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Increasing the productivity of pyramid solar still augmented with biomass heat source and analytical validation using RSM

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ABSTRACT

A pyramid type solar still with 0.82 × 0.81 × 0.75 m has been fabricated with galvanized iron sheet and tried with different water depths of 2–4 cm integrated with biomass heat source. The tail of the basin was attached with a heat exchanger having 0.025 m diameter and 3.5 m length, and having five numbers of bends. The function of the heat exchanger is to remove high temperature energy from biomass heat source to the saline water in the still at a constant current rate using circulation pump. Various solid, sensible, latent heat storage materials and evaporative surface materials are used in the still to increase the saline water temperature. To bring down the glass cover temperature, the outer glass was cooled using sprinkler manually at regular interval of fourth dimension. Experiments were conducted with biomass heat source for once flow mode and continuous stream mode and solar heat radiation mode. Theoretical analysis was performed using response surface methodology (RSM) software trial 9.01 version and compared with experimental values. The performances of modified still were compared with conventional still of the same size running under the same meteorological conditions. Productivity of sensible and evaporative materials was analyzed using RSM. Various heat transfer coefficients and efficiency were found out and the optimization levels were found using RSM. The substantial, sensible heat storage materials produce 48% more productivity than conventional still. Also, evaporative materials produce 19% more productivity than conventional still. The efficiency of the pyramid still with continuous flow mode produces more efficiency than once flow mode and solar mode. The efficiency of conventional still was depressed when compared with all other styles of operation.

Keywords: Solid sensible heat storage materials; Glass cooling; Evaporative surfaces; Water depths; Once flow; Continuous fashion; Pyramid still; Solar mode; RSM; Optimization

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1. Introduction

Water scarcity is the major problem that calls for the development and economy of the country. Major industries are facing water problem, which in turn affects the output operation. Another problem is public in that areas are suffering a great deal due to lack of fresh water for drinking and agriculture purposes. Many people suffered from cholera, jaundice, and waterborne diseases. One of the best and most inexpensive methods to solve those problems are by solar distillation method. The solar stills have many advantages than other methods of desalination. Solar stills are cheap and simple technology that requires less maintenance. The solar energy is clean and free energy. To increase the output of the single basic solar still, many research works are being carried away. Fath et al. [1] fabricate the pyramid solar still and single basin solar still and the results showed that the efficiency of single basin still was sound when compared with pyramid still. Rajesh and Bharath [2] coupled a single basin solar still with a flat plate collector and the study showed that the river water produces 42% productivity than the sea and bore well water. Arunkumar et al. [3] analyses different types of solar still namely spherical, pyramid, concentrated still on them and observed that a concentrated still performs 48% than others stills. Rozos and Makropoulus [4] assessing the combined benefits of water recycling and rain water harvesting improves the water scarcity. Arjunan et al. [5], uses blue metal stones in the catchment area as energy storing materials and increased 5% productivity than conventional still. Badran [6] studied the performance of a single slope solar still using different operation parameters and increased the productivity of the still by 29% using asphalt liner and sprinkler for glass sealing. Mugafag Suleiman and Tarawneh [7] conducted the experiment on the impression of water depth on still; he also uses sprinkler for glass cooling to reduce glass cover temperature and improves productivity by 14% more than conventional still. Hvsham et al. [8] studied the productivity of single basin still using sprinkler and cooling fan to reduce the glass cover temperature and increases the productivity by 31% than conventional still. Medugu and Ndanewong [9] conducted experiments on single basin solar still with different water depths and compares it with theoretical analysis. The results show that instantaneous efficiency increases with an increase in solar radiation. Velmanirajan et al. [10] analyses numerical modeling of aluminum sheets using response surface methodology (RSM). Narayanan and Padmanabhan [11] uses resume in their study for predicting bend force during an air bending process in interracial free steel sheet. Voropoulos et al. [12] experimentally investigated the hybrid still coupled with solar collectors and the results showed that the productivity is doubled by coupling. Kabeel [13] fabricated a concave basin pyramid solar still and a conventional still and the results showed that the productivity was very high for pyramid still when compared with conventional still. Bena and Fuller [14] coupled a natural convection solar dryer with a biomass backup heater; the analysis showed that that biomass backup drier was four times better than the solar dryer. Sathyamurthy et al. [15] fabricated a new pyramid still and uses pcm in the still to increase productivity. The results demonstrated that 35% more output was noted, while using pcm material. Arunkumar et al. [16] performed an experimental analysis using pyramid style and boosting mirrors and increases the productivity by 15% than conventional still. Ghassan et al. [17] fabricated three models of pyramid still and analysis with various water depths and the results showed that the still with lower depth produces more water than others. Arunkumar et al. [18] uses a parabolic concentrator with the pyramid still and the experimental findings show that the pyramid still produces more output of 6 L/m^2. Ali Kianifar et al. [19] fabricated a pyramid still model and compares with conventional still where the pyramid still produces 40% more output than conventional still. Ali Kianifar, Saeed Zeinali Heris, used Diesel generators to provide electricity in remote areas. They typically produce about 40–50% of the energy as low-grade heat, which leaves the engine via the exhaust. By connecting a distillation system to the diesel engine exhaust, it is possible to use this low-grade heat which is currently wasted. Furthermore, the system actively cools the generator, improving its efficiency and, hence, increasing its electricity output. Uninterrupted usage of waste heat from industry requires heavy investment more over the transmission is needed for changing waste heat into the still. The transmission heat losses are high. Quantity of fuel costs is high and the system and still are really nearer to each other. The main point observed from the above survey is water temperature. Increasing the water temperature increases the efficiency in the still. In order to fulfill the gap, efforts are taken to increases the water temperature. The primary aim of this study is to raise the productivity of the pyramid-type solar still by integrating the biomass heat source. Various solid sensible heat storage materials such as stones, metal pieces, and seashells are used in the still. These materials absorb heat and releases slowly. The released heat energy is used to increase the water temperature. Various latent heat storage materials such as water and wax are used to improve efficiency. Evaporative surfaces such as wick and sponges were tested to improve the productivity in the still. To improve the condensation rate, outer glass cover temperature was cooled at regular intervals of 10 min using sprinkler manually. The theoretical analysis was done using the RSM software and the results were compared with experimental values. No other employment was previously performed using RSM in solar still. The primary advantages of using biomass fuels are they are abundant, low cost, high-energy capacity, biomass that does not increase carbon dioxide and has low sulfur content; thus, resists acid rains.

2. Experimental set-up

A pyramid-type solar still was fabricated with 1.4 mm thick mild steel. The size of the basin was 0.81 × 0.82 × 0.75 m. The height of the still was 0.3 m. The basin is painted black to absorb maximum solar radiation. The position and bottom positions of the stills were insulated with 4 mm thick thermocouple insulation layer (0.015 W/m-K thermal conductivity) to cut heat losses in the still. The condensing surface of the blade is made of four plain glass with 4 mm thickness set at 30° inclination (equal to latitude of site) to the horizontal axis having absorptivity of 0.9. A silicon rubber sealant is used to hold the glass intact with the still to prevent the vapor leakage from the still. Collection troughs were provided below the lower border of the ice cover to collect the condensate. Distillate outlets were provided to drain the water through hoses and to store in jars. Provisions were made to supply raw water, run out the basin water, and insert thermocouples. A biomass heat source is a biomass boiler which provides high temperature to the solar still through a heat exchanger attached at the underside of the watershed of the pyramid still. Pyramid stills have more condensing area than the single slope solar still and when the still was coupled with biomass heat source, more evaporation takes place inside the still and in order to convert it into distilled water, more condensing area is needed. In ordinary still, the glass condensing area is less when compared with pyramid still. Heat exchanger is of 0.025 m in diameter and 3.5 m long having five numbers of turns. Heat exchanger on one end is tied to the biomass heat source and the other end is linked to the circulation pump to circulate the working fluid in the heat exchanger back to the kettle. The working fluid in the heat exchanger is water and is made to run at a constant current rate of (0.143 kg/s) the circulation pump. The boiler is of internally fired fire tube boiler. It consists of fire tube, boiler drum, and furnace. The boiler is made of cast-iron having a fire tube of 0.0125 m in diameter. The boiler drum is having 0.133 m inner diameter and 0.145 m outer diameter. The heaviness of the shell is 0.012 m. The total height of the boiler is 0.55 m. The lower part of the boiler is called the furnace, where biomass is fed into the furnace through the fuel input door. The burnt ashes are gathered at the lower end and removed periodically. The lower end of the fire tube is joined to the furnace and the upper end is tied to the chimney. Boiler drum has inlet and outlet to hold the feed water from the kettle. The feed water is furnished to the boiler drum by gravity from the input feed water supply tank, which is located above the elevation of the boiler. Safety valves and pressure gauges are fitted to a higher place of the boiler drum for safety aspects. The kettle barrel is connected to transfer pipes for uniform heating. The exhaust gases after passing through the fire tubes exhaust to the atmosphere through chimney provided at the upper side of the kettle. The boiler is supplied with biomass and fired manually. Usually wood, wood chips, and palm wastes are used as biomass fuels in the biomass boiler. Fig. 1(a) and (b) indicates the scene of the fabricated experimental pyramid solar still. Table 1 shows the heat balance sheet for the biomass boiler system. A conventional still of same area was fabricated and run parallel with the modified still for comparison. Experiments were conducted at Mohamed sathak polytechnic college, Kilakarai, Ramanathapuram, Tamil Nadu, India, during the months of December 2013–February 2014. The interpretations were read from morning 10 am to evening 5 pm for every one hour interval for all the modes. PV sun meter, digital anemometer, and mercury thermometers were used to measure global radiation, current of air speed, and ambient temperatures, respectively. K-type thermocouples with multi-channel digital display unit were used to measure basin, water, and glass cover temperatures. Table 2 shows the error analysis for the above measuring instruments.

3. Modifications in the still

Solid sensible heat storage materials such as metal pieces, stones, and seashells are introduced in the still with 2–4 cm water depths. Various latent heat storage materials such as water and wax are introduced in the galvanized iron billets of size 0.1 m diameter and 0.3 m length. All the liquid materials were filled half of the intensity in the berth. The billets are introduced inside the still with different water depths. Wick, and

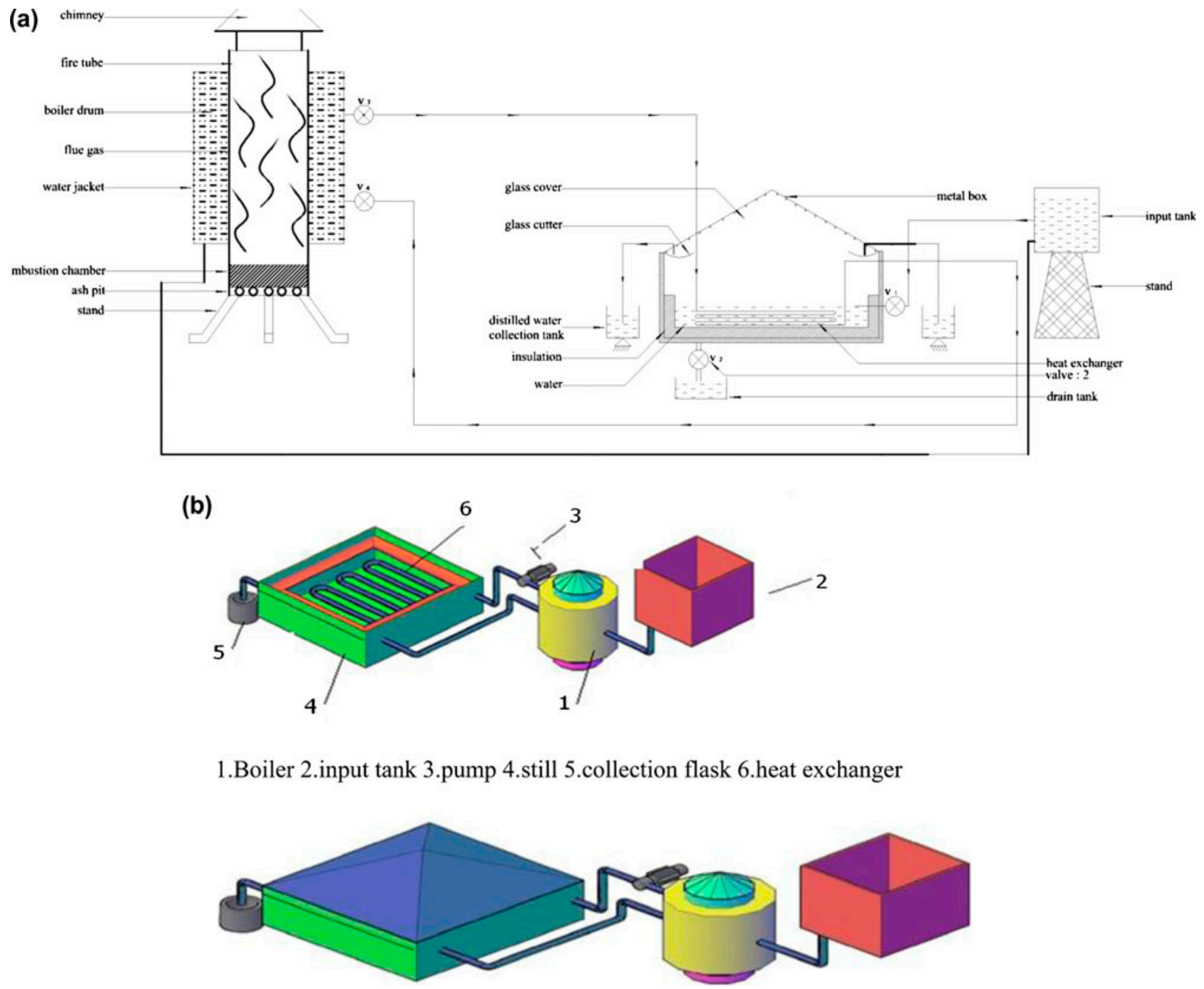

Fig. 1. (a) Schematic view of experimental set-up. (b) 3D view of experimental set up.

Table 1
Heat balance sheet

S. no.	Heat	Amount (%)
1	Heat generated in boiler	2,160 W 100
2	Heat supplied to water	1,829 W 84
3	Heat taken by exhaust gas	300 W 13
4	Heat taken by ash	31 W 1.4

Table 2
Error analysis table

S. no.	Instrumentation	(%) of error
1	Digital temperature indicator	1/30 = 0.03125
2	Anemometer (wind velocity)	0.1/0.1 = 1
3	KippZonanSolarimeter	1/268 = 0.00185
4	Beaker	5/60 = 0.0833

sponges were used to increase evaporation from the still. Biomass is fed in the boiler and burnt and the water is circulated through a heat exchanger into the still; when the water temperature in the still reaches 75℃, the biomass boiler is disconnected by closing the valves in the kettle. This style is called once flow mode. For continuous mode, biomass boiler is continuously burnt and the water is circulated continuously through the heat exchanger. For solar mode, the biomass heat source is disconnected and pyramid still has heat energy when it is exposed to solar radiation. In all the three modes, a conventional still is going parallel with the modified still. Fig. 2 shows the sensible materials used in this work.

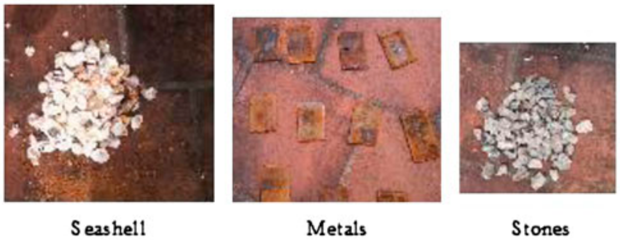

Fig. 2. Sensible materials.

4. Response surface methodology

RSM is a mathematical modeling tool used to predict the output relationship with respect to the multiinput parameters. The mathematical expression for the output responses can be arrived with respect to the input factors. The model predicts the value of the unknown output for any desirable input. The results can be compared with the experimental values. The degree of the closeness of predicted and experimental values will show the excellent fit of the model for the particular experiment. RSM is a type of optimization that applies an approximation technique to the objective and other functions of an optimization problem. The Box–Behnken experimental design of RSM has been chosen to find the relationship between the response functions and variables using the statistical software package Design Expert Software 8.0.7.1. Stat-Ease, NC MN USA). The Box–Behnken design can be considered as a highly fractionalized three-level factorial design where the treatment combinations are the midpoints of edges of factor levels and the center point. These designs are rotatable (or nearly rotatable) and require three levels of each factor under study. Box–Behnken designs can fit full quadratic response surface models and offer advantages over other designs. The advantages of the Box–Behnken design over other response surface designs are: (a) it needs fewer experiments than central composite design and similar ones used for Doehlert designs (b) in contrast to central composite and Doehlert designs, it has only three levels; (c) it is easier to arrange and interpret that other designs; (d) it can be expanded, contracted or even translated (e) it avoids combined factor extremes since midpoints of edges of factors are always used. The second-order design level demands comparatively lesser number of experimental data for precise prediction. Here, a total number of 29 experiments, including three center points are carried out for four parameters. The interaction between the variables and the analysis of variance (ANOVA) has been studied using RSM. RSM is useful for the modeling and analysis of programs in which a response of interest is influenced by several variables and the objective is to optimize this response.

5. Theoretical modeling

The basin plate temperature, water temperature, and glass temperature can be evaluated at every instant by solving the energy balance equation for the absorber plate, brackish water, and glass of the solar still, respectively. The energy received by the basin plate is equal to the sum of the energy gained by the basin plate, and energy losses by convective heat transfer between basin water and glass. This can be written as,

$$I(t)\,A_b\alpha_b = m_b\,C_{bp}\left(\frac{\mathrm{d}T_b}{\mathrm{d}t}\right) + Q_{c,b-w} + Q_{loss} \quad \text{for solar mode} \tag{1}$$

$$Q(t)\,A_b\alpha_b = m_b\,C_{bp}\left(\frac{\mathrm{d}T_b}{\mathrm{d}t}\right) + Q_{c,b-w} + Q_{loss} \quad \text{for biomass boiler mode.} \tag{2}$$

Energy received by the brackish water in the still (from sun and base) is equal to the summation of energy lost by convective heat transfer between water and glass, radiative heat transfer between water and glass, evaporative heat transfer between water and glass, and energy gained by the brackish water.

$$I(t)\,\alpha_w\,A_w + Q_{c,b-w} + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} + m_w C_p, w\left(\frac{\mathrm{d}T_w}{\mathrm{d}t}\right) \quad \text{for solar mode} \tag{3}$$

$$Q_b(t)\,\alpha_w\,A_w + Q_{c,b-w} + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} + Q_{he} + m_w C_p, w\left(\frac{\mathrm{d}T_w}{\mathrm{d}t}\right) \quad \text{for biomass mode} \tag{4}$$

Energy gained by the glass cover (from sun and convective, radiative and evaporative heat transfer from water to glass) is equal to the summation of energy lost by radiative and convective heat transfer between glass and sky, and energy gained by glass

$$I(t)\,\alpha_g A_g + Q_{c,w-g} + Q_{g,w-g} + Q_{e,w-g} = Q_{r,g-sky} + Q_{c,g-sky} + m_g C_{p,g}\left(\frac{\mathrm{d}Tg}{\mathrm{d}t}\right) Q_b(t)\,\alpha_g A_g + Q_{c,w-g} + Q_{g,w-g} + Q_{e,w-g} + Q_{he} = Q_{r,g-sky} + Q_{c,g-sky} + m_g C_{p,g}\left(\frac{\mathrm{d}Tg}{\mathrm{d}t}\right) \quad \text{for biomass mode} \tag{5}$$

Q_b, heat supplied by the biomass boiler; Q_{he}, $mf \times Cp \times (T_{out} - T_{in})$ Q_{he} heat supplied to the heat exchanger; mass flow rate (mf) = density of working fluid × area × length of heat exchanger/60 in kg/s.

At the first iteration, water temperature, glass temperature, and plate temperature are taken as ambient temperature and the increase *n* basin temperature ($\mathrm{d}T_g$) are brackish water temperature ($\mathrm{d}T_w$) and glass temperature ($\mathrm{d}T_g$) that are computed for every time interval ($\mathrm{d}t$) of 5 s by solving Eqs. (1)–(3), respectively. For evaluating the above said temperatures in the simulation, the experimentally measured values of solar radiation, wind velocity, and ambient temperature of the corresponding day and hour are used. This iteration is performed for total duration from 9 am to 5 pm of a day. The mass of water in the still is taken as 12.75 kg. Constant level of water is maintained in the stepped solar still by adding water equivalent to the condensate (m_c) in every half an hour. The area of basin (A_b) and the area of glass (A_g) are taken as 0.6 m^2. The area of brackish water (A_w) is taken as 0.68 m^2. Mass of the glass (m_g) is taken as 12.5 kg. The absorptivity of the still α_b is taken as 0.95. The absorptivity of the water, α_w, and absorptivity of the glass, αg, are taken as 0.05. The specific heat of the brackish water, $C_{p,w}$, is calculated from.

For the next time step, the parameter is redefined as,

$$T_w = Tw + \mathrm{d}T_w$$

$$T_g = T_g + \mathrm{d}T_g$$

$$T_b = T_b + \mathrm{d}T_b$$

The total condensation rate is given by

$$\frac{\mathrm{d}m_c}{\mathrm{d}t} = h_{e,w-g}(Tw - Tg)/h_{fg} \tag{6}$$

In Eqs. (1)–(3) I(t), the total solar flux on an inclined surface is obtained from

$$I(t) = \left(I_g - I_d\right)(\cos\theta_i - \cos\theta_h) + I_d\,(1 + \cos\beta)/2 \tag{7}$$

where θ_i and θ_h are the incidence angles on an inclined surface and horizontal surface, respectively, and are obtained from

The convective heat transfer between basin and water is taken as

$$Q_{c.b-w} = h_{c,b-w} A_b (T_b - T_w) \tag{8}$$

The convective heat transfer co-efficient between basin and water, $h_{c,b-w}$, is taken as 135 W m^{-2} K^{-1},

The heat loss from basin to ambient is calculated from

$$Q_{loss} = U_b A_b (T_b - T_a) \tag{9}$$

where U_b is taken as 14 W m^{-2} K^{-1},

The convective heat transfer between water and glass is given by

$$Q_{c,w-g} = h_{c,w-g} A_w (T_w - T_g) \tag{10}$$

Where the convective heat transfers co-efficient between water and glass is given by

$$h_{c,w-g} = 0.884\left\{(T_w - T_g) + \frac{[P_w - P_g][T_w + 273.15]}{[268.9 \times 10^3 - P_w]}\right\}^{1/3} \tag{11}$$

The radiative heat transfer between water and glass is determined by

$$Q_{r,w-g} = h_{r,w-g} A_w (T_w - T_g) \tag{12}$$

The radiative heat transfer co-efficient between water and glass is given by

$$h_{r,w-g} = \in \mathrm{eq}\sigma\left[(T_w + 273)^2 + \left(T_g + 273\right)^2\right] (T_w + T_g + 546) \tag{13}$$

$$\in equ = \left(\frac{1}{\in g} + \frac{1}{\in b} - 1\right)^{-1} \tag{14}$$

The evaporative heat transfer between water and glass is given by

$$Q_{e,w-g} = h_{e,w-g} A_w (T_w - T_g) \tag{15}$$

The evaporative heat transfer between water and glass is given by

$$h_{e,w-g} = (16.273 \times 10^{-3}) h_{e,w-g} (P_w - P_g)/(T_w - T_g) \tag{16}$$

$$Q_{r,g-sky} = h_{r,g-sky} A_g (T_g - T_{sky}) \tag{17}$$

The radiative heat transfer co-efficient between glass and sky is given by

$$h_{r,g-sky} = \in \sigma \left[\frac{(T_g + 273)^4 - (T_{sky} + 273)^4}{T_g - T_{sky}}\right] \tag{18}$$

The effective sky temperature is taken from

$$T_{sky} = T_a - 6 \tag{19}$$

The convective heat transfer between glass and sky, $Q_{c,g-sky}$ is given by

$$Q_{c,g-sky} = h_{c,g-sky} A_g \left(T_g - T_{sky}\right) \tag{20}$$

where $h_{c,g-sky}$ is taken from

$$h_{c,g-sky} = 2.8 + 3.0 \tag{21}$$

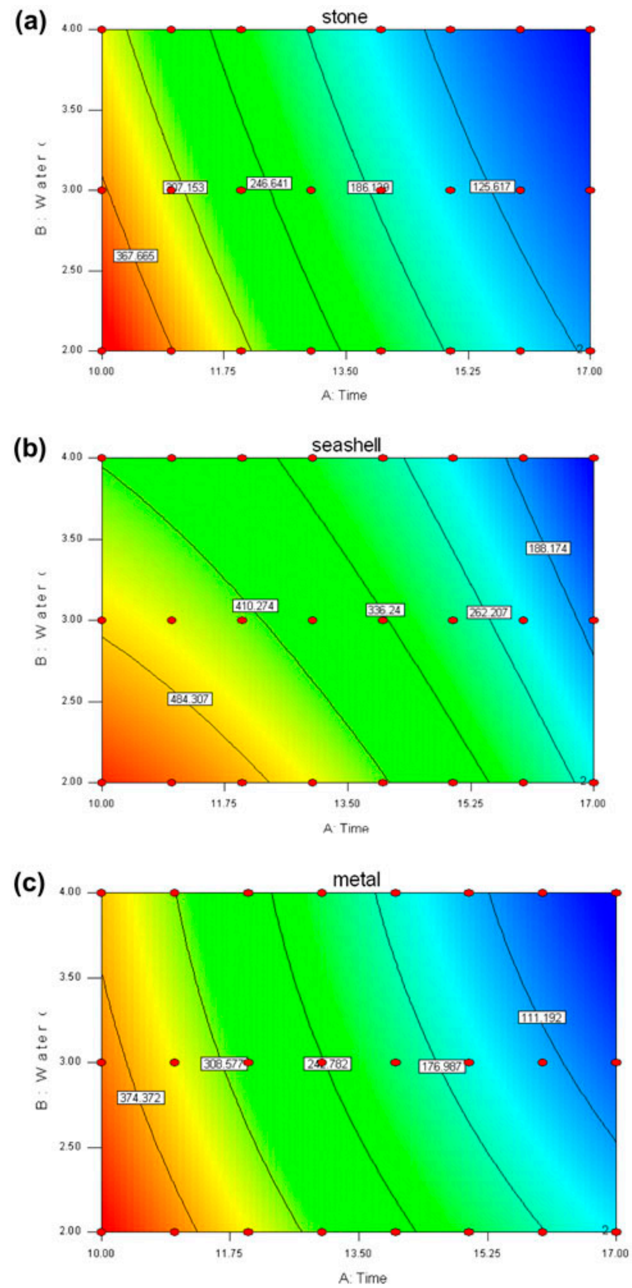

Fig. 3. Productivity of different sensible materials.

6. Results and discussion

6.1. Effect of solid sensible heat storage materials on productivity

The RSM in Fig. 3(a)–(c) shows the productivity of various solid sensible heat storing materials with time. For various materials tested in the still seashell increases the water temperature in stiller than metals and rocks. The productivity ranges of the materials are 3,625 ml/m^2 for the sea shell. Because of the high calcium content, it will absorb more heat than other materials. The productivity of other materials is 2,405 ml/m^2, for metals, and 2,173 ml/m^2 for stones. Sensible heat storage is one of the methods to store energy. There are two modalities of energy transfer; one is during charging period's heat supplied that will be stored as sensible heat. During discharging periods, the same energy is released as sensible heat. Materials such as stones, seashells, and metal pieces absorb more energy from the biomass source and releases slowly. From Figs. (3–6), it was clear that the reddish color suggests the maximum productivity zone, green color suggests the normal region, and blue color suggests the lowest productivity; the maximum productivity was achieved during the starting period for once flow process, because during initial periods, the water temperature reaches the maximum value and after that, the biomass heat source is cut away. The solar still now behaves like a condenser during the remaining periods from 11 to 17 h, the water temperature decreases gradually and it was indicated by the blue color. It is evident that as the water depth increased, the productivity will be decreased. This is due to the increase in the heat content of the water in the basin that results in low water temperature in the basin leading to lower evaporation rate.

6.2. Effect of latent heat storage materials on productivity

The productivity is maximum for wax 2,145 ml/m^2 and lower productivity is 2,005 ml/m^2 for water. Various latent heat storage materials are introduced inside the still in the form of billets and tested. Fig. 4(a)–(b) shows the output of various latent heat storage materials. Because of high heat storage capacity of wax material, the heat stored from wax is utilized to increase the water temperature in the still than water.

6.3. Effect of evaporative surfaces on productivity

As shown in Fig. 5(a)–(b), productivity is increased by about 1,685 ml/m^2 for sponges and 1,520 ml/m^2 for wick. Due to capillary action sponge, wick absorbs more water. Thus, exposure area is increased. This contributes to an increase in the evaporation rate in the still.

6.4. Comparison of efficiency

Fig. 6(a)–(c) shows the efficiency under various modes of procedure. The efficiency was maximum and constant for continuous mode of operation.

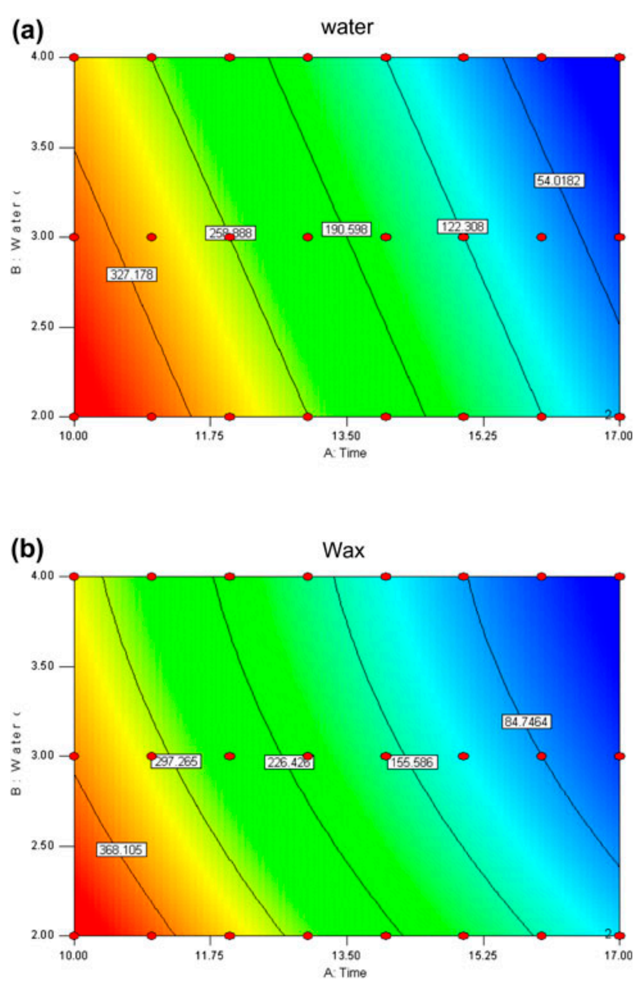

Fig. 4. Productivity of latent heat materials in the still.

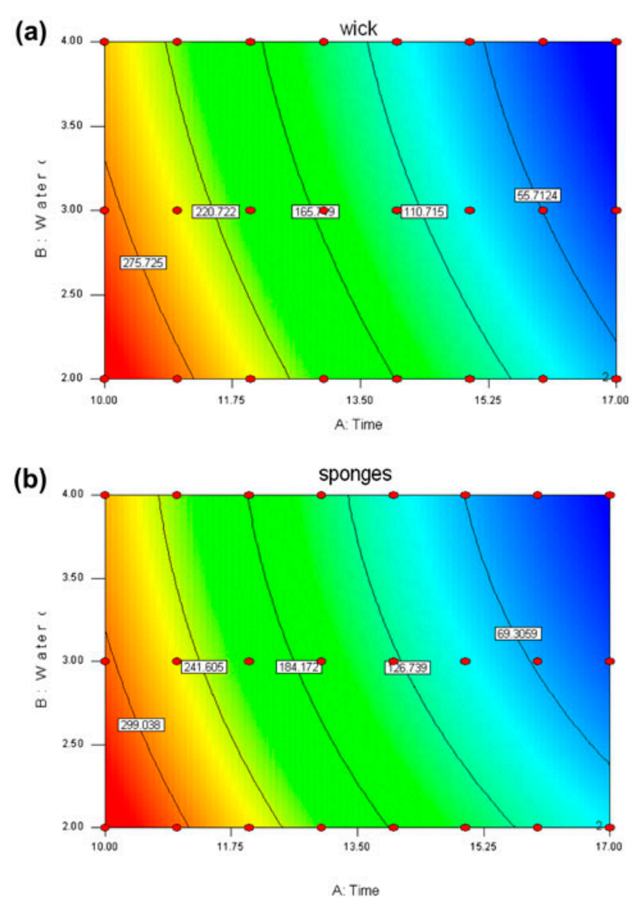

Fig. 5. Productivity of evaporation surfaces.

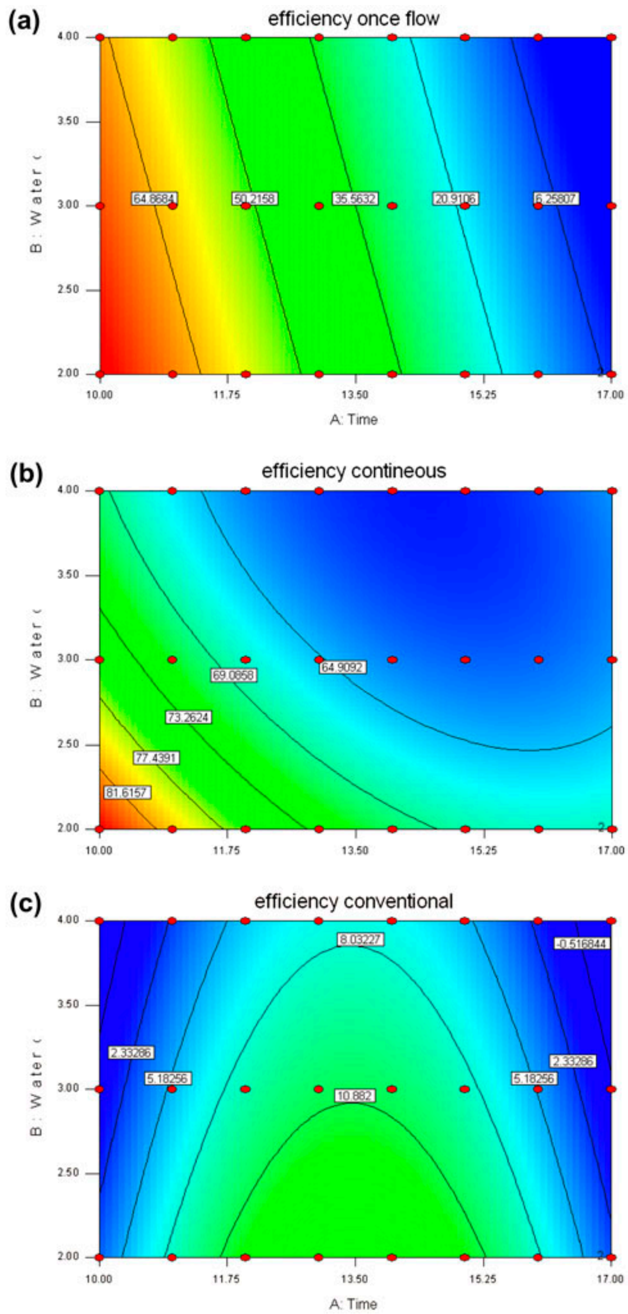

Fig. 6. Efficiency of different modes in the still.

Table 3
Comparision of efficiency under different modes

S. no	Mode of operation	Efficiency (%)
1	Once flow mode	66.5
2	Continuous flow mode	74.2
3	Solar mode	10.23

Efficiency for continuous mode was 60–70%. For once flow mode, the efficiency was high at the starting and decreases gradually from 78 to 20%. the efficiency for solar mode was very low, it was lowest at the setting out, and increases to 15%, and after that, it decreases to 2%. Thus, it was clear that the water temperature is the primary ingredient that bears on the efficiency. High efficiency was reached using biomass heat source than solar energy. Table 3 indicates the efficiencies in different modes of operations.

6.5. Comparison of heat transfer coefficient values under various modes of operations

Fig. 7(a)–(e) shows the comparison of heat transfer coefficient with time and water depths. It was noted that the convective heat transfer coefficient for once flow model was high during initial periods and decreases gradually as indicated by the green color in Fig. 7 The lowest value at the end is shown by the bluish color. The evaporative heat transfer values are minimized at the starting and maximum at the middle and closing. The convective heat transfer for solar mode is maximum at the middle from 11 am to 15 pm.

6.6. The impression of glass cooling on productivity

Fig. 8 shows the temperature of the glass and productivity during various hours. Before cooling, the glass cover produces 1,125 ml/m^2 and after cooling produces 1,482 ml/m^2.

Table 4
Economic analysis table

Types of analysis	Conventional still	PYRAMID still in once flow mode	Pyramid still in continuous mode
Overall cost	Rs 20,000 (320$)	Rs 22,000 (350$)	Rs 22,000 (350$)
Productivity (ml/m^2)	1,400	2,160	6,570
Cost of water produced per litre	Rs 15	Rs 15	Rs 15
Maintenance cost	Rs 2	Rs 4	Rs 6
Payback period (days)	952	667	219

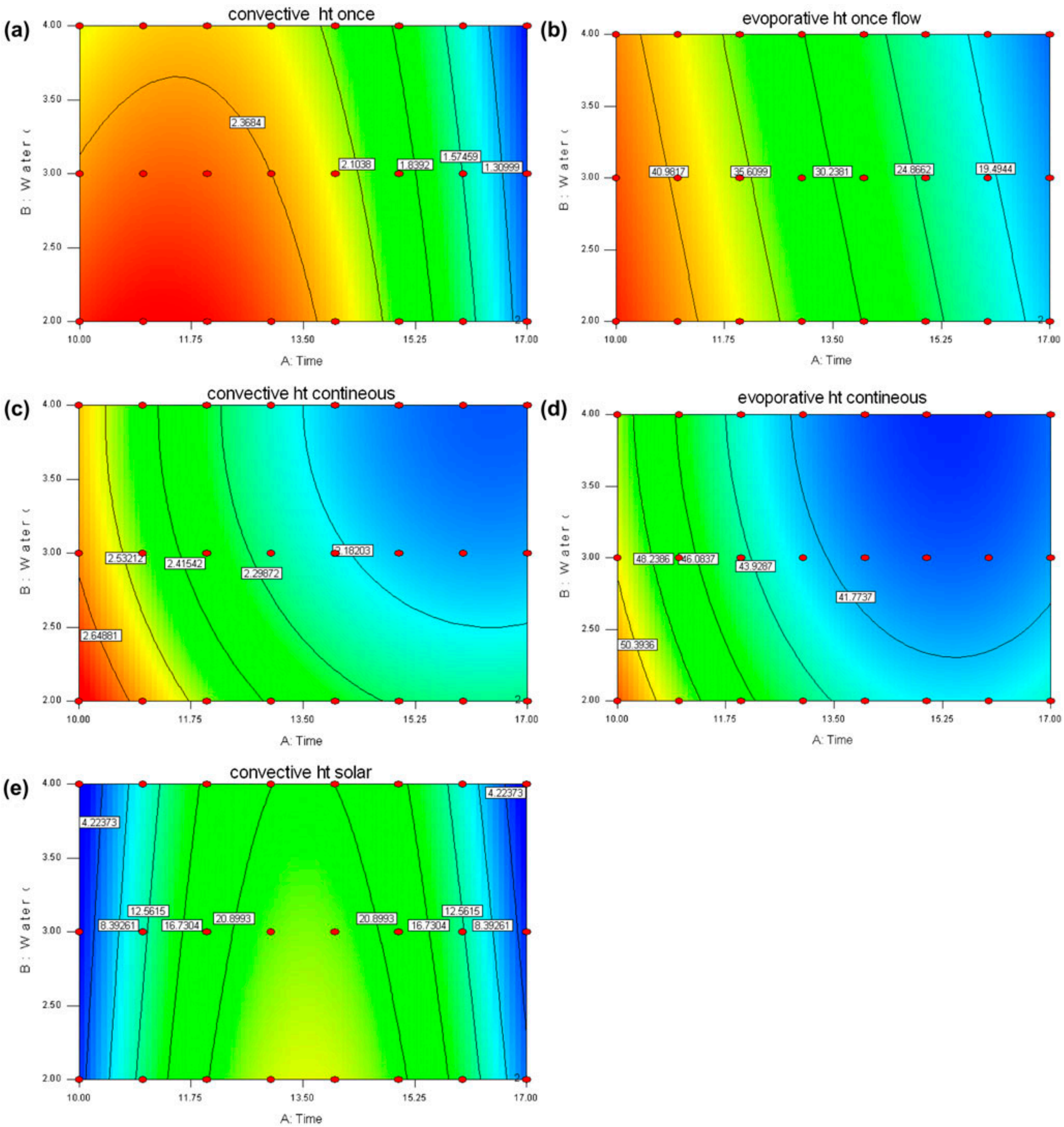

Fig. 7. Different types of heat transfer in the still under various modes.

Glass cooling increases productivity by 24% in the still. This growth in the still yield is due to the difference between the glass cover temperature and water temperature, which will increase the condensation process on the inside stratum of the screen. The glass cooling also reduced the convection and radiation energy losses to ambient. Cooling film acts as a continuous self-cleaning of the ice screen.

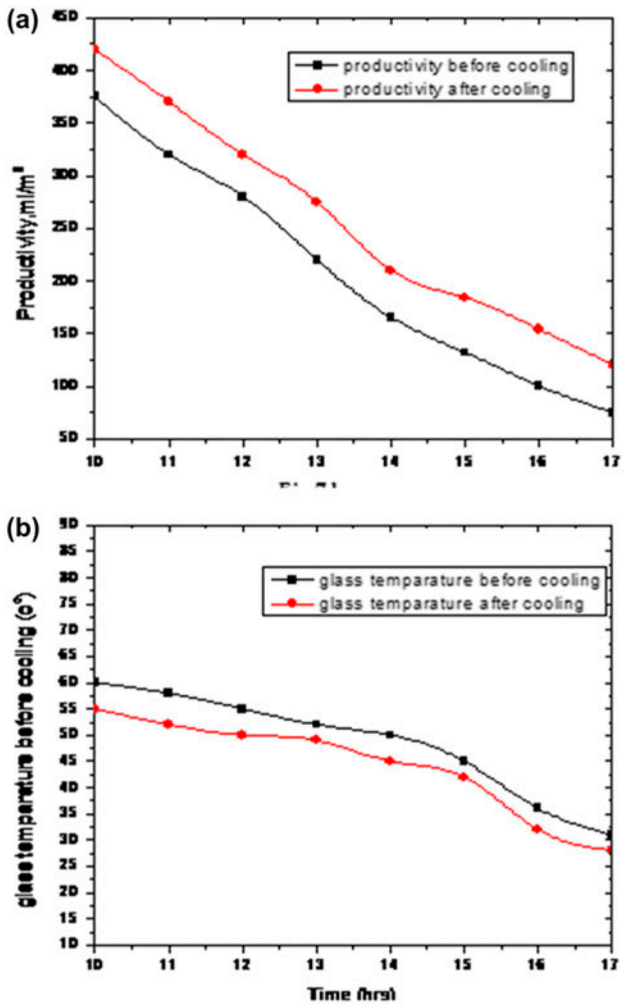

Fig. 8. Effect of glass cooling.

7. Optimization

Graphical optimization displays the area of feasible response values in the vector space. Areas that do not fit the optimization criteria are shaded. Any "window" that is NOT shaded satisfies the multiple constraints on the reactions. The region that satisfies the constraints will be yellow, while the area that does not encounter the criteria is gray in color.

The flags show predictions for all responses at that location in quad. Fig. 9 shows the overlay pot for different sensible heat storages, latent heat storage, and evaporative surfaces with 2 cm water depth for once flow mode. The primary objective of optimization is to

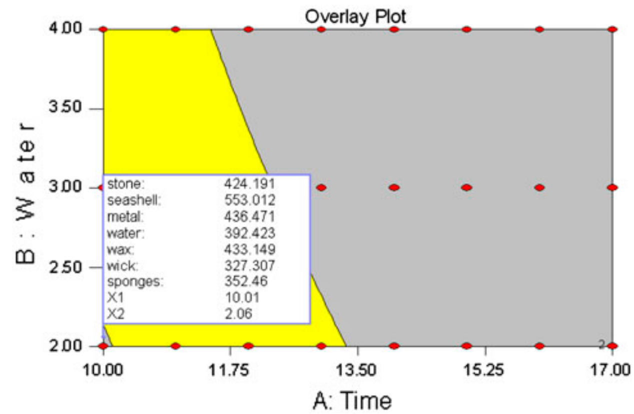

Fig. 9. Over lay pot.

maximize the production between the limits 162 and 460 ml/m^2.

8. Cost analysis

Table 4 indicates the cost analysis for the different stills. From this table, it was found that the payback period for pyramid still with continuous modes of operation is 219 d, whereas the payback periods for conventional and once flow methods are 952, 669 d.

9. Error analysis

Table 5 shows the actual experimental values obtained and the predicted values from a surface response method. From this table, the percent of error for all data is less than 10% limit. Hence, it is resolved that the experimental values are closely agreeing with the theoretical values.

10. Anova output

The following Table 6 shows the ANOVA for the experimental values. The resolution showed that the predictability of the model is 99% confidence and the predicated response fit well with those of experimentally obtained values. The p-value is less than 0.0001 for all the models, which indicates that the model is statistically important.

Table 5
Error analysis

S. no	Description	Actual value	Predicted value	Residual	(%) Error
1	2 cm, stone	300	273.6289	26.37114	8.7
2	2 cm, stone	270	265.7128	4.287238	1.5
3	2 cm, stone	95	87.01053	7.989468	8.3
4	2 cm, stone	125	114.0554	10.94459	8
5	2 cm, stone	340	316.6061	23.39387	6.7
6	2 cm, stone	370	368.8535	1.146468	0.3
7	2 cm, stone	320	314.6693	5.330738	1.6
8	2 cm, stone	120	113.5333	6.466731	5.4
9	2 cm, stone	154	149.3261	4.673851	2.9
10	Seashell	385	383.0212	1.978842	0.5
11	Seashell	185	173.9717	11.02834	5.9
12	Seashell	460	451.5183	8.481663	1.8
13	Seashell	245	234.9745	10.02552	4.08
14	Seashell	320	307.5164	12.4836	3.8
15	Seashell	250	244.6872	5.312796	2.1
16	Seashell	580	558.3407	21.65929	3.7
17	Seashell	250	244.6872	5.312796	2.1
18	2 cm, metal	320	290.8374	29.16258	9
19	2 cm, metal	375	363.1352	11.8648	3.2
20	2 cm, metal	265	258.2227	6.777251	2.6
21	2 cm, metal	400	392.5694	7.430556	1.8
22	2 cm, metal	145	144.6919	0.308057	0.2
23	2 cm, metal	255	254.3681	0.631912	0.24
24	2 cm, metal	165	164.6144	0.385635	0.23
25	2 cm, water	285	258.1457	26.85425	9.4
26	2 cm, water	260	258.7024	1.297619	0.49
27	2 cm, water	310	304.1053	5.894715	1.9
28	2 cm, water	365	350.0648	14.93518	4.08
29	2 cm, water	310	304.6619	5.338081	1.7
30	2 cm, water	125	123.0503	1.949697	1.5
31	2 cm, water	85	77.6474	7.352601	8.6
32	2 cm, wax	275	264.7282	10.27178	3.7
33	2 cm, wax	265	258.7491	6.250931	2.3
34	2 cm, wax	320	316.2204	3.779621	1.1
35	2 cm, wax	340	332.0757	7.92434	2.3
36	2 cm, wax	380	362.2917	17.70833	4.6
37	2 cm, wax	50	48.33551	1.664494	3.32
38	2 cm, wick	200	199.3019	0.698121	0.34
39	2 cm, wick	300	286.1806	13.81944	4.6
40	2 cm, sponge	285	278.8685	6.131517	2.1
41	2 cm, sponge	185	183.1259	1.874069	1
42	2 cm, sponge	100	96.55357	3.446429	3.4
43	2 cm, sponge	260	256.2941	3.705851	1.42
44	2 cm, sponge	320	306.9599	13.04012	4
45	2 cm, sponge	275	261.3402	13.65978	4.9
46	2 cm solar	700	690.1735	9.82646	1.4
47	2 cm solar	320	309.4932	10.50675	3.2
48	2 cm solar	375	366.1237	8.876289	2.3
49	2 cm conventional	620	610.2083	9.791667	1.5
50	2 cm conventional	220	215.2844	4.71564	2.1

Table 6
Annova output

Efficiency once flow	Model	13430.76	5	2,686.15	494.35	<0.0001	Significant
Productivity, sand	Model	1.01E + 05	3	33,542.32	674.19	<0.0001	Significant
Productivity, glass balls	Model	1.01E + 05	3	33,542.32	674.19	<0.0001	Significant
Productivity, cement cubes	Model	1.31E + 05	5	26,245.31	527.79	<0.0001	Significant
Productivity, wick	Model	1.40E + 05	2	69,970.81	815.62	<0.0001	Significant
Productivity, cotton cloth	Model	95146.17	5	19,029.23	383.82	<0.0001	Significant
Productivity, gauss cloth	Model	49273.04	5	9,854.61	303.76	<0.0001	Significant
Productivity, conventional	Model	1.23E + 05	5	24,522.61	243.34	<0.0001	Significant
Efficiency continuous flow	Model	2230.53	5	446.11	156.65	<0.0001	Significant
Efficiency conventional	Model	532.83	5	106.57	6.03	0.0017	Significant

11. Conclusion

An experimental study has been carried on to predict the productivity of a single slope, solar still using different solid, liquid sensible heat storage mediums and various evaporative materials.

Established on the experimental results, the following determinations are reached

- An increase in the still productivity was observed with anincrease in the solar intensity for conventional mode and solar mode.
- The role of solid, sensible heat storage materials in the still improves productivity by 84% than conventional still.
- The latent heat storage materials in the form of billets increase the productivity by 69% than conventional blade.
- The used of evaporative surfaces increases the area of exposure and still productivity by 61% than conventional still.
- Lower water depth in the stool increases the productivity in the blade.
- Manual glass cover cooling in the still increases the productivity by 24% more than without glass cooling.
- Biomass heat source with pyramid still produces more output than the conventional still. This is due to increase in water temperature and area of condensing glass in pyramid still.
- Biomass is cheap and eco-friendly.
- Higher efficiency is achieved in continuous fashion.
- Experimental values are closely agreeing with the theoretical values.
- The error analysis report shows that the experimental values closely match with the predicted values of RSM.
- Optimal levels of several sensitivity, latent heat, and evaporation materials are arrived using the RSM software.
- Economic analysis shows that pyramid still with continuous flow mode has low payback period than conventional still.

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