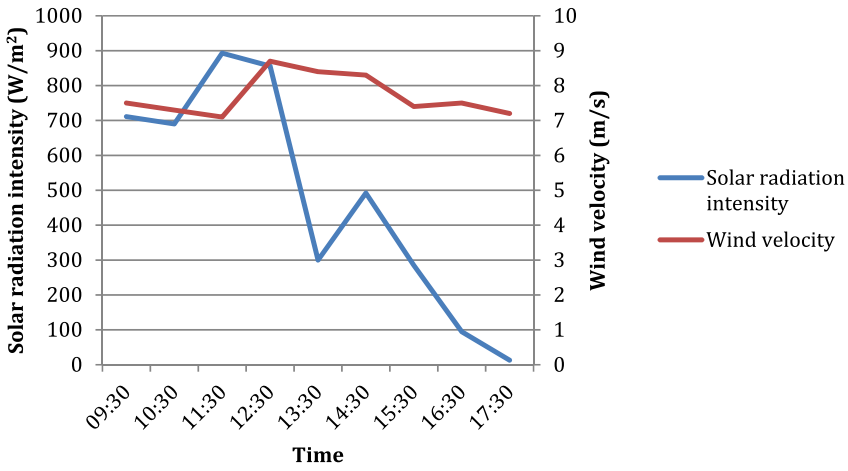

FIGURE 5 Solar radiation intensity and wind velocity with time

TABLE 2 Name and Specification of Measuring Instruments

Device	Range	Standard uncertainty
K-class thermocouple	-100°C to 1300°C	0.06°C
Pyranometer	0–1750 W/m^2	+25 W/m^2 to −25 W/m^2
Anemometer	0.3-30 m/s	+5% to −5%

solar still with Pyrex glass QD is higher in comparison to temperature of water recorded in SSSS. This has happened because Pyrex glass QD has increased the absorption of solar energy in the basin which increases the water temperature higher than SSSS.

Figure 7 shows the temperature distribution of inner side of the glass and theoretical temperature prediction in SSSS and SSSS with QD. From the graph, it has been observed that for the depth of 0.02 m, for simple solar still, the glass has the highest temperature of 46°C at 13:00 hours, and theoretically the highest temperature was around 43.14°C at 12:30 hours. When Pyrex glass quantum dot with black paint is used in a basin of solar still for depth of 0.02 m, then the highest temperature of glass achieved was around 44°C at 12:30 hours, and theoretically highest temperature was around 45°C at 13:30 hours.

Figure 8 shows the distillate output (in ml) on hourly basis of SSSS and SSSS with QD experimentally and theoretically. The maximum distillate output experimentally in simple solar still was 0.260 L at 13:30 hours at an average intensity of 578 W/m^2, and theoretical maximum output in solar still (SS) was 0.1809 L at 12:30 PM at an average intensity of 874.5 W/m^2. When SS with QD is used, then the maximum distillate output (in mL) obtained experimentally is 0.310 L at 13:30 hours and theoretical maximum output with QD (in mL) was 0.28645 mL at 13:30 hours at an average intensity of 578 W/m^2. This was happened because when Pyrex glass QD was used, it increases the absorption coefficient of

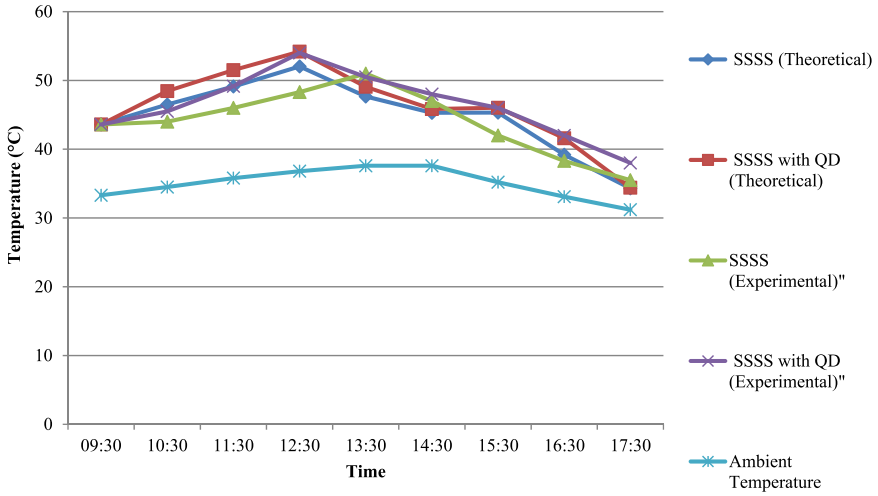

FIGURE 6 Maximum temperature of water (in °C) in single slope solar still (SSSS) and SSSS with quantum dots (QD)

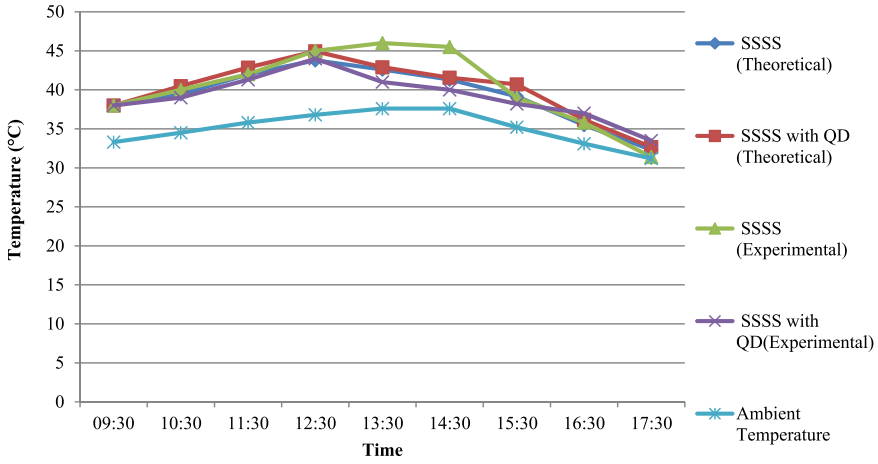

FIGURE 7 Temperature variation inner side of glass (in °C) in single slope solar still (SSSS) and SSSS with quantum dots (QD)

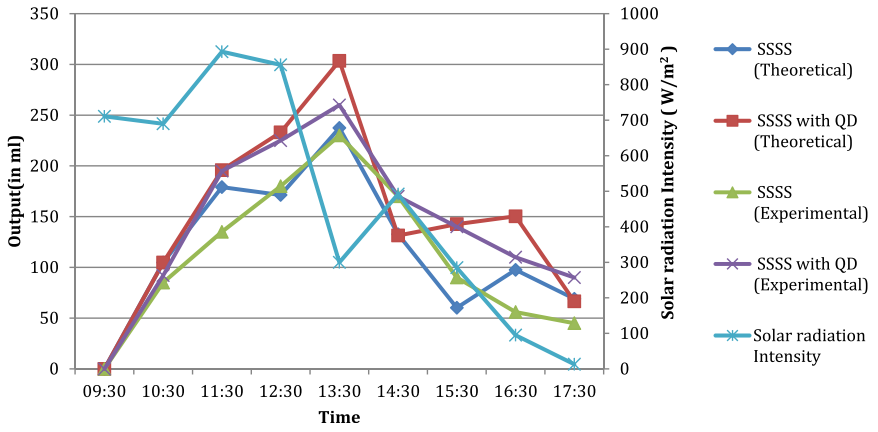

FIGURE 8 Distillate output (in mL) hourly basis in single slope solar still (SSSS) and solar still with quantum dots (QD)

basin, which results enhancement of the temperature of water and hence evaporation of basin water increases (since evaporation is directly depends on temperature, more the temperature more the evaporation from the surface), which in turn increases the distillate output of solar still which has Pyrex glass QD as basin material in comparison to simple solar still. We have also observed from Figure 7 that there is sudden drop of output for theoretical values at 14:30 hours, this is due to sudden drop in intensity from 856 to 300 W/m^2 because of cloud shading

and calculation was done by assuming 578 W/m^2 which is average value of 856 and 300 W/m^2 for 14:30 hours.

Figure 9 shows the cumulative output (in ml) experimentally and theoretically in SS and solar still with QD. The total distillate output experimentally in SSSS was 1.031 L and for SSSS with QD was 1.362 L and the total distillate output theoretically in SS was 1.052 L and solar still with QD was 1.211 L. So there is 29.36% increase in distillate output experimentally by using QD in the basin of solar still in comparison to SSSS and 29.94% increase in distillate output by using QD in comparison to simple solar still theoretically. This was happened because when Pyrex glass QD was used, it increases the absorption coefficient of basin which in turn enhances the temperature of water and hence evaporation of basin water increases (since evaporation is directly depend on temperature, more the temperature more the evaporation from the surface) which increases the distillate output of solar still which has Pyrex glass quantum dot as basin material in comparison to simple solar still.

Figure 10 shows the graph of solar still efficiency of SSSS and SSSS with QD. We can see that there is an increase in solar still efficiency of SSSS with QD comparison to simple solar still. With the use of Pyrex glass quantum dots in the basin, the temperature of water has increased, which results in an increase of the temperature difference (ΔT) between glass and water. Due to this, the average increase in solar still efficiency is 74.74% experimentally and 61.03% theoretically in SSSS with Pyrex glass quantum dot in comparison to SSSS.

There was a difference in the experimental and theoretical results of distillate output as shown in Figure 11. This happened because in theoretical modeling, we assume that the set up is completely insulated while practically it is impossible to do perfect insulation of an experimental set-up. The second assumption was that intensity is changing after every 1 hour, but in reality, intensity is changing at every instant due to the change in sun's position. Also, it depends upon climatic condition of the site. We did analysis by considering temperature of water and glass constant for every 1 hour. But in reality, both were

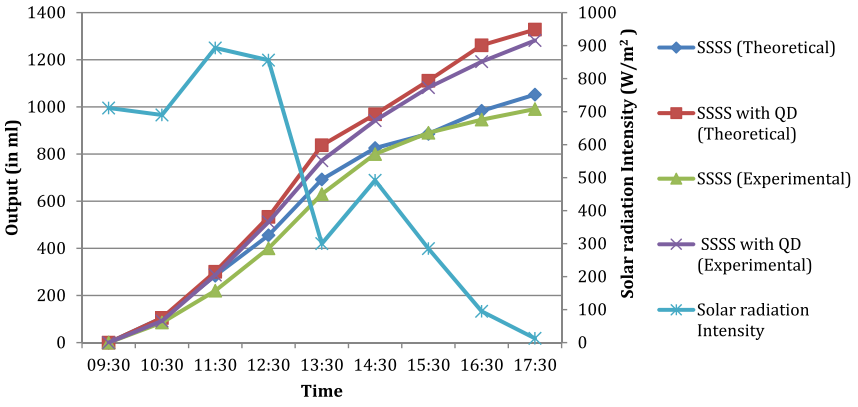

FIGURE 9 Distillate output (in mL) cumulative in SS and solar still with quantum dots (QD)

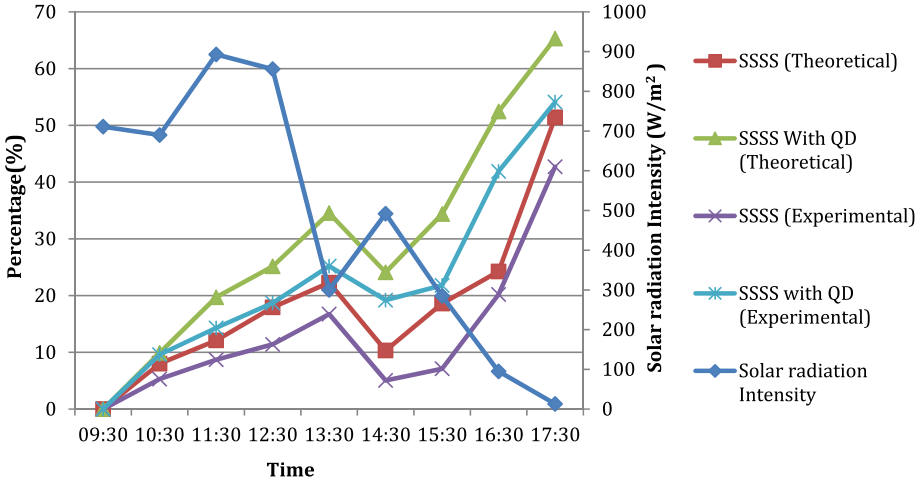

FIGURE 10 Solar still efficiency (hourly basis)

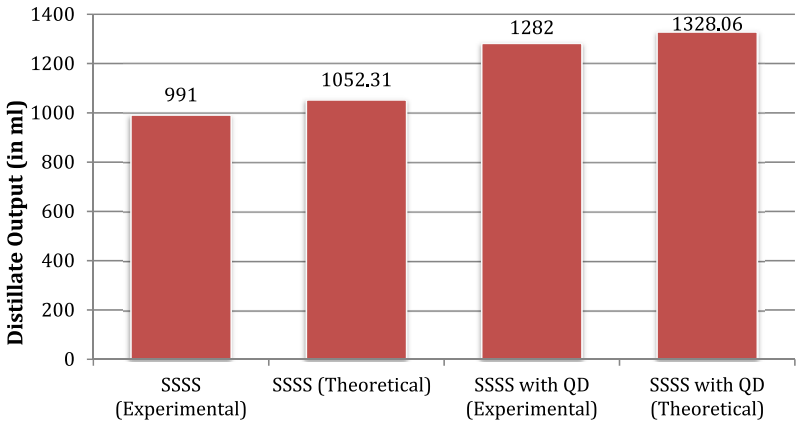

FIGURE 11 Comparison of experimental and theoretical distillate output

changing at every instant due to change in intensity and other climatic parameter like wind velocity, surrounding temperature, etc. Also we assumed wind velocity to be constant for every 1 hour, but practically, it was changing at every instant. Because of these assumptions, the theoretical distillate output slightly differs from experimental distillate output in this study.

7 | CONCLUSION

This study investigates the performance analysis of solar still with and without QDs in the tropical climate of India. An experimental setup was developed using two similar solar still, one with Pyrex glass QDs and another without QDs. Both the solar still was tested in real outdoor tropical environment for 1 day. Mathematical model was also developed to validate the experimental results. When Pyrex glass QD with black paint is used, then it gives higher yield comparison to SSSS. Following are the concluding remarks from the study:

1. The distillate output of SSSS is 0.991 L experimentally, whereas the distillate output of SSSS with QD as basin material is 1.282 L experimentally for a depth of 0.02 m.
2. The mathematical analysis results are in better agreement with experimental results, thereby validating the experimental results. The distillate output of SSSS is 1.052 L theoretically, whereas the distillate output of SSSS with QD as basin material is 1.367 L theoretically for a depth of 0.02 m.
3. The percentage increase in distillate output experimentally by using Pyrex glass QDs in the basin of solar still is 29.36% experimentally and 29.94% theoretically in comparison to SSSS.
4. By using Pyrex glass QDs, the solar still efficiency is also increased by 74.74% and 61.03% on experimental and theoretical basis, respectively.
5. Pyrex glass powder QDs with black paint have energy absorbing properties due to which the rate of evaporation of water in the basin is increased which in turn increases the distillate output.
6. The theoretical prediction of distillate outputs from mathematical modeling is a good match with experimental results with a maximum difference in distillate output of approximately 7%.
7. The overall efficiency of SSSS by using Pyrex glass powder QDs has also increased in comparison to simple solar still.
8. The velocity of wind plays an important role in the condensation and evaporation process.

NOMENCLATURE

A_s	area of basin (in m^2)
P_s	perimeter of basin (in m)
L_c	characteristic length of basin (in m)
L_b	thickness of basin (in m)
L_{in}	thickness of insulation material (in m)
M_w	mass of water (in kg)
C_w	specific heat capacity of water (in J/kg·K)
h_{gw}	total heat transfer co-efficient between water and glass ($W/m^2 \cdot K$)
$h_{radiation, g\text{-}w}$	radiation heat transfer coefficient between glass and water ($W/m^2 \cdot K$)
$h_{convection, g\text{-}w}$	convection heat transfer coefficient between glass and water ($W/m^{2\cdot}K$)
$h_{evaporation, g\text{-}w}$	evaporation heat transfer coefficient between glass and water ($W/m^{2\cdot}K$)
h_{ga}	total heat transfer co-efficient between glass and surrounding ($W/m^{2\cdot}K$)

$h_{\text{radiation, g-sky}}$	radiation heat transfer coefficient between glass and sky (W/m^2·K)
$h_{\text{convection, g-air}}$	convection heat transfer coefficient between glass and outside air (W/m^2·K)
h_{bw}	convection heat transfer between basin and water (W/m^2·K)
h_{ba}	total heat transfer between basin and outside air (W/m^2·K)
h_{air}	average heat transfer co-efficient of air (free convection in W/m^2·K)
$I(t)_{\text{average}}^{\text{i}}$	average intensity for *i*th period(W/m^2)
T_{w}	temperature of water (in K)
T_{g}	temperature of glass (in K)
T_{a}	temperature of air (in K)
T_{b}	temperature of basin (in K)
T_{sky}	temperature of sky (in K)
$(\text{MC})_{\text{w}}$	product of mass of water and specific heat of water (J/K)
V	velocity of air (m/s)
Gr	Grashof number (dimensionless)
Pr	Prantl number (dimensionless)
k_{b}	thermal conductivity of basin (W/m· K)
k_{w}	thermal conductivity of water (W/m· K)
k_{in}	thermal conductivity of wool (W/m ·K)
ν_{w}	kinematic viscosity of water
α_{w}	absorptivity of water or fraction of solar energy absorbed by water (dimensionless)
ε_{w}	emissivity of water (dimensionless)
ε_{g}	emissivity of glass (dimensionless)
α_{b}	absorptivity of basin or fraction of solar energy absorbed by basin (dimensionless)
η_{i}	solar still efficiency (for i$^{\text{th}}$ period in %)
ΔT	temperature difference between basin and water (in K)
β_{w}	coefficient of volumetric thermal expansion (K^{-1})
μ_{w}	viscosity of fluid (N·s/m^2)
σ	Stefan–Boltzmann constant (W/m^2 K^4)

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DATA AVAILABILITY STATEMENT

Data sharing not applicable

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