Performance Study of Compound Parabolic Collector for Solar Water Heater

Mr. Yashawantha K M(1) Jawaz Pasha(2) Abdul Mujeeb M S (3)

1 Department of mechanical engineering Srinivas institute of technology, Mangalore
2 Department of mechanical engineering P A college of engineering, Mangalore
3 Department of mechanical engineering P A college of engineering, Mangalore

Abstract— Conventional sources of energy are depleting in future and non-conventional energy like solar energy will be playing a dominant role. In this work, the concept of Compound Parabolic Collector (CPC) is used to heat the water and is possible to achieve a maximum water temperature of 80°C with a small aperture area as compared to other available collectors. Collector efficiency is nearly 45%, however if all the control about reflecting rays and insulation is used for reducing the heat loss; possibility efficiency increasable comparitably. The studied system is of reasonable cost because of using less expensive material in the system.

Key words — CPC, solar water heater, collector efficiency, validation

Introduction

Since the invention of the compound parabolic concentrator (CPC), many papers have been published that deal with a wide range of designs and analysis of these systems [1]. However, a close examination of these papers reveals that the great majority of them are devoted to the optical, geometrical, and thermal analysis of the CPC with a tubular receiver. The CPC is a good choice for applications in direct evaporation or water heating near its boiling point, because these stationary collectors have a good quality rate etween cost and performance at medium temperature levels [2]. The CPC could be used in a great variety of solar applications such as [3] passive (integrated collector storage) and active (direct and indirect circulation) solar water heating; space heating and hot water production, heat pumps, and sorption cooling and refrigeration systems; industrial air and water systems for process heat; desalination (multistage flash, multiple effect boiling, vapor compression); and solar chemical systems for thermal power systems.

Compound parabolic collector (CPC) or Winston collector as shown in figure 2.1 . The CPC consists of two parabolic reflectors which funnel the incident solar radiation on to the absorber. The right and left halves belong to different parabolas. Each parabola is passing through the focus of the other parabola. The distance between two focuses is the absorber. The CPC can be used in no tracking mode with seasonal tilt adjustments and can provide concentration ratios in the range of (3-7). [4, 5].

In this work a compound parabolic trough solar collector (CPC) is designed and studies theoretically. The dimensions of the designed model of CPC solar collector will be calculated by the using the equations which are explained later and the specifications of it will be selected.

Our work will cover (3-7) concentration ratio and the CPC type collector is suitable work with this area without need to the tracking system, but the other types of solar collectors needs the tracking system in additional to auxiliary systems and this will complicate the design and mean additional cost.

Bloisi et. al [7] study four type of (CPC) collector. The four type of CPC collector are different in shape of absorber. The researchers study the effect of acceptance angle, height and width to the design of collector. Zaki et. al. [8] report that thermal losses from the CPC collector, due to a smaller absorber surface area, were significantly reduced resulting in an increased thermal efficiency

2. DESCRIPTION OF THE CPC

CPC consist basically of three elements:

Receiver- The receiver should have the highest absorptancefor solar radiation as possible and must be constructed with high-conductivity metals in order to conduct efficiently the absorbed heat into the heat transfer fluid. Most receiver materials do not have a very high absorptance, and they need to be covered with special solar selective surface coatings [10]. A commercial selective surface for applications in solar energy made from a silicon polymer, with an emissivity from 0.28 to 0.49 and absorptance values from 0.88 to 0.94 was applied on the surface of this receiver.

Cover- The ideal cover is a transparent insulation that allows the passage of solar radiation to the reflector and receiver, having a high transmittance of solar radiation, and a low transmittance of the thermal radiation from the receiver; also, it must have high durability and low cost. The cover used was a low-iron tempered glass with a thickness of 4 mm**.**

Reflector- Reflectors for solar concentrators should have the highest reflectance as possible. Its function is to focus beam-solar radiation onto the receiver, which is located at the focus of the system. Two aluminum sheet segments with a reflectance of 0.87 were used to construct the reflector sides.

3.1 The geometry of an ideal two-dimensional CPC

Concentrator consists of two segments 'AB' and 'DC'. As shown in figure 2.1[4]

- 'AD' is the aperture of width '*W*'.
- 'BC' is the absorber surface of width 'b'. Axis of two parabolas is oriented such that 'C' is the focus of parabola T and' 'B' is the focus of parabola '2'
- Tangents at A and D are parallel to the axis of "CPC".
- Acceptance angle "AED" is obtained by joining each focus to the opposite aperture edge.
- Concentration ratio - C= (W/b) ------------- (2.1)

Using x-y coordinate with origin '0' at vertex of parabola 2, equation for parabola 2 is

$$Y = \frac{X^2}{2b(1+\sin\theta_a)} \quad \text{-------------} \ (2.2)$$

Focal length OB= $OB = \frac{b}{2}(1-\sin\theta_a)$ ---- (2.3)

Co-ordinates of the end point of the segment CD are

Point C $x = b\cos\theta_a$ ------- (2.4)

$$y = \frac{b}{2}(1-\sin\theta_a) \quad \text{-------} \ (2.5)$$

Point D $x = (b+W)\cos\theta_a$ ------ (2.6)

$$y = \frac{b}{2}(1-\sin\theta_a)\left[1+\frac{1}{\sin\theta_a}\right] \text{--} \ (2.7)$$

The height to aperture ratio of the concentrator is given by

$$\frac{H}{W} = \frac{1}{2}\left(1+\sin\theta_a\right)\left(\cos\theta_a\right) \text{---------} \ (2.8)$$

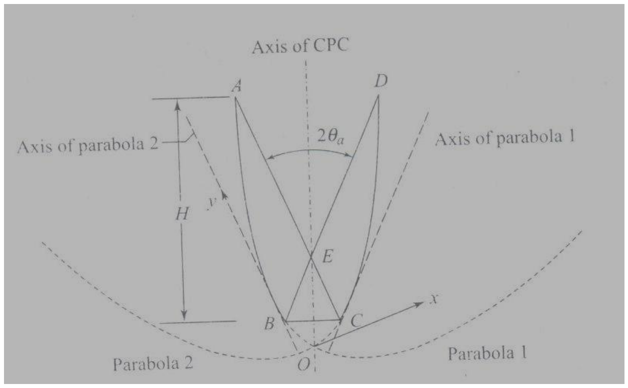

Figure 2.1: geometry of compound parabolic collector

3. EXPERIMENTAL SET UP

Figure 3.1 shows CPC is to be placed in a suitable place, where the availability of sunlight is more for the study. Absorber tube is placed at the focal point by using suitable fixtures. A piece of glass is kept on the absorber tube to enhance the penetration of sunlight towards the absorber tube. Storage tank is placed at suitable height to provide continuous flow through absorber tube. Arrangement is made to record the water temperature. Experiments are carried out with different types of absorber tubes on basises of day timings usual intervals of every one hour from begining of morning 9 AM and the collector efficiency of the system is calculated by using Equations listed in 3

Figure 3.1: experimental setup

Table 3.1: Specification of Compound Parabolic Collector

Sl. No	Description	parameters
1	Profile	Parabola
2	Concentration ratio	5.24
3	Aperture width(w)	500mm
4	Height of trough	1600mm
5	Length of trough	700mm
6	Aperture area of trough	2.184m^2
7	Diameter of absorber tube	6.5 mm
8	material for absorber tube	Copper
9	Material for reflector surface	Al sheet

4. MATHAMATICAL MODEL FOR COLLECTOR

4.1 Declination: Phase lag

$$\delta = 23.45 \sin\left(\frac{360}{365}(284+n)\right) \ldots\ldots\ldots\ldots \quad (4.1)$$

4.2 Tilt factor for instantaneous/hourly diffuse radiation

$$r_b = \frac{\sin\delta \sin(\phi-\beta) + \cos\delta \cos\omega \cos(\phi-\beta)}{\cos\theta_z} \ldots\ldots \quad (4.2)$$

4.3 Zenith angle

$$\cos\theta_z = \sin\phi \sin\delta + \cos\delta \cos\omega \cos(\phi-\beta) \ldots\ldots \quad (4.3)$$

4.4 Collector efficiency factor

$$\frac{1}{F'} = U_l\left[\frac{1}{U_l} + \frac{b}{N\pi D_i h_f}\right] \ldots\ldots\ldots \quad (4.4)$$

4.5 Collector heat-removal factor

$$F_R = \frac{m' c_p}{b U_l L}\left[1 - e^{\frac{-F' B U_l L}{m' c_p}}\right] \ldots\ldots\ldots\ldots\ldots \quad (4.5)$$

4.6 Incident solar flux absorber in the absorber plate or tube

$$S = \left[I_b r_b + \frac{I_d}{C} \right] \tau \rho_e \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots \; (4.6)$$

$$I_{bn} = A * e^{-B/\cos\theta_z} \quad \ldots\ldots\ldots\ldots\ldots\ldots \; (4.6.1)$$

4.7 Instantaneous /hourly beam radiation on a horizontal surface

$$I_b = I_{bn} * \cos\theta_z \quad \ldots\ldots \; (4.7)$$

4.8 Rate of useful heat gain

$$q_u = F_R W L \left[S - \frac{U_l}{C}\left(T_i - T_a\right) \right] \quad \ldots\ldots\ldots\ldots \; (4.8)$$

$$r_d = \frac{\left(1 + \cos\beta\right)}{2} \quad \ldots\ldots\ldots \; (4.8.1)$$

4.9 Collector efficiency

$$\eta_v = \frac{q_u}{\left[I_b r_b + I_d r_d \right] W L} \quad \ldots\ldots\ldots\ldots \; (4.9)$$

5. RESULTS AND DISCUSSION

Figure 5.1 explains the collector efficiency variation with respect to temperature difference. The study results revealed that the efficiency of collector increases with temperature difference.

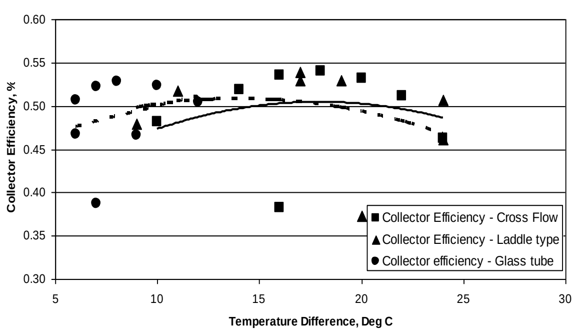

Figure 5.1: Variation of Collector Efficiency w.r.t Temperature Difference

The experimental study indicated most efficient absorber tube arrangement is ladle type as compared to crossflow and glass tube. This is due multi pass tube arrangement which helps the water to gain more heat while flowing in the respective tube.

Figure 5.2 elucidates the collector efficiency variation with respect to incident solar flux. The study results highlight that efficiency of collector increases with incident solar flux and all the absorber tubes have the same efficiency . This is due to area of convergence will introduces the same heat flux; because all 3 arrangements have same total internal reflection of numerical aparture area of CPC.

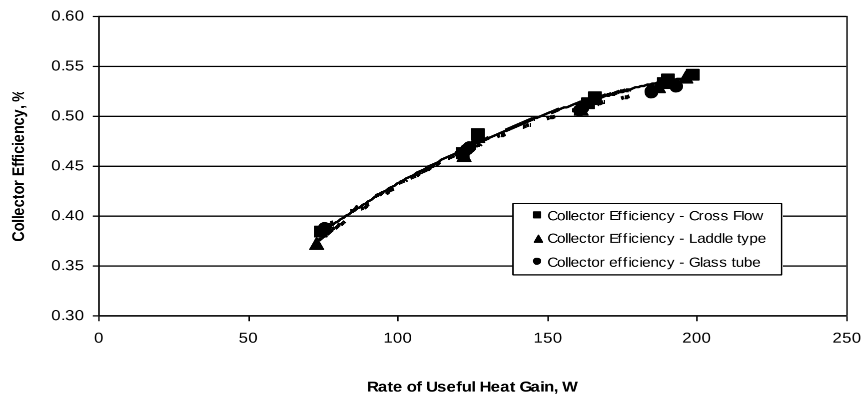

Figure 5.2: Variation of Collector Efficiency w.r.t Rate of Useful Heat Gain

Figure 5.3 explains collector efficiency variation with respect to rate of useful heat gain and the study indicates that efficiency of collector increases with rate of useful heat gain. The experimental results clearly indicate that the ladle type absorber tube have higher efficiency as compared to other arrangements and is due to high temperature difference with ladle type arangement. Thus, the study emphasize for ladle type absorber tube is having higher efficiency than other types.

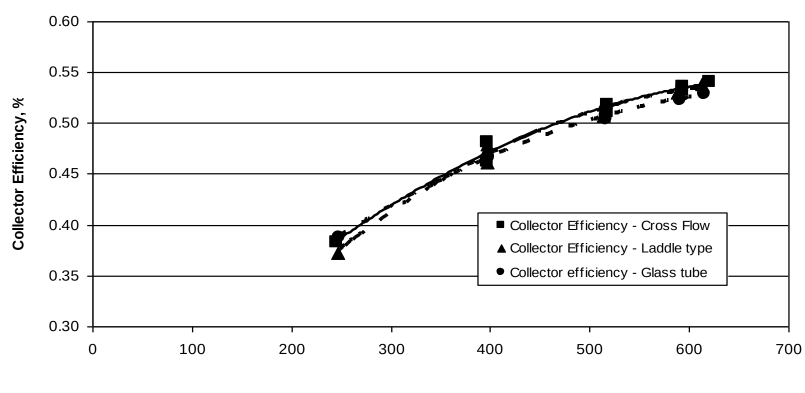

Figure 5.3: Variation of Collector Efficiency w.r.t Incident Solar Flux

In this work, the studies on different types of absorber tube coatings have not made which in turn enhance the thermal loss from the system. Absorber tube coating facilitates the absorbing capacity of solar rays from the Sun and thus, increases the efficiency.

By incorporating the adjustment for the angle inclination with respect to the time, system improves the efficiency. However, in the current work the concept is not used and it will not focus the all the incident rays on absorber tube and thus decrease the absorbing capability of the system. In addition, uneven and frequent changes in the climate lead to thermal loss from the system. The clouds interrupt the solar rays, the intensity of the solar ray decreases.

6. CONCLUSION

In this work, the concept of Compound Parabolic Collector (CPC) is used to heat the water and is possible to achieve a maximum water temperature of 80°C with a small aperture area as compared to other available collectors. The studied system is of reasonable cost because of using less expensive material in the system.

Collector efficiency is nearly 45%, however if all the control about reflecting rays and insulation is used for reducing the heat loss may be efficiency increasable comparitably.

Three different types of absorber tubes (Cross flow type, Ladle type and Glass tube) are studied and the experimental results suggest that efficiency is more with more contact surface in the form of absorber tube. This is because the time taken for the water to flow inside the tube is more, and gradually heat gain will be more, thus enhances the heat transfer rate during the flow through absorber tube.

List of Symbols

n	days o the year; number of year
r_d	tilt factor for instantaneous/hourly diffuse radiation; depreciation rate.
r_b	tilt factor for instantaneous/hourly beam radiation
φ	latitude; plate effectiveness
B	slope of tilt; coefficient of volume expansion, K^{-1}
ω	hour angle, angular velocity.
θ_z	zenith angle
F'	collector efficiency factor
F_R	collector heat-removal factor
U_l	overall loss coefficient, W/m^2-K

b	width of absorber surface of CPC.
D_i	inner diameter of tube in m
h_f	heat transfer coefficient on inside surface of tube, W/m^2-K
$m^\cdot$	mass flow rate, kg/s
C_p	specific heat kj/kg-K.
L	length of absorber plate, m.
S=	incident solar flux absorber in the absorber plate or tube, W/m^2.
I_b	instantaneous /hourly beam radiation on a horizontal surface, W/m^2.
I_d	instantaneous /hourly diffused radiation on a horizontal surface, W/m^2.
C	concentration ratio.
τ	transmissivity of cover or covers.
ρ	effective reflectivity of a CPC.
α	absorbability of absorber surface for a solar radiation, m^2/s.
q_u	rate of useful heat gain, W.
W	pitch of tubes, m.
T_i	temperature of fluid at inlet, K.
T_a	ambient temperature, K.
δ	Declination; Phase lag

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