Design and Development of a Beach Sand Solar Collector

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Nomenclature

I	Rate of total radiation incident on the absorber surface
A_C	Collector area (m^2)
Q_U	Rate of useful energy collected by the air (W)
q_u	Energy per unit area (W/m^2)
Q_{COND}	Rate of conduction losses from the absorber (W)
Q_R	Rate of conduction losses from the absorber (W)
Q_{CONV}	Rate of convective losses from the absorber (W)
Q_ρ	Rate of reflection losses from the absorber (W)
Q_L	Overall heat transfer coefficient of the absorber (W)
T_C	Temperature of the collector's absorber (K)
T_A	Ambient air temperature (K)
τ	Transmittance of glass cover
Nu	Nusselt number
P	Reflection coefficient of absorber
Gr	Grashoff number
c_{pa}	Specific heat capacity of air
η	Thermal efficiency
m	Mass of air per unit time
U	Overall heat transfer coefficient
K	Thermal conductivity of air

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1 Introduction

With the advent of the twentieth century, renewable energy sources have completely transformed the energy market. These energy sources are in-exhaustible and environment friendly compared to conventional energy sources. Renewable energy sources include solar, wind, hydel, biomass, and tidal energy. Almost 26.2% of entire electricity is generated from renewable energy sources, out of which 2.4% are from solar photovoltaic and 0.4% are from concentrated solar power [1]**.** Solar thermal energy systems work by capturing the heat generated from the sun, and further, this heat is used for heating and/or production of electricity. Solar collectors fall under the category of solar thermal energy systems. Solar collectors can be classified into two categories—concentrating and non-concentrating collectors. Concentrating solar collectors use reflective surfaces such as mirrors or lenses to concentrate sunlight into a particular area, where it is absorbed or further converted to heat. In a non-concentrating solar collector, the area which is collecting the energy from the sun is the same as the area which is absorbing the energy from the sun. A flat plate collector is a non-concentrating type of solar collector. It basically comprises three main components—a transparent cover, an absorber plate, and a heat transport system. The absorber plate is usually a sheet of copper or aluminum painted black to absorb the maximum amount of solar radiation which is used as a source to either heat air or water. The transparent cover is made out of either glass or plastic. Dust deposition density, angle of tilt as well as surface orientation in regard to the dominant wind direction influence glass normal transmittance [9]. Sand can be used as a medium for the transfer of heat from the absorber plate to the fluid inside the pipes. The heat transfer in the sand particles mostly takes place by conduction. The major thermal properties of sand are its specific heat capacity (c) and thermal conductivity (k). The specific heat determines the heat energy needed to change the temperature of the sand which further has an effect on the time required to reach the steady-state conditions. The thermal conductivity affects the temperature field and heat flow inside the sand at equilibrium. The major challenges that need to be taken into account while considering sand as a heat transfer media are the mass loss due to calcination and agglomeration phenomena [4].

1.1 Flat Plate Collector vs Evacuated Tube Collector

There are several advantages offered by flat plate collectors. They are comparatively easy to manufacture, and due to their simple design, the cost is also lower. They also require less maintenance due to no moving parts involved. Additionally, these collectors have the capability of capturing both beam and diffuse radiation. They offer more sunlight absorbing area. Moreover, the glass cover employed on flat plate solar collectors is tempered glass which is durable and weather resistant.

The evacuated tube collectors, on the other hand, have a complex design. The requirement for maintenance is high for these types of collectors. These collectors offer less amount of sunlight absorbing area. Overall, evacuated tube collectors are comparatively more expensive than flat plate collectors, but, however, these collectors have the capability of attaining higher temperatures and they can be installed easily on roofs.

2 Literature Review

Sun et al. 2016 [9] studied and reviewed the effects of nanostructured silicon on flexible photovoltaics, thermoelectric generators, and piezoelectric devices. They found that the optical and electrical properties of nanostructured silicon are heavily dependent on the surface effects. Surface modification in nanostructured silicon leads to enhanced supra-indirect gap absorption, reduced thermal conductivity, and induced piezoelectricity, which strengthens the ability of electricity generation for various generators. Dayan et al. 2017 mentioned that compared to a traditional parallel tube collector, a serpentine tube collector has the ability to function better in low-flow systems due to the prior start of turbulent flow. Additionally, it has also been mentioned that the difference in terms of performance between a conventional header-riser collector and a serpentine collector can be attributed to the internal heat transfer coefficient. Bhowmik et. al. 2017 [5] have used a solar reflector on the solar collector to improve its efficiency. Experiments showed that with the use of solar reflectors, the efficiency of the solar collector has increased to 10%. Diago et. al. 2015 [3] have thermally analyzed the suitability of desert sand samples as a thermal storage media. It was shown that there were relative mass losses in the sand samples during the calcination process due to the high calcite content in the sand. Further, it was seen that most of the sand particles tend to form agglomerates at higher temperatures rendering their ability to act as a heat transfer media. There were color changes from lighter tones to whiter tones which were also being observed. It suggested that it had an impact on the radiative properties of samples like solar absorptivity values. Saraf et al. 1988 [6] mentioned that the optimum tilt angle should be kept as low as 15 ° during the month of June and as high as 63 ° during the month of December to maintain the effectiveness of the solar thermal system. Gomariz et al. 2019 [8] mentioned that most of the flat plate solar collectors are used for applications such as drying of crops and space heating. Gomariz et al. 2019 [8] mentioned that serpentine type collectors have lower manufacturing costs, perform better at low flow rates and also, simplify the hydraulic connection of many collectors.

3 Theoretical Formulations

The energy balance on the absorber is obtained by equating the total heat gained to the total heat lost by the heat absorber of the solar collector. Therefore,

$$I\,A_c = Q_U + Q_{\mathrm{COND}} + Q_{\mathrm{CONV}} + Q_R + Q_\rho \tag{1}$$

where

I = rate of total radiation incident on the absorber's surface (W/m^2).
A_c = collector area (m^2).
Q_U = rate of useful energy collected by the air (W).
Q_{COND} = rate of heat losses from the absorber (W).
Q_{CONV} = rate of convective losses from the absorber (W).
Q_{R} = rate of longwave re-radiation from the absorber (W).
Q_{P} = rate of reflection losses from the absorber (W)

$$Q_L = Q_{\mathrm{COND}} + Q_{\mathrm{CONV}} + Q_R \tag{2}$$

If τ is the transmittance of the top glazing and I_T is the total solar radiation incident on the top surface, therefore,

$$I\,A_c = \tau I_T A_c \tag{3}$$

The reflected energy from the absorber is given by the expression

$$Q_\rho = \rho\tau I_T A_c \tag{4}$$

where

ρ = the reflection coefficient of the absorber.
Substitution of Eqs. (2), (3), and (4) in Eq. (1) yields:

$$\tau I_T A_c = Q_U + Q_L + \rho\tau I_T A_c$$

$$Q_R Q_U = \tau I_T A_c(1 - \rho) - Q_L$$

For an absorber $(1-\rho) = \alpha$, where α is solar absorptivity and hence,

$$Q_U = (\alpha\tau)\,I_T A_c - Q_L \tag{5}$$

Q_L is composed of different convection and radiation parts.
It is presented in the following form

$$Q_L = U_L A_C(T_C - T_A) \tag{6}$$

T_A = ambient air temperature (K).

From Eqs. (5) and (6), the useful energy gained by the collector is expressed as:

$$Q_U = (\alpha\tau)\, I_T A_C - U_L A_C (T_c - T_a) \tag{7}$$

Therefore, the energy per unit area

$$q_u = (\alpha\tau) I_T - U_L (T_C - T_A) \tag{8}$$

where

U_L = overall heat transfer coefficient of the absorber.

T_C = Temperature of the collector's absorber (K).

If Q_g is the heated air leaving the collector is at collector temperature, the heat gained by the air is:

$$Q_g = m_a C_{pa} (T_c - T_a) \tag{9}$$

where

m_a = mass of air per unit time (kg/sec).

C_{pa} = specific heat capacity of air (kJ/kg-K).

The collector heat removal factor $\mathrm{F_R}$ can be given by the equation:

$$F_R = m_a C_{pa} (T_c - T_a) / A_C [(\alpha\tau)\, I_T - U_L A_C (T_C - T_A)] \tag{10}$$

$$Q_R Q_g = A_C F_R [(\alpha\tau)\, I_T - U_{L.} A_C (T_C - T_A)] \tag{11}$$

The thermal efficiency of the collector is given by the collector

$$\eta = Q_g / A_c I_t \tag{12}$$

4 Design and Methodology

The main motive of the project is the design and construction of a beach sand solar collector. The collector as mentioned beforehand is of two main types: Flat plate collector and Evacuated tube collector. The collector that will be employed in the project will be a serpentine flat plate collector. Serpentine flat plate collector consists of single continuous tubes running from the inlet to the outlet of the collector. The collector will be made out of concrete because it is durable, maintenance-free, and also exhibits good thermal storage qualities because of its high specific heat capacity and density. The inner part of the collector will be painted matt black in order to absorb the maximum amount of sunlight. The collector will be inclined at an angle equivalent to the latitude of the location to receive the maximum amount of radiation from the sun. Being a serpentine flat plate collector, single continuous tubes would run from the inlet to the outlet of the collector. Copper tubes would be the best choice in this case because of its high temperature resistance, high mechanical strength, and also, it can be easily bent into tubes. In the proposed project, beach sand would be used for the generation of heat. A single-stage centrifugal air blower of power 200 Watts will be used for blowing the heated air from the sand into the inlet of the collector. The heated air from the inlet would move through the tubes into the outlet from where it can be stored or collected for different household or commercial applications. This nonlinear movement of air through the copper tubes has another advantage in the form that air will take more time to travel and thereby help in increasing and maintaining the temperature of the heated air. The temperature at the entry and exit of the solar collector will be measured using a digital LCD thermometer.

4.1 Components of a Beach Sand Solar Collector

A. **Solar Collector**: The heat absorber of the solar collector can be constructed using a 1 mm thick aluminum plate, painted black. The collector will be insulated with concrete of thickness 2.5 cm and having a thermal conductivity of 0.6 W/mK on all sides. Copper tubes would run in a single serpentine manner from the inlet to the outlet of the collector.

B. **Cover Plate**: The cover plate is made of transparent glass which transmits radiation to the absorber. It also prevents radiative and convective heat losses from the surface. Glass and plastic are the two most common materials for making cover plates. Plexiglass having a length of 170 cm, breadth of 110 cm, and a thickness of 0.3 cm can be employed. Plexiglass is more durable, fracture-resistant, and more resistant to erosion compared to normal glass. In order to attain maximum efficiency, absorption, and reflection should be less while transmission should be as high as possible. Plexiglass has an overall light transmission of 92%.

C. **Absorber Plate:** The absorber plates are flat, corrugated, or groove plates to which the tubes are attached. It is either made of copper, steel, or aluminum which have high thermal conductivity. The surface of the absorber plate is covered with black material in order to increase its absorptance. In order to maximize the solar absorptance, a selective coating can be applied on the absorber plate. Aluminum can prove to be much better compared to copper or steel in terms of heat dissipation capacity.

D. **Insulation:** Insulation is used to prevent heat loss from the system. Different types of insulating materials exist in the form of foam rubber, polystyrene, mineral wool, etc. Insulation can be applied over the tubes running inside the collector for any undesirable heat loss as well as over the outer portion.

E. **Air Blower:** The air blower that will be used will be a single-stage centrifugal air blower having a rated power of 200 W and a maximum speed of 2800 rpm.

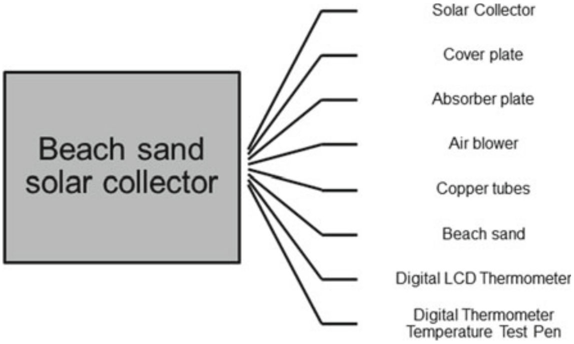

Fig. 1 Beach sand solar collector theoretical model

The main aim of an air blower will be to force the heated air from the sand up through the collector.

F. **Copper Tubes:** The copper tubes are mounted directly to the absorber plates by soldering, brazing, or bonding. The copper tubes are used to carry the heat transfer fluid such as water or air.

G. **Beach sand:** Sand will be the source of heat generation. The concept of generation of heat from beach sand is quite a new concept. The general properties of beach sand are: However, the heat capacity of the sand will vary depending upon the relative proportions of the constituent materials making up the sand grain. Dry quartz sand which makes up the desert has a specific heat of about 0.19 cal/gram °C. Beach sand for instance is not entirely composed of quartz. It also contains considerable amounts of calcium carbonate, feldspar, gypsum, etc. But, however, wet beach sand has a high heat capacity since the specific heat of water is higher compared to any other substances which are around 4,186 Joules/kg-°C.

H. **Digital LCD thermometer**: These will be used for measuring the temperature at the inlet and outlet of the collector. The specifications are listed below: (Figs. 1 and 2; Tables 1 and 2).

5 Results and Discussion

A flat plate solar collector consists of a glazing surface, and an absorber plate painted black to maximize the heat input and an insulated cover (Figs. 3 and 4 ; Tables 3 and 4).

The glazing surface is plexiglass which has a high transmissivity value of about 92%.

If the angle of incidence is 60 °, then the absorptance of the black plate will be 0.85.

The solar irradiance I_{in} incident on the cover glass is given by

$$I_{\text{in}} = I_b \cos(\theta) + I_d \tag{13}$$

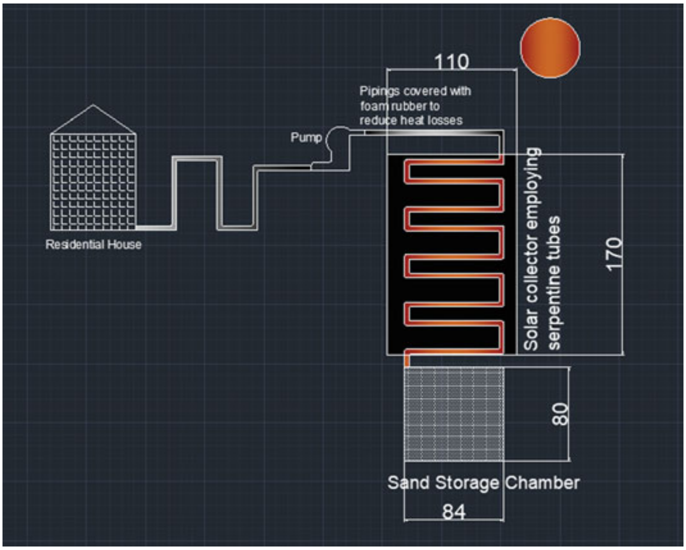

Fig. 2 A 2-D model of the proposed beach sand solar collector

Table 1 Properties of beach sand

Thermal conductivity: 0.6 W/m/C°
Electrical conductivity: 41.37 ± 1.25μS/cm
Specific gravity: 2.6–2.8
Fineness modulus: 2.64
Dry bulk density: 1468 kg/cm
pH: 8.6
Moisture content: (0.5–2) %
Dry density: (100–110) pcf
Optimum moisture content: (8–10)%
Liquid limit: 37%
Plastic limit: 16%

where

I_b= beam solar irradiance

θ = angle of incidence.

I_d = diffuse irradiance.

If there is only one glazing surface, then the solar irradiance on the black plate will be given by

$$(\theta)\ =\ \cos\theta \cdot \mathrm{I}_{\mathrm{b}+}\tau \cdot \mathrm{I}_{\mathrm{d}}$$

where τ_m is the mean value of $\tau(\theta)$.

Table 2 Specification of the digital LCD thermometer

Operating temperature: 40–70 °C
Measuring humidity range: 10–99% RH
Humidity accuracy: 5%
Humidity display resolution: 1% RH
Temperature accuracy: 1°C
Operating voltage: 1.5 V, or LR44 batteries (included)
Dimensions: 48 × 28.5 × 15.2 mm
LCD dimension: 40 × 17 mm
Installation dimensions: 46 × 27 × 13.5 mm
Color: White

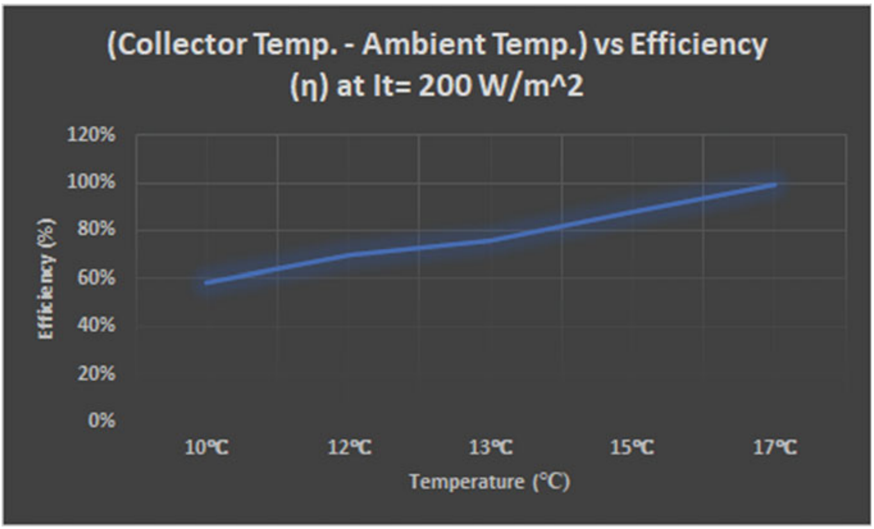

Fig. 3 Efficiency at different values of collector temperature (in °C) at It = 200 W/m^2

The glazing cover, i.e., the plexiglass acts as a black body for longwave radiation. We have the emittance of glass cover (plexiglass) = 0.85 and the emittance of the absorber plate for longwave radiation depend upon whether the surface is selective or non-selective. So, we have an emittance of absorber plate = 0.92 for a non-selective surface and 0.10 for the selective surface.

Let

$$T_a = \text{ Ambient temperature}$$

$$T_b = \text{ Black plate (absorber) temperature}$$

$$T_c = \text{ Glass cover temperature}$$

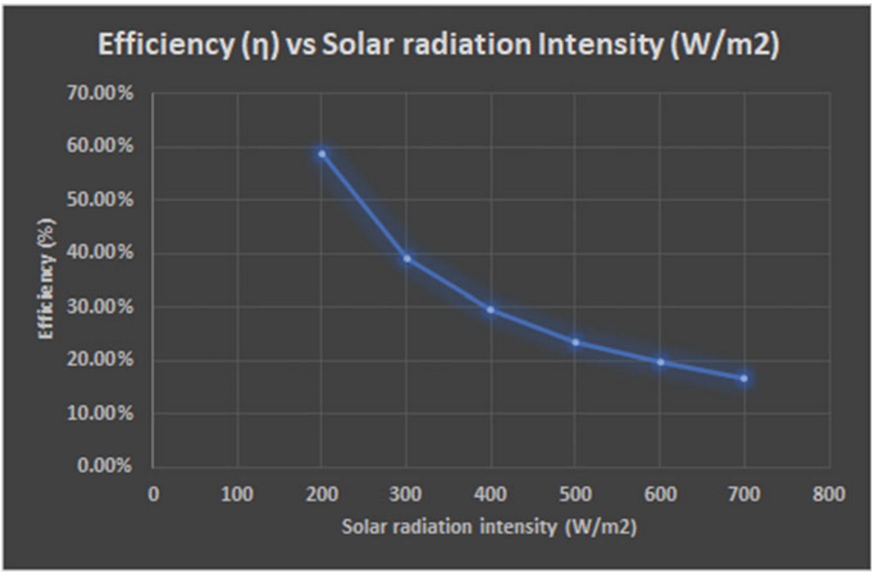

Fig. 4 Efficiency vs Solar Radiation Intensity at Normal Temperature

Table 3 The efficiency of solar radiation intensity

Solar radiation Intensity (W/m^2)	200	300	400	500	600	700
Efficiency (η)	58.7%	39.17%	29.38%	23.5%	19.6%	16.79%

Table 4 Efficiency at different values of collector temperature (in °C) at $I_t = 200$ W/m^2

Collector temperature (T_C)—ambient temperature (T_a)	10°C	12°C	13°C	15°C	17°C
Efficiency at $I_t = 200$ W/m^2	58%	70%	76%	88%	99%

Heat is lost from the absorber plate to the glass cover by convection and radiation. For free convection, the Nusselt number (Nu) is given as.

$\mathrm{Nu} = 0.152Gr^{0.281}$ for horizontal plate.

$\mathrm{Nu} = 0.093Gr^{0.310}$ for plates tilted at an angle of 45°.

Grashoff number is given by $= g \cdot \beta \cdot (Tb - Tc) \cdot L^3/U^2$.

where $g = 9.81$ m/s^2 (acceleration due to gravity).

Coefficient of thermal expansion, $\beta = 1/T = 0.0034/K$ (at normal standard conditions)

$$T_b - T_c = (80 - 35)°\mathrm{C} = 45°\mathrm{C} = 318\,K$$
$$L = 0.075m \text{ (spacing between plates)}$$

Kinematic Viscosity, $\nu = 1.562 \times 10^{(-5)}$ m^2/sec (at 25 °C which is the standard temperature)

$$\begin{aligned} Gr &= (9.81 \times 0.0034 \times 318 \times 0.075^3)/(1.562 \times 10^{-5})^2 \\ &= 18.3 \times 10^6 \end{aligned}$$

Assuming a tilt angle of 45°, then

$$\begin{aligned} Nu &= 0.093 Gr^{0.310} \\ &= 0.093 \times (18.3 \times 10^6)^{0.310} \\ &= 16.58 \end{aligned}$$

$$\begin{aligned} &\text{Nu} = h \times L/k \\ &h = \text{Nu} \times k/L \\ &k = 0.02624\, W/mK \text{ is the thermal} \\ &\text{conductivity of air at } 25\,{}^{\circ}C \\ &h = (16.58 \times 0.02624)/0.075 = 5.8 W/m^2K \end{aligned}$$

If $I_t = 200 W/m^2$ (transmitted solar irradiance)

$$\begin{aligned} &1/U_l = 1/h \times A_c + k \times A_c/L + 1/h \times A_c \\ &1/U_l = 0.828 \\ &U_l(\text{overall heat transfer coefficient}) = 1.21 W/m^2K \\ &Q_l = U_l \times A_l \times (T_c - T_a) = 1.21 \times 1.83 \times (35 - 25) = 22.14\, W \end{aligned}$$

If $I_t = 200$ W/m^2.
Rate of useful energy collected by air

$$\begin{aligned} Q_u &= (\alpha \times \tau) \times I_t \times A_c - Q_l \\ &= (0.92 \times 0.85) \times 200 \times 1.83 - 22.14 \\ &= 264.072\, W \end{aligned}$$

The collector heat removal factor, F_r is given by

$$\begin{aligned} &F_r = \left(m_a \times C_{pa} \times (T_c - T_a)\right)/A_c \times (\alpha \times \tau \times I_t - U_l \times (T_c - T_a)) \\ &F_r = (0.0214 \times 1005 \times (35 - 25)/1.85 \times (0.85 \times 0.92 \times 200 - 1.21 \times (35 - 25)) \\ &F_r = 0.815 \end{aligned}$$

Now the heated air leaving the collector is denoted by Q_g, so heat gained by air

$$
\begin{aligned}
Q_g &= A_c \times F_r \times ((\alpha \times \tau) \times I_t - U_l \times A_c \times (T_c - T_a)) \\
Q_g &= 1.83 \times 0.815((0.85 \times 0.92) \times 200 - 1.21 \times 1.83 \times (35 - 25)) \\
Q_g &= 215\, W
\end{aligned}
$$

The efficiency of the collector

$$
\begin{aligned}
\eta &= Q_g / A_c \times I_t \\
&= 215/1.83 \times 200 \\
&= 58.7\%
\end{aligned}
$$

When performing thermal analysis, the factors which affect the solar collector performance include the operating temperature, the solar radiation intensity, and the severity of the ambient outdoor temperature. From Fig. 3, it can be observed that when the difference between the collector and ambient temperature is high, the efficiency of the solar collector increases. The effectiveness of a solar collector depends upon whether they can produce a temperature which is sufficient to meet the needs of any attached heating job at any moment. It can be further observed that with the increase in solar radiation intensity, the efficiency of the solar collector falls. When designing solar heating systems, it is always paramount to maintain a balance between temperature and energy output. If a proper balance is not maintained, then it can ultimately have negative influence over the overall performance level.

6 Conclusion

After completion of the experiment, it can be concluded that with the increase in temperature, the collector efficiency also increases. Moreover, the angle at which the collector is inclined also plays a critical role. In order to attain maximum amount of solar radiation, the collector should be inclined at an angle equal to the latitude of the place. With a solar radiation intensity of 200 W/m2, an overall solar collector efficiency of 58.7% can be achieved. Wet beach sand has a high heat retention capacity, so, it has a potential to generate a good amount of heat which can be used for residential/commercial purposes in a sustainable manner.

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