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Design, Optimization and Thermal analysis of Compound Parabolic Concentrator

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Abstract - *Among every type of concentrators, compound parabolic concentrators (CPCs) are designed as stationary solar collectors for relatively high temperature operations with high effective cost. The CPCs are potentially the favorable option for high temperature solar thermal system. It reviewed optical models and geometric modelling of CPCs. This paper also provided information about development of solar absorber which combined the external compound parabolic concentrator (CPC) and the all-glass evacuated tube. This paper covered basic concepts, principles, design, thermal analysis of CPC and comparing the performance with solar evacuated tube.*

***Key Words*: CPC, Concentration Ratio, Half acceptance angle, Solar Radiation, Solar Dryer.**

1. INTRODUCTION

Human beings started to accumulate and use solar energy thousands of years ago. The flat plate, as the first invented, are used in a system is to be operated at temperature below 100 ºC due to limited energy intensity on the solar panels, whose peak is about 1 kW/m^2 from the sun. To break the temperature limit, one approach is concentrating solar incident on a large area to a small enough area to increase solar energy intensity. Therefore, many types of concentrators were invented such as parabolic trough concentrators, parabolic dish concentrators, lens concentrators, central tower concentrators, Fresnel concentrators and so on. However, all the concentrators require accurate tracking systems to ensure that solar radiation can be concentrated on the receiver precisely. Tracking error has directed and significant influence on solar collectors' performance. To remove the effect of tracking error, compound parabolic concentrators (CPCs) were investigated to collect considerable amount of solar energy without tracking systems.

The non-imaging CPC was designed in the 1960s and it is developed by Winston. It consists of two parabolic reflectors at the two ends of the absorber. The 2-D CPC have an ability to receive radiation through a very big angular spread and also stay focused onto a linear receiver. The main purpose of the design was to collect as much as possible rays and then direct them by reflection for heat up heat exchanger or send direct to PV cells collectors for electricity production. CPC is a non-imaging concentrator, which is not require for rays to be parallel or aligned with the axis of the concentrator.

A compound parabolic concentrator (CPC) combined with evacuated tubular collector use air as working fluid is designed to supply hot air at high and moderate temperature. Liu et al. (2013) experimentally investigated that solar collector integrated with open thermosyphon has a better performance in terms of thermal efficiency. Mishra et al. (2015) have been experimentally validate the thermal modelling of evacuated tubular collector (ETC) integrated with compound parabolic concentrator (CPC) have been performed which is very useful in the preheating processes for very high temperature industrial applications. Bellos et al. (2015) have designed and simulated the CPC with an evacuated tube, while both an optical and thermal analysis has been conducted and also compared thermal efficiency between pressurized water and thermal oil as working fluids is presented for different operating conditions.

The performance of the integrated collector storage solar water heater ICSSWH can be improved by employing compound parabolic concentrator (CPC) collector. Compound parabolic concentrators (CPCs) play a vital role in the low temperature applications. Most of the beam and diffuse radiations can be collected and reflected on the absorber surface. ICSSWH with flat type storage tanks require well-built structure to resist the pressure of water mains. The cylindrical water tanks can be directly connected to the water mains. In 2004, Kalogirou, reviewed the applications of different types of solar collectors and also presented the developments in CPC. Recently Shukla et al. reviewed the developments in solar water heaters and also presented the progresses in solar water heaters and highlighted the design developments in CPC. This work critically reviews the research progresses in the CPC and its development in solar water heating which has not been reported so far.

1.1 PRACTICAL DEVELOPTMENT OF CPC

The major objective of using concentration in solar thermal collectors is to enhance the performance by reducing heat losses. Nevertheless, use of a spectrally selective coating and evacuated absorbers reduced a considerable quantity of heat losses. Unlike other solar concentrators, CPCs provide efficient conversion of solar energy to thermal energies at temperatures well above 200 ºC without requiring elaborate tracking system. The selective coatings with an emittance, approximately 0.1 or less significantly suppress the conduction and convection losses. The vacuum insulation in the infrared region of 1.33×10^{-4} Pa or less reduced greatly these losses. Hence the low concentration achievable with CPCs results in a collector with excellent thermal efficiency for a stationary non-tracking collector. Over the past 30 years, researchers have been worked on the design and development of CPC incorporated with non-evacuated and evacuated absorbers. The forthcoming sub details, the various developments of CPCs over the years and also their potential applications.

CPC without evacuated tube absorbers

In 1960, Winston discovered CPC and it was accepted for solar energy collection in the USA in 1974. CPCs are non-imaging concentrators and they have the capability to reflect all the incident radiation to the absorber. A fully stationary CPC (C=1.6) with a non-evacuated absorber (ε=0.9) delivered the thermal efficiency of 19.7% at T_{abs} = 110 ºC. Comprehensive treatment of radiation and convection heat losses through a CPC incorporated with a flat absorber was discussed by Rabl. Winston et al. confirmed that the conduction losses between absorber and reflector can be reduced by creating gaps between them. The results showed that the modified design considerably reduced conduction losses. Various practical problems in the design of CPCs such as the choice of a receiver type, optimum method for fixing a gap between receiver and reflector to decrease the optical as well as thermal losses and the effect of a glass cover around the receiver were discussed by Rabl et al.

The shape of the absorber has a significant effect on the performance of CPC. To enhance the thermal and optical performance of CPC, different shapes of absorbers were proposed. Use of a CPC solar collector with a curved inverted-Vee absorber fin was proposed by Norton et al., and found that the modified absorber geometry can significantly reduce the gap optical losses. Keita et al. compared the performance of two similar CPCs with single and segmented absorbers. The results confirmed that the performance of the segmented absorber was about 13% higher compared to the non-segmented absorber. Carvalho et al. presented an analysis of a CPC solar collector with an inverted V shaped receiver. The results show that system could perform better than flat plate collectors and evacuated tubes. Tripa-nagnostopoulos et al. presented an analysis on CPCs with four channel absorbers. These absorbers could attain effective operation at a temperature in the range of 100 to 200 ºC. Kothdiwala et al. carried out experimental studies on an asymmetric inverted absorber line axis compound parabolic concentrating collector (IACPC) under a solar simulator. It was reported that IACPC could achieve a maximum stagnation temperature of 109 ºC and 157 ºC with and without water, respectively in the absorber. Tripanagnostopoulos et al. designed and investigated a non-evacuated stationary CPC with flat bifacial absorbers. Experimental results showed that solar collectors had obtained maximum efficiency of about 0.71. Several experimental studies were carried out on the CPC solar collector to improve its thermal performance. Cairo et al. designed and tested a refrigerant charged CPC under non-boiling, boiling and superheated conditions. They concluded that the performance of the refrigerant charged CPC was better than a flat plate solar collector. Khonkar and Sayigh created multi-cavities with high solar intensities at the circumferential area of the tubular absorber of a CPC, to reduce the radiation losses. Eames and Norton introduced a baffle into the cavity of a non-evacuated CPC. The result shows that convection heat loss and optical efficiency could be considerably decreased.

CPC with Evacuated tube absorbers

In 1970, Argonne National Laboratory designed a first generation of the evacuated compound parabolic concentrator in which external compound parabolic concentrator (XCPC) incorporated with a Dewar-type evacuated tube. It comprised of two concentrating glass tubes, and the spaces between the tubes were evacuated. The outside surface of a glass tube was coated with selective surface. This tube was inserted into a larger-diameter domed glass tube. Sanil et al. developed an Integrated Stationary Evacuated Concentrator (ISEC). It comprised of vacuum insulation; selective coating and compound parabolic concentrator combined together as a single unit that made an evacuated tube into the CPC. It was reported that the system could achieve optical and thermal efficiency of 65% and 50% respectively. Kim et al. compared the performance of the tracking and stationary types of evacuated CPC solar collectors. The results showed that the thermal efficiency of the tracking type of evacuated CPCs was 14.94% higher than the stationary type of evacuated CPCs. Nkwetta et al. conducted a comparative study between a flat single-sided absorber within a CPC (SSACPC) and a double-sided absorber within a CPC (DSACPC). Both the models were coupled with the heat pipe. They concluded that the performance of the DSACPC was better. Li et al. have compared two truncated external CPC (XCPC) solar energy collectors incorporated with the U- shape evacuated tube. Both the models have different half-acceptance angles and concentration ratios and it was found that the daily thermal efficiency of 6 CPC was significantly better.

2. DESCRIPTION AND WORKING OF CPC REFLECTOR

Description

A compound parabolic collector has the highest possible concentration permissible by thermodynamic limit for a given acceptance angle. Due to large acceptance angle helps in intermittent tracking towards the sun. A compound parabolic collector is mostly orientated with its long axis along the east– west direction and for a location in northern hemisphere; its aperture is tilted towards south, in order to that the sun rays are incident on compound parabolic collector aperture. The tilt of the compound parabolic collector has to be adjusted periodically when the incident solar radiation moves outside the acceptance angle of the collector.

CPC's basically consists of three elements:

Receiver: The receiver must have the high value of absorptance for solar radiation and also must be constructed with high-conductivity metals in order to conduct efficiently the absorbed heat into the heat transfer fluid. Most receiver materials don't have a very high absorptance so they need to be covered with special solar selective surface coatings materials. A solar coating like Solkote (Make: Solec, US) these losses can be reduced substantially (Absorptivity=0.9137 and emissivity=0.244) had been applied on the surface of the receiver. For good absorptivity, receiver must be cleaned properly.

Cover: The cover is a transparent insulation that permits the solar radiation to the reflector and receiver which having a high transmittance of solar radiation, and a low transmittance of the thermal radiation; also, it should have high durability and low cost.

Reflector: Usually the non-imaging reflectors are CPC reflectors. It is made up of a metal sheet or aluminum sheet with high reflectivity (90% to 95%). Reflector reflects maximum amount of sun's radiation towards the receiver. Reflector should be cleaned frequently in order to achieve good reflectivity. Its use to focus beam-solar radiation onto the receiver, which is placed at the focus of the system. aluminum sheet was used to construct the reflector sides. For achieving the best CPC performance, each material component was carefully selected. The general range of Concentration Ratio for a CPC reflector is around 3 –10.

Design of Compound Parabolic Concentrator.

Mostly for designing the CPC the parabolic or truncated method are used, but for optimization we are used the involute method to modify the shape and reducing occupied area.

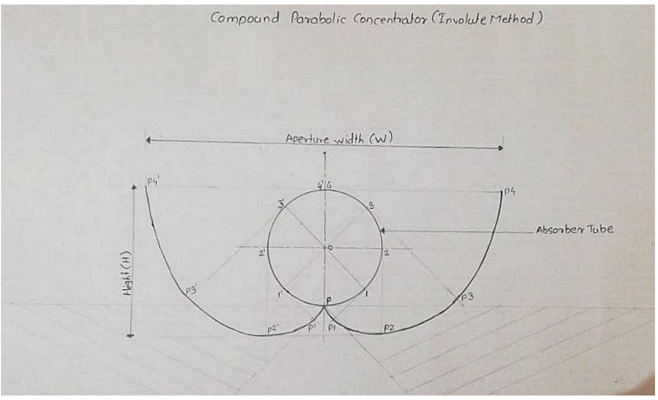


Fig. 1: Basic sketch of CPC

Working of a compound parabolic concentrator

Compound parabolic concentrator (CPC) is a solar energy collector. It collects and focus large amount of solar radiation onto a smaller area with minimum loss. Compound parabolic collector (CPC) is also called as of non-imaging collector.

Compound parabolic concentrators can collect incoming solar radiation over a wide range of angles. With the help of multiple internal reflections, any radiation that is getting into the aperture in between the collector acceptance angle, finds its way to the absorber surface located at the bottom of the collector. The absorber can be cylindrical or flat

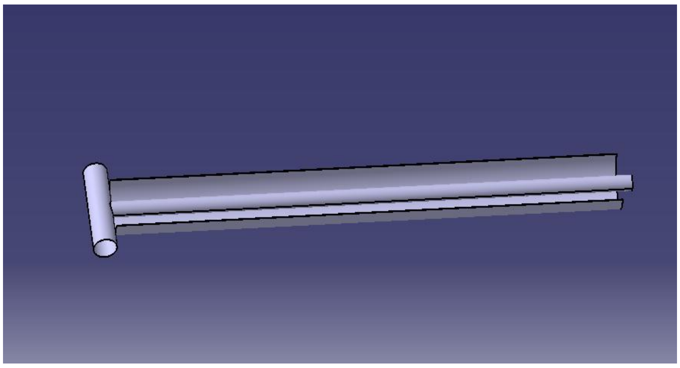


Fig.2 Basic Shape of a Compound Parabolic Collector (a)

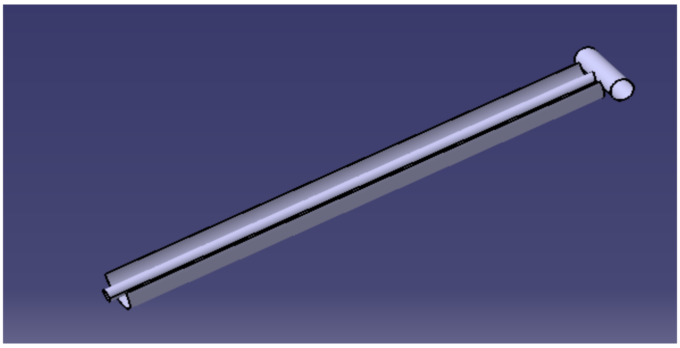


Fig.3 Basic Shape of a Compound Parabolic Collector (b)

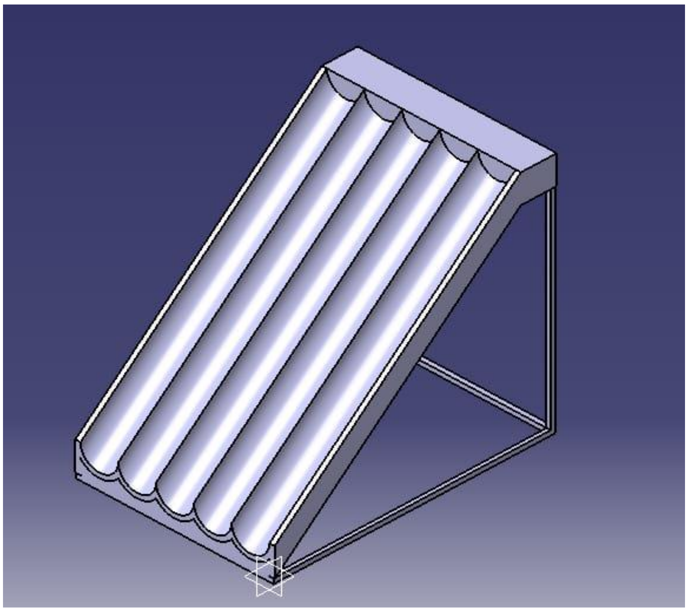


Fig. 4 Frame assembled with five CPCs

3. ANALYSIS OF COMPOUND PARABOLIC COLLECTOR

3.1 Geometry of collector

Half Acceptance angle **(θ_a) = $\sin^{-1}$ (1/C)**

The concentration ratio of the collector

C = W/b = (Aperture width/Absorber width)

The surface area of the concentrator

(A_{conc}/WL) = 1+C For the concentration ratio value C > 3

3.2 The Declination (δ)

$$\delta = 23.45 \sin [(360/365)(284 + n)]$$

Where n is the day of the year.

3.3 Heat Transfer Coefficient on inside surface of the Absorber Tube (h_f)

$h_f = (N_u*K)/D_i$

Reynolds number (R_e) = $(4m/\pi D_i \mu)$

Nusselt number (N_u) = $0.023 * R_e^{0.8} * Pr^{0.4}$

3.4 Solar Radiation on Tilted Surfaces

Beam Radiation

For this case of a tilted surface facing south

$$\cos\theta = \sin\delta \sin(\phi-\beta) + \cos\delta \cos\omega \cos(\phi-\beta)$$

While for a horizontal surface

$$\cos\theta_z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega$$

$$r_b = (\cos\theta / \cos\theta_z)$$

3.5 Total flux entering the aperture plane

$$S = [I_b r_b + I_d /C] \rho_e \tau \alpha$$

3.6 Effective Reflectivity (ρ_e) = ρ^m

Rebl has also shown that the average number of reflections m for all radiation falling inside in the acceptance angle, before reaching the absorber surface, is given by the expression

$$M = [(1/2\sin\theta_a)(A_{conc}/WL)] - \{[1-\sin\theta_a (1+2\sin\theta_a)] / [2\sin^2\theta_a]\}$$

3.7 Overall loss coefficient (U_L)

Rebl has estimated the value of U_L for different values of the absorber plate temperature, plate emissivity and the concentrator ratio. It is seen that they vary from 4 to 19.4 W/m^2.

3.8 Collector efficiency factor (F')

$$(1/F') = U_L [(1/U_L) + (b/N\pi D_i h_f)]$$

3.9 Heat Removal Factor (F_R)

$$F_R = (mc_p) \{1- \exp[(-F' b U_L L)/(mc_p)]\}$$

3.10 Useful heat gain rate

$$q_u = F_R WL \{[S - (UL/C)(T_{fi}-T_a)]\}$$

3.11 Heat transfer rate

$$q_u = mc_p\Delta T = m*c_p*(T_{fo} - T_{fi})$$

3.12 Thermal Efficiency

The instantaneous efficiency can be calculated on the basis of beam radiation

$$\eta = [q_u /(A_a*I_b)]$$

4. RESULTS

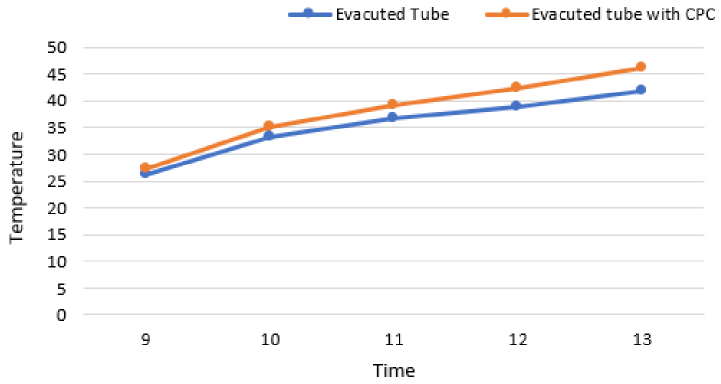
Table 1: Hourly variations of solar intensity and various temperatures of evacuated tube.

Time(h)	I(t) (W/m^2)	T_a(^{0}C)	T_{in}(^{0}C)	T_{out}(^{0}C)
9	510	25.3	25.3	26.2
10	750	31.5	31.5	33.3
11	895	33.7	33.7	36.8
12	976	34.5	34.5	38.8
13	1003	37.3	37.3	41.8

Table 2: Hourly variations of solar intensity and various temperatures of evacuated tube integrated with CPC reflector.

Time(h)	$I(t)$ (W/m^2)	T_a (^0C)	T_{in} (^0C)	T_{out} (^0C)
9	530	25.0	25.0	27.3
10	790	32.4	32.4	35.2
11	910	34.2	34.2	39.2
12	980	36.1	36.1	42.5
13	1024	38.2	38.2	46.1

Chart 1: Variation of outlet temperature over time.



5. CONCLUSIONS

On the basis of present studies following conclusions have been drawn:

It is concluded that 1) CPCs have relatively low concentration ratio compared with tracking concentrators but are able to collect both beam radiation and diffuse radiation without complex tracking systems; 2) the profiles of CPCs should be determined individually according to different types, sizes and placement of receivers. Edge-ray principle is usually utilized for CPC design; 3) ray tracing is the most widely used technique in optical modeling; 4) The maximum difference of air temperature between inlet and outlet in evacuated tube with CPC reflector is found to be 10 ^{0}C, whereas it is about 6 ^{0}C in evacuated tube without CPC.5) CPC is a promising collector design which can be adopted in various applications; however, issues on cost, designs for industrial manufacture and maintenance demands further investigation to be solved.

6. NOMENCLATURE

A_{conc}	Surface Area of the Concentrator, m^2
b	Absorber Surface Width, m
C	Concentration Ratio
C_P	Specific Heat of Water, J/kg K
D_i	Tube Inner Diameter, m
D_o	Tube Outer Diameter, m
F′	Collector Efficiency Factor
F_R	Heat Removal Factor
h_F	Heat Transfer Coefficient on inside surface of the tube. W/m^{2}K
k	Thermal conductivity, W/m K
L	Length of the Collector, m
$\dot{m}$	Mass Flow Rate of Fluid, kg/hr.
n	Day of the year
N	Number of Tubes
Nu	Nusselt number
Pr	Prandtl number
q_u	Useful heat gain rate, W
r_b	Tilt factor
Re	Reynolds number
S	Total flux entering the aperture plane
T_{fo}	Outlet temperature, ° C
T_{fi}	Inlet temperature, ° C
T_a	Ambient Temperature, ° C
U_L	Overall Loss Coefficient
W	Aperture Width, m

Greek symbols

A	absorptivity of absorber surface
β	the slope
δ	the declination angles
ε	emissivity
η	efficiency
μ	viscosity, N s/m^2
ω	hour angle
ϕ	the latitude
ρ	reflectivity
ρ_e	effective reflectivity
θ_a	half acceptance angle
τ	transmissivity of glass cover

Subscripts

a	acceptance
conc	concentrator
e	effective
fo	fluid outlet

fi	fluid inlet
fm	mean fluid
i	inner
l	loss
o	outer
u	useful

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