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Performance Analysis and Thermal Modeling of A Solar Flat Plate Collector With Concave Ridged Profile

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Abstract

Solar flat plate collectors are one of the most popular and cost effective ways of trapping the sun's heat energy for domestic as well as industrial applications. They are relatively cheap, simple in design and highly useful in tropical climatic conditions. Over a period of time various new designs for the solar flat plate collector have come up leading to more efficient collector setups. This paper evaluates the results of an experimental investigation on the performance of a solar flat plate collector when the conventional absorber plate profile is replaced with a concave-ridged profile. It is known theoretically that for the same aperture area the concave-ridged profile will provide larger surface area for the collection of heat energy from incoming solar radiation (insolation) as compared to the conventional flat profile. Further the concave-ridged profile has a larger shape factor with respect to itself than a conventional profile which leads to better entrapment of heat received from solar radiation. A scaled down model of a commercial solar flat plate collector was fabricated and experiments were conducted using both of the above mentioned profiles at the same geographical coordinates. The results of the experimental studies as well as the comparison of collector efficiencies are presented. Thermal analysisof the concave-ridged profile using ANSYS 14.5 was also done in order to study the distribution of temperatures and thermal fluxes within the profile.

Keywords: Solar Energy, Flat Plate Collector, Concave Ridged Profile, Thermal Flux, Collector Efficiency

Introduction

The sun radiates energy in the form of heat and light as a result of nuclear fusion reactions. The solar energy received on Earth in the form of radiation can be used for heating as well as generation of electricity. Solar energy received on earth has very low power density, generally lying in the range of 0 to 1 kW/m^2. Further, the solar energy received on the ground level is also dependent on atmospheric clarity, latitude of the geographic location, local weather conditions etc. This necessitates the collection and concentration of incoming radiant energy from sun to effectively use this unlimited yet diffused source of energy.

Solar energy can be used for domestic purposes out of which the most common is the use of solar energy to heat water using a solar water heater. These solar water heaters employ a collector setup which absorbs incoming solar radiation from the sun and uses it to heat the water and thereby can supply hot water for domestic purposes. The most commonly used type of collector is the “Flat Plate Collector”. Flat plate collectors, developed by Hottel and Whillier in the 1950s, are in widespread use domestically. These collectors can achieve temperatures up to 90 °C. It is highly suitable for locations with tropical climatic conditions where sunlight is available in plenty. They can absorb both direct and diffuse radiations. Their relatively simple design and ease of use makes them extremely popular.

A typical flat plate collector is a metallic box with a black absorber plate covered by a glazing surface (usually toughened glass). The absorber plate is placed in an insulated casing to prevent heat losses due to conduction. The top of the casing is covered with a glazing surface such as glass. The absorber plates are painted with a black selective coating for better absorption and retention of heat from the sunlight that strikes it after passing through the glazing surface. The liquid passing through the pipes absorbs the heat from the absorber plate. By using selective coatings it is possible to reduce the emissivity factor and improve the absorptivity. Absorber plates are usually made of metal, typically copper or aluminum. Flat plate collectors require less maintenance than their evacuated tube counterparts. These collectors become less effective as ambient temperature reduces.

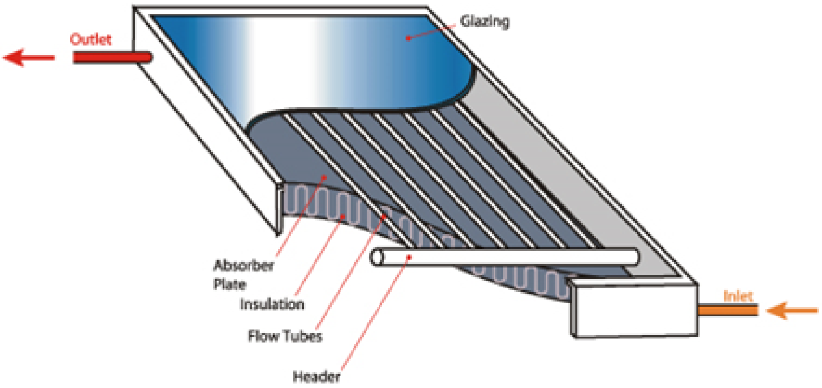

Figure 1: Flat Plate Collector

Theory of Working

The experimental setup consists of the flat plate collector, water tank, submersible water pump, a calibrated measuring flask, hose pipes, flow control valve, digital scientific thermometer, stop watch and digital irradiance meter. The entire setup was placed outdoors on a clear day under direct sunlight. The tank was filled with water and the submersible water pump was immersed into it. A hose pipe was connected to the water pump with its other end connected to the flow control valve. The water pump was connected to 220V electric supply and the switch was turned on. The flow control valve was adjusted to set the mass flow rate of water through the submersible pump and the time taken to collect 1000ml of water in the measuring flask was observed using a digital stopwatch in order to measure the mass flow rate. All the experiments were conducted in the month of March at geographical location with coordinates 11º 00' N and 77º 00'E (Ettimadai, Coimbatore), which lies in the northern hemisphere. The flat collector setup was hence set facing true south after performing necessary magnetic declination angle correction using a compass.

The flat plate collector was kept at angle of 24º with the horizontal surface. The inlet of the flat plate collector is connected to the free end of the flow control valve with the help of a hose pipe and the outlet is connected with another hose pipe. The inlet temperature of the working fluid (water) in the tank was tabulated by submersing the probe of the digital scientific thermometer. The receiver of the digital irradiance meter is attached to the flat plate collector such that it doesn't affect the performance of the same. Making sure that the sky was clear throughout the experimentation process, the reading of the digital irradiance meter was tabulated over the length of the experiment. The switch was turned on and without changing the position of the knob of the flow control valve 1000ml of the working fluid (water) was collected in the measuring flask. The switch was turned off. The outlet temperature of the working fluid was taken by submersing the probe of the digital scientific thermometer into the measuring flask. The procedure was repeated for both the absorber plate profiles alternatively for 4 different values for mass flow rates. A comparative study of the performance of the flat profile and the concave-ridged profile was done. Efficiency of the collector is defined as the ratio of the useful heat energy absorbed to the amount of solar insolation incident on the collector's aperture.

Once it was established that the concave ridged profile had higher efficiency in comparison to the conventional profile, further experiments were performed on the modified profile by varying the mass flow rates and angle of inclinations. Angle of inclination was varied by placing wood logs of known thickness under the solar flat plate collector setup. To increase the inclination angle, additional wood logs were added. For each angle of inclination, the mass flow rate of water through the heat exchange tubes was varied. The temperature differences were noted down and the necessary calculations were done.

Figure 2: Experimental Setup

Results and Discussion

All the experiments were conducted during the 2pm to 4pm time interval and at the exact same geographic location. Convection and radiation are assumed to be the main causes of heat loss. The casing of the flat plate collector is assumed to be completely insulated on its bottom and sides and conduction losses through these parts are assumed to be negligible. Mass flow rates of heat transfer fluid (water) were fixed and readings were obtained for both profiles alternatively. For both the profiles the collector plate was kept inclined to the horizontal surface at an angle of 24°.

Comparative Study of the Conventional and Modified Profiles

1. Flat Profile

Table 1: The Flat Profile Is Found To Have An Average Efficiency of 30 % Over A Range of Mass Flow Rates and Solar Irradiances

S No	Mass Flow Rate x10^{-3} (kg/s)	Irradiance meter readings(W/m^2)	Input (W)	Output (W)	Efficiency (%)
1	2.857	980	190.25	57.71	30.33
2	4.878	920	178.00	41.18	23.05
3	6.250	955	185.40	65.29	35.57
4	11.11	885	171.80	54.71	31.84

2. Concave-Ridged Profile

Table 2: The Concave-Ridged Profile Is Found To Have An Average Efficiency of 38.94% Over A Range of Mass Flow Rates And Solar Irradiances.

Sl. No.	Mass Flow Rate $\times 10^{-3}$ (kg/s)	Irradiance meter readings (W/m^2)	Input (W)	Output (W)	Efficiency (%)
1	2.857	726	140.94	47.09	33.41
2	4.878	785	152.40	53.65	35.10
3	6.25	929	180.35	67.83	37.60
4	11.11	950	184.40	91.56	49.65

The concave-ridged profile is observed to have a better efficiency of the two. On an average the modified profile offers an increase in efficiency of about 8.7% in the weather conditions in which the experiments were conducted. It is also seen from the plot of the results that as solar insolation value increases the efficiency of the collector plate, be it conventional or modified, increases and the vice-versa is true. The conditions under which the experiments were conducted were usually sunny and India being a tropical country receives a lot of sunlight and hence provides favorable conditions for usage of solar flat plate collectors. So it is definitely better to use the modified profile as it occupies same installation space with nominal cost offsets while providing a significant increase in efficiency.

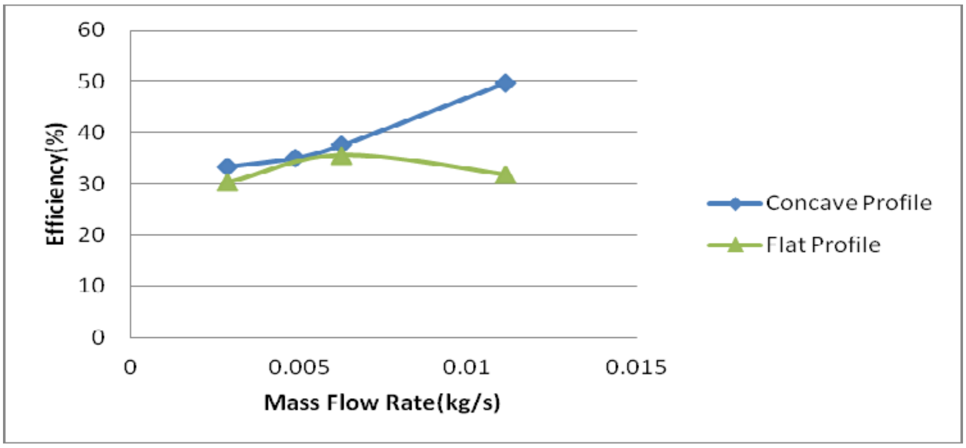

Figure 3: Mass Flow Rate Vs Efficiency

Variation in Efficiency with Inclination Angle for Modified Profile

After performing the comparative study between the two collector profiles, the best angle of inclination for the modified profile was determined. The following section tabulates the results of study on variation of efficiency with inclination angle and helps determine the angle of inclination for maximum efficiency.

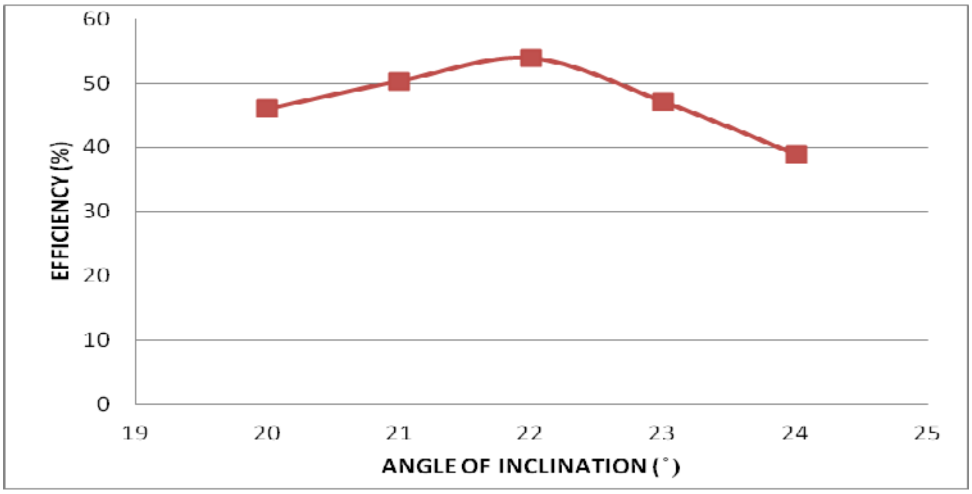

Figure 4: Angle of Inclination Vs Efficiency

The highest average efficiency of 53.88% is found at an angle of inclination of 22º.

Thermal Analysis of Concave Ridged Profile

2-D thermal analysis was done on the concave ridged profile in order to establish the thermal gradient, flux and temperature distribution in the collector setup. The analysis was done in ANSYS 14.5 using plane 77 thermal mass element. An incoming heat flux of 800 W/m^2 is assumed. The convex side of the profile is set as insulated and other requisite boundary and initial conditions were set. The results thus obtained were as follows.

1) Thermal flux

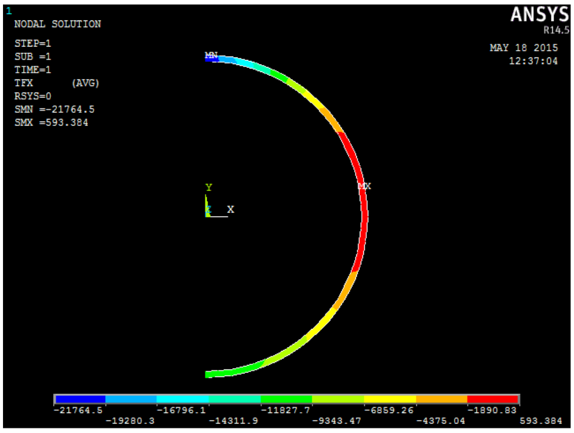

Figure 5: Thermal Flux on A Concave Ridged Profile

Thermal flux within the profile, as expected, is concentrated at the center of the profile. Maximum direct solar insolation tends to concentrate at the central regions of the profile as dictated by the profile's shape.

2) Thermal Gradient

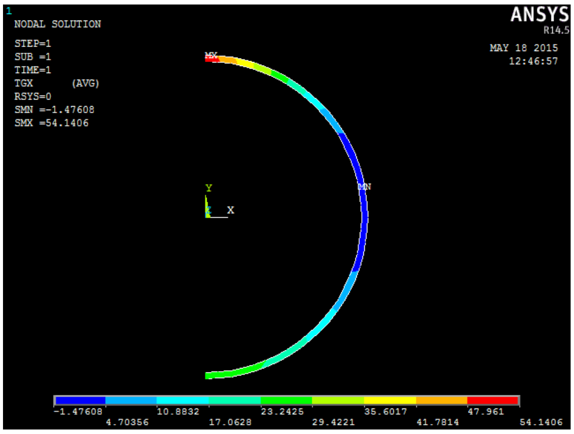

Figure 6: Thermal Gradient In A Concave Ridged Profile

Thermal gradient inside the profile along its thickness is as shown. The temperature in the central region of the profile is almost constant and hence the thermal gradient is very low. Temperatures start decreasing as we move towards the periphery of the profile and as a result the thermal gradients become more significant although edge effects also need to be accounted for.

3) Temperature

Figure 5: Temperature Distribution on A Concave Ridged Profile

Maximum temperature within the profile is also seen to occur at the center of the profile which is due to the accumulation of large amounts of thermal flux in the central regions of the profile.

Conclusion

Within the limits of experimental errors, the above study establishes that collector profile modification can lead to significant increase in the efficiency of a solar heat collector setup. Replacing the conventional collector profile by a concave-ridged profile collector enhances the efficiency of the collector setup by an average of 8.71% over the range of solar irradiances and weather conditions in which the experiments were conducted. Further, the most suitable angle of installation is found to be 22º for the geographic location in which the experiments were performed. The thermal analysis in ANSYS shows a concentration of thermal flux in the central regions of the concave ridged profile which ensures that heat is transferred much more effectively to the working fluid. This further strengthens the argument that the concave ridged profile is a better alternative over the conventional flat profile. The concave-ridged profile can provide better returns for investments made on the solar collector setups at nominal increase in costs.

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