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Solar Geyser Using Spot Fresnel Lens

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Abstract

Fresnel lens based concentrating devices are not only gaining scope in the Photovoltaic industry, but also in solar thermal based industries. Fresnel lens is an optic device which concentrates the incoming light onto a spot or onto a line. This means that the temperature at that point will be significantly high. Utilizing this temperature for solar thermal applications will definitely be helpful for solar thermal power plants as the water can directly be converted into steam. This paper discusses about the various applications of Fresnel lens and how advantageous it can be to be utilized in solar thermal applications. Also better improvement on the collector design is projected that shows improvement in the overall performance of the system.

Keywords: Fresnel lens; Concentrated solar power; Photovoltaics; Thermal

Introduction

Photo-voltaic (PV) concentrator systems and thermal concentrator systems are known to be gaining much scope over the past years. The PV concentrating system is an upcoming field where concentrating systems are used to direct the radiation onto a photovoltaic absorber that is specially manufactured for concentrating purpose. Parabolic trough collectors are another technology of advanced solar thermal heating systems. This technology uses significant amount of collector area [1]. Fresnel lens and Fresnel reflector technology reduces this size to only the aperture area and focal length of the lens. There are a lot of advantages of using Fresnel lens both in thermal and photovoltaic systems [2].

Technologies based on Fresnel Reflectors and Fresnel Lens

Fresnel lens PV concentrator systems

Fresnel lens is a component which focuses light onto a single point or a line. There are basically two types of Fresnel lenses. One is the Spot Fresnel lens and the other is the Linear Fresnel lens. The spot Fresnel lens focuses the light onto a spot on the object and the linear Fresnel lens focuses light onto an entire line on the object (Figures 1 and 2) [3].

The lens consists of concentric groves in spot Fresnel lens and parallel groves in linear Fresnel lens.

The groves are the main part of the lens. It focuses light according to its design based on concentric or parallel nature of the groves. Concentric groves focus light onto a single point and parallel lens focuses onto a line.

Major development in the field of Fresnel lens PV concentrator systems are being made due to the fact that radiation on the cell increases with increase in temperature.

Dual axis tracking, point focus Fresnel lens is used for concentrating the radiation on to the center. Currently there is a plant operating in Riyadh, Saudi Arabia. This plant produced 505Wh of Electricity in 12 hours.

The absorber is an Insulated Metal Substrate (IMS) board specially made for concentrating PV systems. The maximum temperature achieved by this technology is 92.4°C.

Figure 3 shows the graph that shows the maximum achieved temperature by the technology according to [1].

This proves that the Fresnel lens technology is definitely helpful for Solar Thermal Technology since the temperature achieved is high.

Although there is a significant temperature rise over the solar cell, there might be difficulties when operating at higher temperatures. Since the maximum temperature achieved is 92.4°C under STC, it might go high on field conditions making the IMS vulnerable to higher temperatures.

For a PV system, this might not be a good option since there is a risk of losing the circuit board due to high temperatures even though special protection measures are taken for high temperature operation.

Flat plate collector (FPC) with fresnel cavity receiver

According to Iuliana [4], the Fresnel lens is a flat stretched glass with groves to focus the light onto the absorber plate.

The absorber is a U shaped glass tube made of copper.

The arrangement and the effect of sunlight on the absorber are shown in the Figure 4 [4].

The variation of thermal efficiency with difference in temperature of fluid mean temperature and ambient temperature with solar radiance divided. This is as shown in Figure 5 [4].

This study was observed over 4 seasons, summer sunny, summer cloudy, winter sunny and winter cloudy.

The insolation over the 4 seasons are,

Summer sunny - 905W/m^2

Summer cloudy - 462W/m^2

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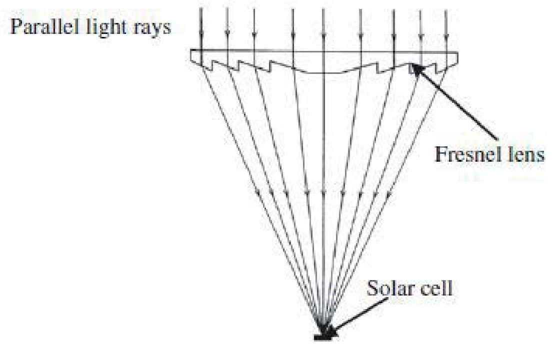

Figure 1: Fresnel lens [3].

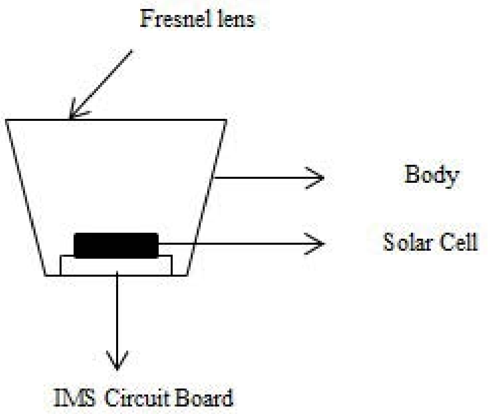

Figure 2: Cross section of the system [3].

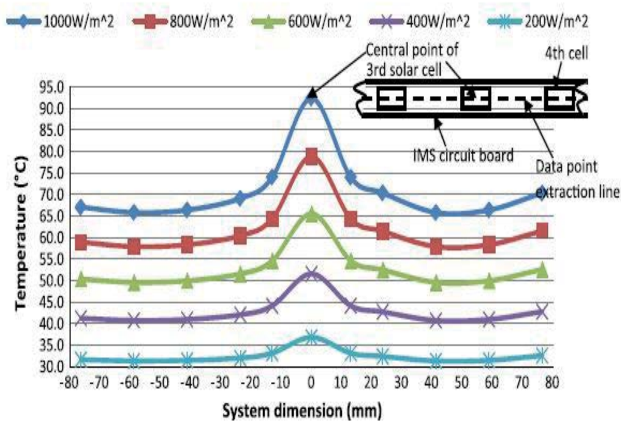

Figure 3: Distribution of Temperature for different radiations [3].

Winter sunny - 140W/m^2

Winter cloudy - 68W/m^2

The plot of tube length v/s fluid temperature during summer sunny and winter sunny is as shown in Figure 6 [4].

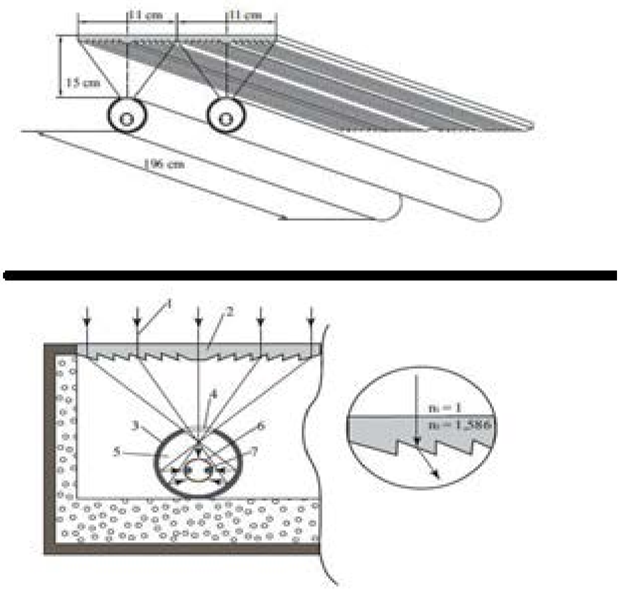

Figure 4: 1. Sunlight 2. Lens 3. Glass tube 4. Aperture 5. Vacuum 6. Fin 7. Copper U tube.

According to Iuliana [4], there was significant increase in the Fresnel lens based collector efficiency.

This technology makes a good impact on the solar thermal energy concept. Bringing this technology into large scale production can be a difficult task since custom made Fresnel lens tends to be more expensive.

Also the absorber tubes may undergo chemical changes due to such high temperatures leading to corrosion.

Flat linear Fresnel lens with sun tracking system

This technology is much similar to that of Iuliana, but the major difference is that there is a sun tracking system which gives in more efficiency.

This study was done in Iraq which involved two lenses in series and two aluminum fin absorber tubes with black coating. Single lens and a single tube produce an output temperature of water of 37°C.

The maximum thermal efficiency achieved was 65% with a mass flow rate of 0.0070815 Kg/s.

This technology was a prominent and a promising technology according to [5].

A single lens and a single absorber produce 37°C output water. This means that more lenses and more absorbers in a single system produce a significant output temperature of water that can be used for both domestic and industrial uses (Figure 7).

This is a plot on all day efficiency where in the maximum obtained efficiency was 58% which was an acceptable value for a solar thermal system.

As the technology involves tracking, it is natural that the economic aspect of installing this system in developing countries is futile.

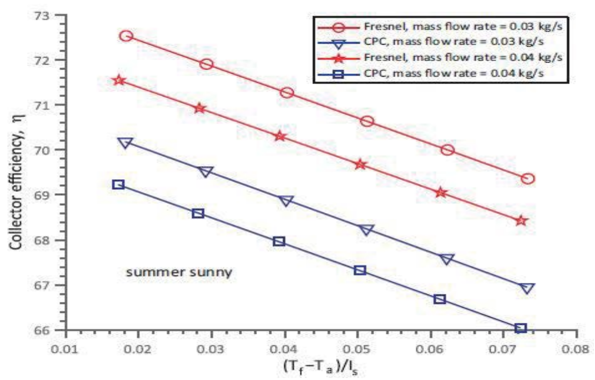

Figure 5: Variation of thermal efficiency.

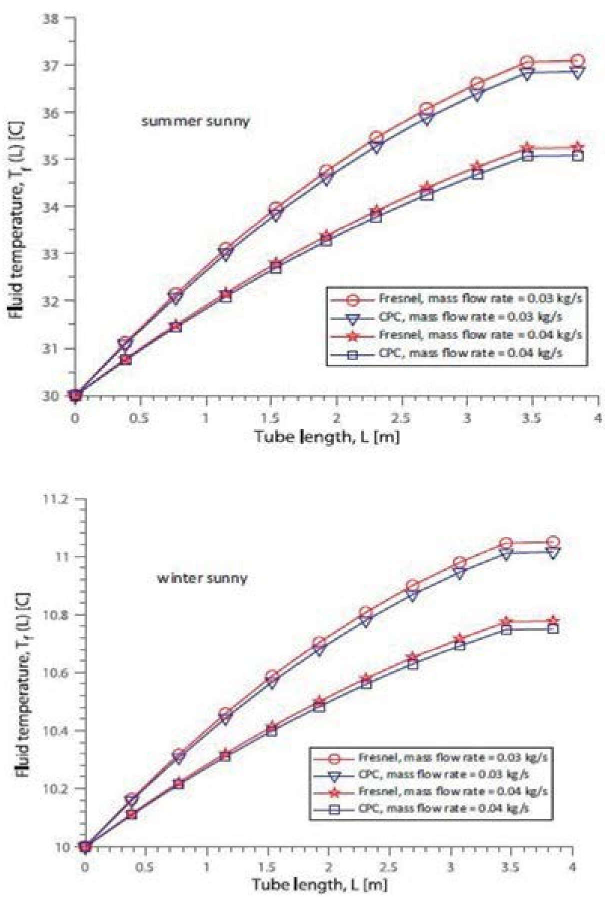

Figure 6: Plot of tube length v/s fluid temperature.

Although there are a lot of systems already installed with tracking system, additional cost of running a thermal plant along with it makes it more expensive.

Technology wise, many losses are incurred with extra wiring for making way for the tracking system. Separate power consumption is also seen from the motors driving the tracking unit.

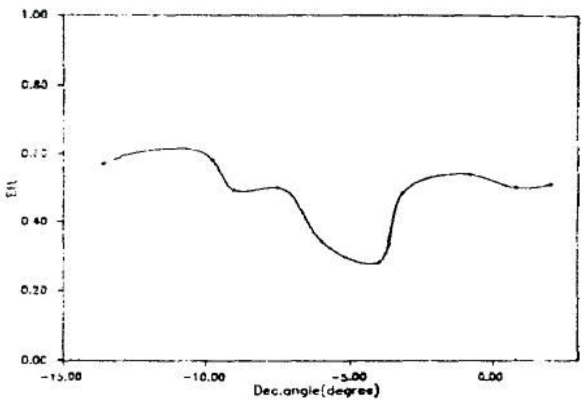

Figure 7: Efficiency variation with respect to the declination angle.

Fresnel lens temperature and energy generation of concentrator PV system

According to Thorsten [6], there are basically two types of Fresnel lenses that are commercially available. One is the lens made up of PMMA (Poly-methylmethacrylate) and the other made up of a transparent silicone rubber on a glass. This is also called as SOG (silicone on glass).

Experiments were made and the two lens technologies was tested which resulted in proving that silicone based Fresnel lens are better than the conventional PMMA lenses.

Again, the cost of using silicone lens is high making the developing countries to look for another technology that is affordable.

Fresnel reflector array technology

According to Abbas [1], this technology consists of basically reflectors and not lenses. This is another unique technology that is used for solar thermal applications that provides high temperature water as output.

The reflector used in this technology is called as the linear Fresnel reflector (LFR) technology. This is an important concentrated solar power (CSP) application.

Another technology which is very close to this technology is the Parabolic trough collector (PTC) technology which consists of a parabolic trough where at its focal point lays an absorber tube used for carrying water or any working fluid.

Abbas has stated that the Linear Fresnel reflector technology is better than the PTC technology. This is because there are practically no joints or welds in the LFR technology.

The setup is called as the Fresnel solar field. This basically consists of a series of Fresnel reflectors that are placed just like heliostats that focuses the radiation onto two absorbers. The absorbers consisting of a bundle of tubes, carries water or any working fluid. This is as shown in Figure 8.

Since there is absence of all moving parts, an important option would be direct steam generation.

Abbas has also stated that the efficiency of this technology is close to that of the PTC technology and the only weakness of this solar field is the concentration factor which was found to be lower than that of the PTCs.

A solution also has been given which says that instead of using the energy directly, thermal storage can be done to achieve better efficiencies.

This technology deems itself to be very expensive and applied only at a large scale making it unaffordable to developing countries like India.

Large area is also required which affects the lives of the rural people. This is not a feasible solution in developing countries since the main occupation of the villagers is actually farming. Acquiring large area of lands is a major issue in countries like India.

Also, this system must be integrated with thermal power plants for power generation, again more land, more investment.

Fresnel lens over LFPC

This technology was a test to determine any changes in the water temperature after just placing the Fresnel lens over the conventional LFPC (Figure 9).

This technology showed an increase of 20% instantaneous efficiency of that of an LFPC [7].

Figure 10 shows the variation of instantaneous efficiency along the day at different mass flow rates and both with and without the Fresnel lens.

We can easily see that the efficiency is significantly higher with the Fresnel lens.

Figure 11 shows the variation of glass temperature with respect to time at different mass flow rates.

Since the whole system is just a retrofit, all the losses that occur by incorporating the new system along with the losses of the previous system must be considered.

So, it can be seen that the glass temperature is very high at peak concentration temperatures.

This affects the efficiency of the system very much leading to undesired output and degradation.

The effect of output temperature throughout the day with different mass flow rates and both with and without lens is shown in Figure 12 [7].

Again, we can see the significant rise in output temperature of water with the lens retrofitted to the conventional system.

Just by retrofitting a conventional LFPC, we could see the rise in instantaneous efficiency and output temperature which gives more scope of new design of Fresnel lens based collector system for heating applications.

Advantages of using fresnel lenses

Looking at all the technologies that are using Fresnel lens, much improvements and designs can be made for various applications bearing lesser cost and higher efficiencies.

Technologies can be so designed for solar thermal applications such that the primary optical element will be the Fresnel lens itself [8].

Fresnel lens based technologies produce ultra-high temperature of the working fluid.

The Fresnel lens technology is almost maintenance free.

Thermal efficiencies can be achieved at a higher level.

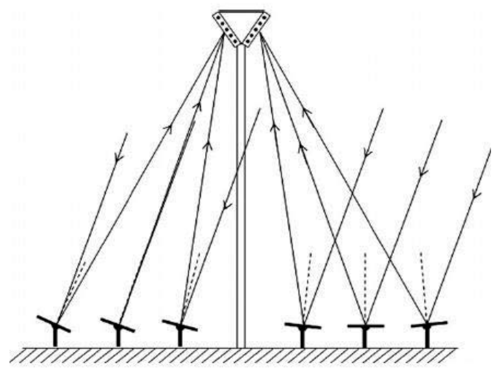

Figure 8: Fresnel solar field.

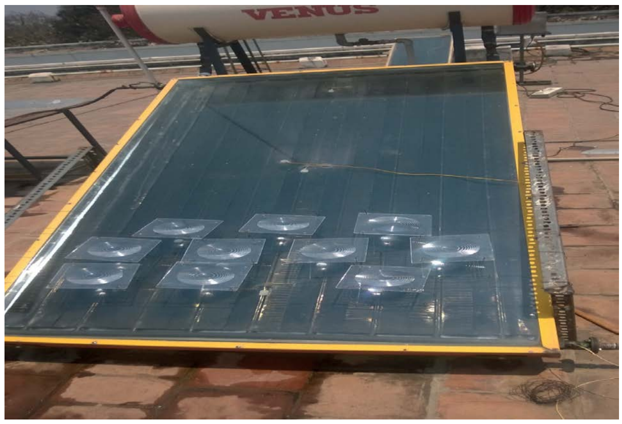

Figure 9: Fresnel lens over the conventional LFPC.

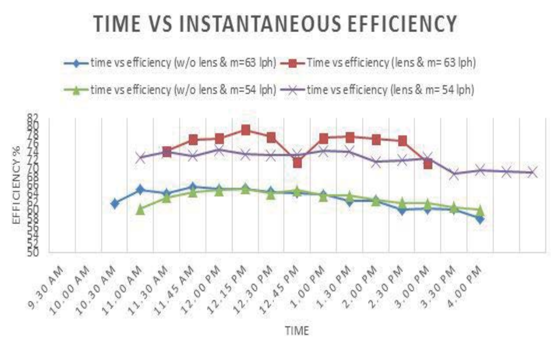

Figure 10: Variation of instantaneous efficiency.

Anti-reflection coating is not needed and also there is no need of reflecting surfaces [2].

By looking into all the technologies, Fresnel lens technology can further be improved by making innovative changes in the collector design.

The changes must be simpler, cheaper and more reliable so that it can be used by most people for domestic heating purposes.

Review Conclusion

A general review of the technologies used using Fresnel lens is been

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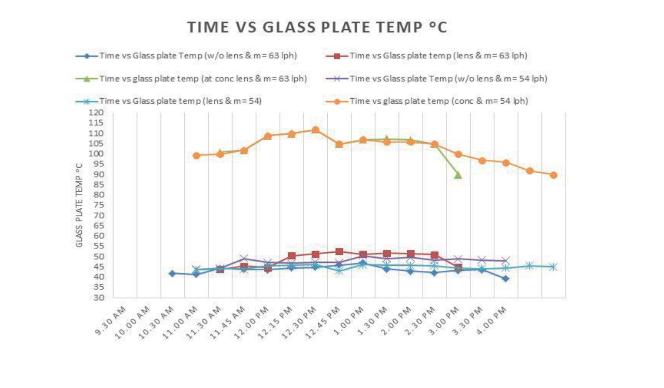

Figure 11: Variation of glass temperature.

Figure 12: Effect of output temperature throughout the day.

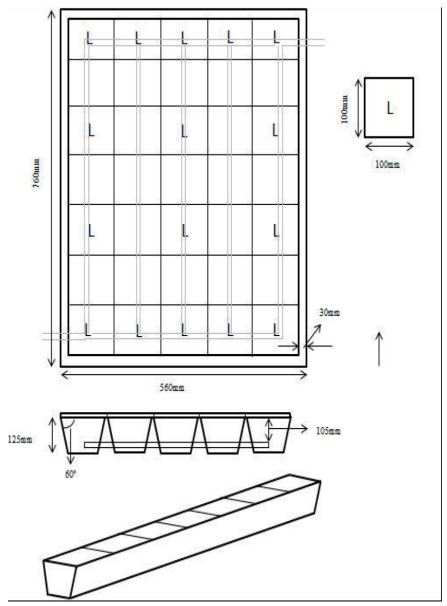

Figure 13: Basic overview of the design.

presented in this paper. Fresnel lens is a promising optical element that can be used to achieve high output temperatures of water in the solar thermal sector that can be used both for domestic and industrial usages. Cheaper and smaller water heaters for domestic purposes can be designed where electricity is scarce in developing and underdeveloped countries. Advanced technologies of manufacturing Fresnel lens like the FK concentrator and the F-RXI concentrator [8] can be used for industrial and power plant sectors coupled with solar thermal systems.

The temperature achieved by Fresnel lens based technology and parabolic trough technology is comparable and is proved by [2] that Fresnel lens temperature is faster which means that more quantity of water can be heated throughout the day.

Fresnel lens is the most promising technology for the future designs of advanced water heaters.

Design Proposed

By looking into the basic overview and all the advantages of using Fresnel lens, an innovative design is been presented in this paper that shows significant improvement in efficiency of the system and reduction in cost.

The design is as shown in Figure 13.

Construction

The construction of this design is as follows.

Only the collector is designed and the rest of the system follows the conventional design. This system is designed for a tank capacity ranging from 50 to 200 liters. The dimension of the collector is 760 mm X 560 mm. The design is tapered at an angle of 60^0 so as to follow the concentration pattern of the lens. L represents the Fresnel lens being used for concentrating the radiation onto a spot on the absorber. The lighter lines under the lens represent the absorber tubes. The cross sectional view of one segment is as shown in Figure 13.

The lens specifications are given below.

- Material: Poly Methoxy Methyl Acrylate (PMMA)
- Refractive Index: 1.49 (taken from catalogs)
- Type: Radial and not linear.
- Purpose: Solar thermal
- Maximum temperature at the focal spot: 400°Celsius at bright sun.
- Shape: Circular inside a square. The corners of the square have four holes for fixing in frames (R&D purpose)
- Size: 100 mm × 100 mm × 3 mm
- Groove density: Low for the purpose of long life (for avoiding scratches)
- Focal length: 105 mm

The piping system is 650 mm × 400 mm with an Outer diameter (OD) of 13.7 mm and Inner Diameter (ID) of 12.5 mm. The material used is Galvanized iron (GI)/steel with a thermal conductivity of 50 W/m^2k.

Working

The lens is placed at the top of the frame without any glass or plastic cover since the lens itself is very robust.

Sunlight passes through the lens and strikes the absorber tube, which heats up, changing solar energy into heat energy. The heat is transferred to liquid passing through pipes attached to the absorber tube. Absorber tubes are usually made of metal-typically copper or aluminum-because the metal is a good heat conductor. Copper is more expensive, but is a better conductor and less prone to corrosion than aluminum. In locations with average available solar energy, flat plate collectors are sized approximately one-half- to one-square foot per gallon of one-day's hot water use.

In this case, the sunlight passes through the lens and strikes the absorber tube. The Fresnel lens focusses the sunlight onto the absorber tube with a focal length of 100 mm.

The temperature achieved at the focal point is 400°C at peak sunshine. When water enters the collector, it is heated to a very high temperature. The water flow may or may not be via forced circulation.

The analysis of this design was done in MATLAB. This analysis shows the output temperature and the instantaneous efficiency achieved by the new design.

Analysis

MATLAB analysis was done using the below mentioned inputs and successful outputs was obtained.

The location is considered as Dehradun, India on 15th May, 135th day of the year. The maximum radiation is considered to be 680 W/m² and the minimum to be 300W/m².

The latitude angle is 30°. The tilt of the panel is also taken to be the same as 30°. For the following inputs, we obtain outputs as mentioned.

Inputs

1. Length of collector = L_a = 0.76 m
2. Width of collector = W_a = 0.56 m
3. Outer diameter of tube = D_o = 0.0137 m
4. Inner diameter of tube = D_i = 0.0125 m
5. Tube center to center distance = W = 0.1 m
6. Thickness of lens (or cover plate) = 0.003 m
7. Refractive index = 1.49
8. Reflectivity = 0.2
9. Location = Dehradun
10. Latitude = φ = 30° for Dehradun
11. Day = n = May 15th = 135
12. Tilt = β = Same as latitude
13. Beam radiation = I_b = 680 W/m²
14. Diffuse radiation = I_d = 300 W/m²
15. Water flow rate = m = 10 kg/hr.
16. Inlet temperature = T_{fi} = 60°C
17. Ambient temperature = T_a = 25°C
18. Wind speed = W_s = 3.1 m/s
19. Back insulation thickness = 0.05 m
20. Reflectivity of surrounding surfaces = 0.2
21. Side loss = 10% of bottom loss
22. Thermal conductivity of steel = I_t = 50W/m²-K
23. Permittivity of steel = ε_p = 0.23

Declination angle

$$\delta = 23.45 * Sin\left(\frac{360}{365} * (284 + n)\right) = 18.79^{\circ}.\ n = 135 \text{ on May } 15^{th}$$

Local apparent time

LAT = 12h ± [4° (Std. Longitude – Longitude of location) + EAT] = 11 h 48 min

Time correction

EAT = 9.87° Sin (2B) - 7.53° Cos (B) - 1.5° Sin (B) = 12.04 mins, where B = (n-1)° (360/364) ω = 3.01°.

Angle of incidence of beam radiation

$$Cos\theta = Sin(\delta) Sin(\varnothing - \beta) + Cos(\delta) Cos(\omega) Cos(\varnothing)$$

= 0.9453 and θ_z = 19.02°.

$$Cos\theta_z = Sin(\delta) Sin(\varnothing) + Cos(\delta) Cos(\varnothing) Cos(\omega)$$

= 0.9798 and θ_z = 11.53°.

Solar flux incident on collector

$$r_b = \frac{\cos\theta}{\cos\theta_z} = 0.9658$$

$$r_d = \frac{1 + \cos\varnothing}{2} = 0.9316$$

$$r_r = 0.2 * \left(\frac{1 - \cos\varnothing}{2}\right) = 0.0136$$

$I_T = I_b r_b + I_d r_d + I_g r_r$ = 949.15W/m²

$(\tau\alpha)_b$ and $(\tau\alpha)_d$

For beam radiation,

Angle of refraction = $\theta_1 = \sin^{-1} \dfrac{\sin\theta}{Refractive\, index}$ = 12.7670°

$$\rho = 0.5 * (\rho_1 + \rho_2)$$

$$\rho_1 = \frac{sin^2(\theta_2 - \theta_1)}{sin^2(\theta_2 + \theta_1)} = 0.0428$$

$$\rho_2 = \frac{tan^2(\theta_2 - \theta_1)}{tan^2(\theta_2 + \theta_1)} = 0.0313$$

$$\tau_{r1} = \frac{1 - \rho_1}{1 + \rho_1} = 0.9179$$

$$\tau_{r2} = \frac{1-\rho_2}{1+\rho_2} = 0.9393$$

$$\tau_r = \frac{\tau_{r1}+\tau_{r2}}{2} = 0.9286$$

$$\tau_a = e^{\frac{-k*\delta_c}{\cos\theta_2}} = 1$$

This value is 1 since δ_c, the cover thickness is 0. This is because the lens itself acts as the cover.

$$\tau = \tau_r * \tau_a = 0.9286$$

For diffuse radiation, Angle of refraction = θ_1 = $\sin^{-1}\frac{\sin\theta_2}{Refractive\,index}$ = 40.2685°, θ_2 = 60° for diffuse radiation.

$$\rho = 0.5*(\rho_1+\rho_2)$$

$$\rho_1 = \frac{sin^2(\theta_2-\theta_1)}{sin^2(\theta_2+\theta_1)} = 0.1177$$

$$\rho_2 = \frac{tan^2(\theta_2-\theta_1)}{tan^2(\theta_2+\theta_1)} = 0.0042$$

$$\tau_{r1} = \frac{1-\rho_1}{1+\rho_1} = 0.7894$$

$$\tau_{r2} = \frac{1-\rho_2}{1+\rho_2} = 0.9916$$

$$\tau_r = \frac{\tau_{r1}+\tau_{r2}}{2} = 0.8905$$

$$\tau_a = e^{\frac{-k*\delta_c}{\cos\theta_2}} = 1$$

This value is 1 since δ_c, the cover thickness is 0. This is because the lens itself acts as the cover.

$$\tau = \tau_r * \tau_a = 0.8905$$

$$\rho_d = \tau_a - \tau = 0.1095$$

$(\tau\alpha)_b = \frac{\tau\alpha}{1-(1-\alpha)*\rho_d}$ = 0.8787, Consider beam radiation values of τ and α.

$(\tau\alpha)_d = \frac{\tau\alpha}{1-(1-\alpha)*\rho_d}$ = 0.8426, Consider diffuse radiation values of τ and α.

Incident flux absorbed by absorber plate

$S = [I_b\, r_b{}^*(\tau\alpha)_b] + [(I_d\, r_d + I_g\, r_r)^*\,(\tau\alpha)_d]$

Collector heat removal factor and overall loss coefficient

Assume U_l = 2 /m²-K.

$$m = \sqrt{\frac{U_l}{I_t * Plate\,thickness}} = 4.4721\ \text{m}^{-1}$$

$$m\left(\frac{W-D_o}{2}\right) = 0.1930$$

$$\Phi = \frac{\tanh(0.1930)}{0.1930} = 0.9878$$

$$F' = \frac{1}{U_l*W*\left[\frac{1}{U_l*[(W-D_o)*\varnothing_1+D_o]}+\frac{1}{\pi*D_i*h_f}\right]} = 0.9765,$$

h_f is the heat transfer coefficient of the inner walls of the tube and is assumed to be 380 W/m²-K for water as fluid and steel as the absorber.

A_p = Total area of tubes = $\frac{\pi*D_o*L_a*5}{2}+\frac{\pi*D_o*L_a*2}{2}+(L_a*W_a)$ = 0.3579.

The area of the collector is taken as the area of the tubes running throughout the collector area. Vertically there are 5 pipes and so, in the 1st equation, 5 is used. Similarly horizontally there are 2 pipes. Although this may not be the exact area, it can be assumed that the taken area is correct.

$F_r = \frac{\dot{m}*C_p}{U_l*A_p}*\left[1-e^{\frac{-U_l*A_p*F'}{\dot{m}*C_p}}\right]$ = 0.9477, $\dot{m}$ = 10 kg/hr and C_p = 1.1611, specific heat of air.

$$q_u = F_r * A_p[S - U_l*(T_{fi}-T_a)] = 255.5569\text{W}$$

$$q_l = S*A_p - q_u = 39.1621\text{W}$$

Also, $q_l = U_l*A_p*(T_{pm}-T_a)$, From this, we can find the value of T_{pm}. So, T_{pm} = 352.7086 K = 79.7086°C. $T_{sky} = T_a - 6$ = 292 K = 19°C.

h_{p-c} = heat transfer coefficient between plate and cover is 0 since there is no cover involved.

So, $$\frac{q_t}{A_p} = h_{p-sky}*(T_{pm}-T_{sky}) + \frac{\sigma*(T_{pm}4-T_{sky}4)}{\frac{1}{\varepsilon_p}-1}$$

$h_{p-sky} = h_w = 8.55 + 2.56*W_s$ = 16.486 W/m²-K.

So, $\frac{q_t}{A_p}$ = 1001 W/m²

$$U_t = \frac{q_t}{A_p*(T_{pm}-T_a)} = 18.2964\text{W/m}^2\text{-K}$$

$$U_b = \frac{k_i}{\delta_b} = \frac{0.04}{0.05} = 0.8\text{W/m}^2\text{-K}$$

$$U_s = 0.1 * U_b = 0.08\text{W/m}^2\text{-K}$$

$$U_l = U_t + U_b + U_s = 19.1764\text{W/m}^2\text{-K}$$

Water outlet temperature

$q_u = \dot{m} * C_p * (T_{f_0} - T_{f_i})$ Substituting the values of $\dot{m}$ C_p, T_{fi} and q_u, we get T_{fo}. T_{fo} = 355.0099K = 82.0099°C

Instantaneous efficiency

$$n_i = \frac{q_u}{I_t * A_c} * 100 = 63.263\%$$

Summary

The analysis is done according to the inputs given. Here, the declination angle is calculated to 135th day of the year. Accordingly, the local apparent time is calculated.

Solar flux incident on the collector is calculated with the geographical data assumed.

The main factors, heat removal factor and the overall loss coefficient are calculated for loss analysis for the given size of the collector.

The output temperature and the instantaneous efficiency are calculated for the obtained values of the loss coefficients and heat transfer coefficients.

Results and Discussion

$$F_r = \frac{\dot{m} * C_p}{U_l * A_p} * \left[1 - e^{\frac{-U_l * A_p * F'}{\dot{m} * C_p}} \right]$$

This is the main equation guiding the output of the system. This equation guides the overall heat lost from the collector, q_u. This further guides the efficiency of the system.

The output of the conventional system is 65°C and 43%. This design gives a higher output temperature and higher instantaneous efficiency.

Assumption of a few parameters in the design analysis gave us higher temperature and higher efficiency. This may vary on field. Also, this system is a basic design on which further improvements can be made by incorporating a motor for forced circulation so as to get better efficiency.

The system is made from less expensive materials such a ply wood and cheap glue materials. Industrial standard grade materials can be used which increases the cost slightly without affecting the performance of the system.

This design analysis gave us 63.263% efficiency with an outlet temperature of 82°C. This is still under the theoretical calculations involving assumptions. Practically this is going to be more efficient and the temperature is going to be high considering a lot of practical parameters.

This system is cost effective and smaller in size making it easier for transportation and installing it in rural areas for the welfare of the poor and where electricity is scarce.

This output water which is of a higher temperature can be used for cooking in big institutions.

Further, this system can be integrated with water driven Vapor Absorption Machine (VAM) for building cooling systems. VAM can operate easily with hot water as the input. Since the hot water obtained in this application is about 85 to 90°C, water driven VAM can be operated without any issues.

Conclusion

The thermal analysis and cost analysis was done and it showed that the new design is more efficient, less expensive and smaller in size when compared to conventional flat plate collector.

The same analysis is done for a conventional Flat plate collector and the efficiency and the outlet temperature is 43% and 65°C respectively.

This design can also be installed at places where solar radiation is low since the lens focusses the light onto the absorber at a temperature of 400°C making the water to be heated even at low radiation.

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