Compound Parabolic Concentrator

Parikh Aradhya Anil

Roll No.: 10105066

M. Tech – Solid Mechanics and Design

Mechanical Engineering Department

Indian Institute of Technology, Kanpur

Kanpur – 208016

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ABSTRACT

Compound Parabolic Concentrators (CPC) is used in industrial application where medium pressure steam at around 150ºC is required. Flat Plate Collectors are not efficient enough to deliver water at temperature more than 100ºC. Hence Concentrating Collectors are used. The name CPC may suggest that this collector also belongs to the family of focusing collector, but in fact this is more alike to FPC, due to its mostly fixed orientation and medium temperature water delivery.

The tracking if needed can also be provided. Apart from water heating, CPC has application in the field of power generation, solar air conditioning, etc. As the CPC are different to the conventional concentrating collectors, their principle of working, collector efficiency, construction need to be studied. In the following seminar detailed study about the CPC has been made.

Keywords: Solar Collector, water pasteurization

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NOMENCLATURE

The following are the meaning of symbols / letters appearing in the report.

Symbol	Meaning	Unit
T	transmittance of the transparent covering	--
A	absorbance of the absorber plate	--
T_f	average temperature of the fluid	ºC
T_a	ambient temperature	ºC
I_b	incident global radiation on the collector	W / m^2
A	collector surface	m^2
UL	global coefficient of losses	--
H_{refl}	height of the reflector	m
C	concentration factor of the sun	--
θ_c	Acceptance half-angle of the CPC	--
C_p	specific heat	kJ/kg- K
w	width of the aperture	m
B	width of the absorber	m

CHAPTER 1: CONCENTRATING COLLECTORS

1.1 Introduction

Collector is that part of the solar heating system where the solar energy is incident and is collected and then reflected to the receiver. A concentrating collector further focuses the solar energy on the receiver resulting in higher thermal efficiency and generating larger temperatures. The word **collector** is applied to the total system including the receiver and the concentrator. The receiver is that element of the system where the radiation is absorbed and converted to some other energy form; it includes the absorber, its cover and the insulation. The concentrator is the part of the collector that directs radiation to the receiver.

Concentrating collectors are require where the temperature requirement are above 100ºC. Applications of concentrating collectors lie in medium or high temperature energy conversion cycles and for supplying industrial process heat at intermediate temperatures from 100ºC – 400ºC, or even higher temperature above 400ºC. They have also potential application in photovoltaic utilization and power generation of the solar energy.

Compound Parabolic Concentrator (CPC) is a special type of solar collector fabricated in the shape of two meeting parabolas. It belongs to the non-imaging family, but is consider among the collector having the highest possible concentrating ratio. Also because of its large aperture area, only intermittent tracking is required.[1]

In the following seminar, first a brief classification of several concentrating collector has been made. Then Compound Parabolic Concentrator is discussed. The working, construction and application of CPC are then discussed. Finally the comparison of CPC with Flat Plate Collector (FPC) and other Concentrating Collectors like Parabolic Trough Collector and Parabolic Dish Collector is made. The relative advantages, disadvantages and field of application are then discussed.

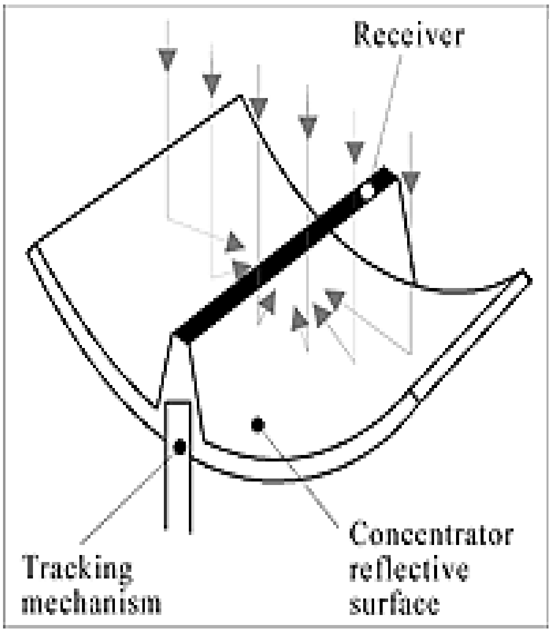

Fig 1: Cylindrical Parabolic Concentrator[1]

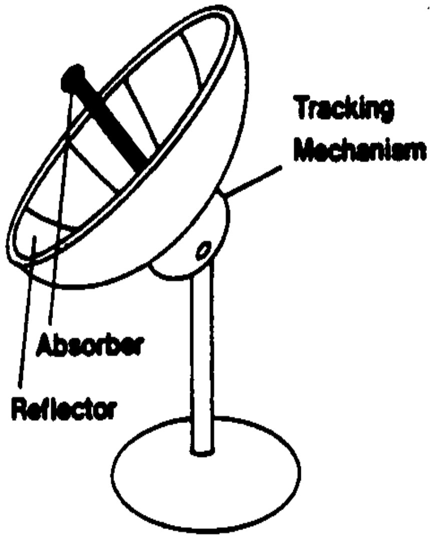

Fig 2: Parabolic Dish Collector[1]

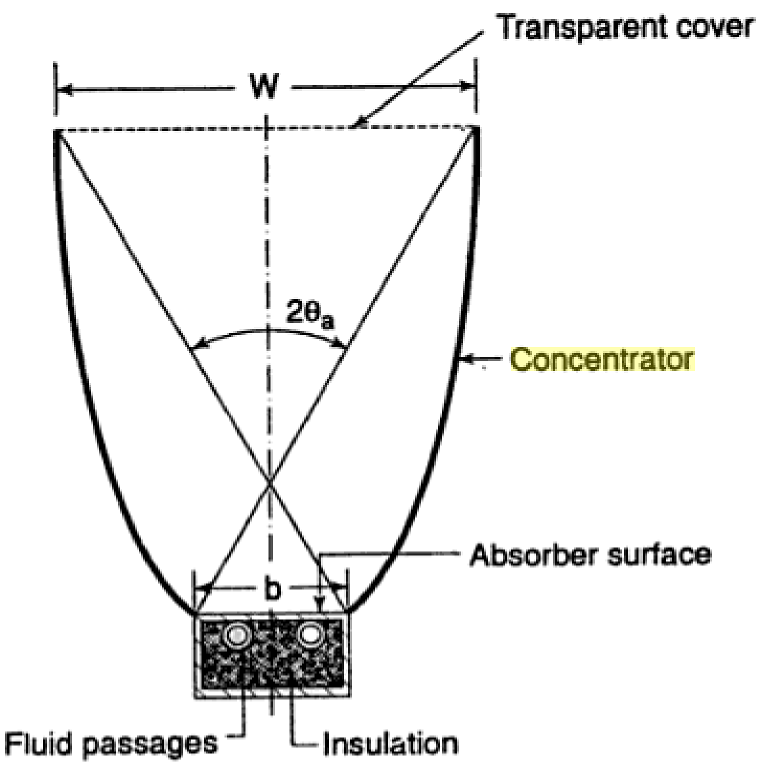

Fig 3: Compound Parabolic Concentrator[1]

1 Understanding Solar Concentrators by George Kaplan.

1.2 Classification of Concentrating Collector

The different concentrating concentrators are generally classified as under:

1. Focusing and Non-Focusing type. Whether the Collector focuses the solar radiation on the absorber or just diverts it. Focusing type collectors are further classified in line focusing and point focusing collector.
2. Tracking and Non Tracking type: Whether the Collector is provided with Tracking Mechanism so that it can follow the sun or is of Fixed Orientation. Tracking type is further classified as Single axis tracking and Double axis tracking. Tracking can be intermittent (daily or weekly tracking) or Continuous Tracking.
3. Concentrating Ratio achievable. Concentration ratio achievable can be between 1 (limiting value for Flat Plate Collector) to 10,000 (Parabolic Dish Collector). Concentration ratio also approximately determines the operating temperature of the collector.

In this seminar the collector that can be compared with Compound Parabolic Concentrator are discussed. They are

1. Cylindrical Parabolic Concentrator: it is conventional imaging collector. It focuses the solar energy on a line, through which water flows. The aperture areas vary from 1 – 6m^2. The concentration ratio is in the range of 10 – 80. Temperature up to 400ºC can be obtained. A simple working model is shown in figure 1.

2. Parabolic Dish Collector: This is similar to cylindrical parabolic concentrator except here the focusing is point focusing instead of line focusing. Hence a very high concentration ratio is achieved. The delivery temperature created by this collector is the highest among all the collectors around 600ºC. Figure 2 describes the working of Parabolic Dish Collector.

A more sophisticated parabolic collector trough can be designed, that avoids the need to track the sun altogether, by combining two parabolas together, to form the "Compound Parabolic Trough Solar Collector." When this is done, the co-focal point then becomes a co-focal line. If a coolant filled pipe solar energy absorber pipe, or a tubular evacuated tube solar energy absorber tube is co-located at the co-focal line, there will then be a maximum of concentrated solar energy delivered and transferred to the energy absorber tube! Such solar collectors do not need tracking, and require only occasional season angle adjustments (several times a year) are required to keep the aperture perpendicular to the noonday sun, to the maintain maximum power output![2]

By selecting non-imaging optics we can thus avoid the need to keep the collector aperture pointed at the sun. Instead, we can collect and concentrate Solar Energy from multiple directions separately or at once. So while the sun moves across the sky, we can still accept and concentrate the Solar Thermal Energy all day using a properly designed compound Parabolic Trough Concentrating Solar Collector coupled with Evacuated (vacuum) tube Solar energy Capture Tubes. Using this type of collector, the output energy of a Solar Energy Capture Tube can be increased by a factor of 4- 6 times using a stationary solar collector.

1.3: Definition of Terms that characterize Concentrating Collectors[3]

Underneath are some of the terms that are present when discussing Concentrating Collectors.

1. Aperture Area (A_a): It is the plane opening of the concentrator through which the incident solar flux is accepted.
   For a cylindrical or linear concentrator it is characterized by the width, while for a surface of revolution it is characterized by the diameter of opening.

2. Absorber Area (A_{abs}): It is the total area receiving the concentrated radiation. It is also the area from which useful energy is delivered to the system

3. Acceptance Angle ($2\theta_c$): It is the limiting angle over which incident ray path may deviate from normal to the aperture plane and still reach the absorber.
   Concentrators with large acceptance angle need to be moved on seasonally while concentrators with smaller acceptance angle need to be moved continuously to track the sun.

4. Geometric Concentrating Ratio (C): It is the ratio of effective area of the aperture to the surface area of the absorber. Value of concentrating ratio varies from 1 (limiting value for a flat plate collector) to few thousand (for a paraboloid collector).

   $$C = A_a / A_{abs}$$

5. Local Concentration Ratio: It may so happen that the absorber in some systems may not be fully or uniformly illuminated, thus in order to characterize this local concentration this term is defined. It is defined as the ration of flux arriving at any point on the absorber to the incident flux at the entrance aperture of the concentrating system.

6. Intercept Factor (Y): It is the fraction of focused energy intercepted by the absorber of a given size. For a typical concentrator receiver design its value depends on the size of absorber, generally is has a value greater than 0.9. However if the radiation is normal to the aperture, its value is 1.

7. Collector (Thermal) Efficiency (η_c): It is the ratio of the useful energy delivered to the absorber to the energy incident on the aperture.

$$\eta_c = q_u / I_b$$

q_u is the rate of useful energy per unit aperture area and
I_b is the incident solar energy

8. Optical Efficiency (η_o): It is defined as the ratio of the energy absorbed by the absorber to that incident on the collector.
It includes the effect of mirror surface, shape, transmission losses, tracking accuracy, shading by receiver, absorption and reflection properties, solar beam incident angle.

$$\eta_o = q_u / (\alpha\tau I_b)$$

q_u is the rate of useful energy per unit aperture area
I_b is the incident solar energy and
α, τ are the function of angle of incidence of radiation on the aperture

The useful energy per unit aperture area delivered to the absorber is given by:
q_u $= \eta_o I_b - U_c(CR)(T_c - T_a)$

U_c, is the heat loss coefficient based on receiver area,
T_a and T_c are the ambient temperature and collector temperature

The concentration ratio is limited as the sun is of finite size, determined by the shape factor; the concentration ratio for 2-D collector like cylindrical parabolic collector is limited by the value $1 / \sin \theta_{max}$. If the acceptance angle is equal to θ_{max}, the concentration ratio comes to be about 210. Similarly for 3-D collector as parabolic dish, concentration ratio can be as high up to 10,000.

CHAPTER 2: COMPOUND PARABOLIC CONCENTRATOR

2.1 Compound Parabolic Concentrator

The Compound Parabolic Concentrating Collector is non-imaging like a flat plate collector. The collector concept was originated by Winston in 1978. The concentration ratio up to 10 can be achieved in the non-tracking mode easily. Thus it leads to cost savings. A lot of work has been done in the field of compound parabolic concentrator by Rabl and Kreith.

It is one of the collectors which has the highest possible concentration permissible by thermodynamic limit for a given acceptance angle. Its **large acceptance angle** results in intermittent tracking towards the sun.

2.2 Construction and working of CPC[3]

The geometry of a CPC is shown in figure 4. It has two parabola sections AB and CD of parabola 1 and 2 respectively. AD is the aperture area with width *w*, while BC is the absorber area with width *b*. the axis are oriented in such a way that C is the focus of parabola 1 and B is the focus of parabola 2. Also the height of the collector is so chosen that tangents at A and D are parallel to the axis of the collector.

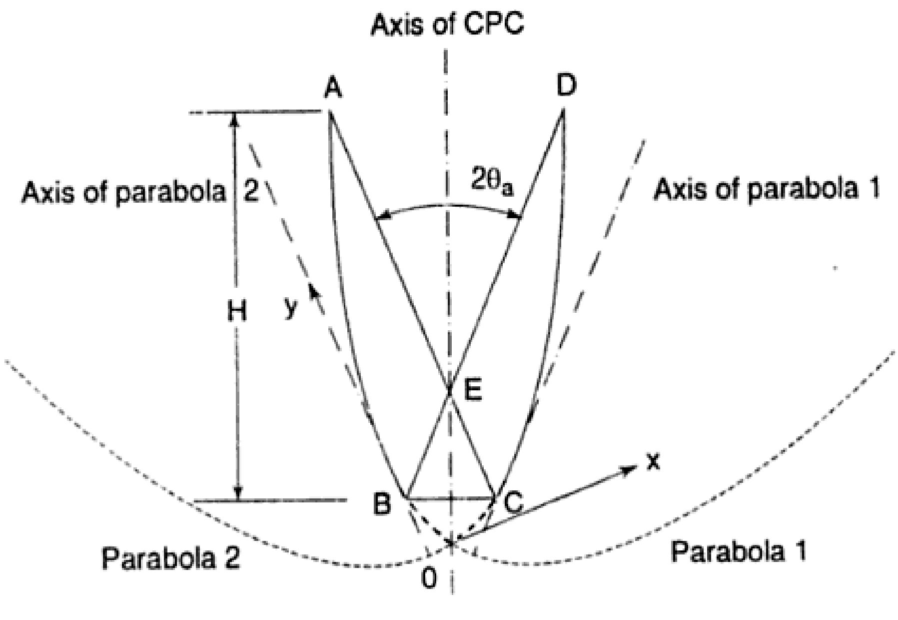

Fig 4: Construction of a Compound Parabolic Concentrator[1]

1 Solar Energy - by S P Sukhatme

The acceptance angle of the CPC is the angle AED. It is obtained by joining the focus to the opposite aperture edge. The concentration ratio is given by *w/b*. The height and aperture area for a CPC are calculated as per the desired operating temperature. To reduce the cost the height is generally truncated to half as it doesn't much affect the concentration ratio. The acceptance angle is also generally kept large so that tracking may be required intermittent only. The optical efficiency for CPC is around 65%, which is 8% more as compared to a parabolic trough collector.

For a concentrating collector the amount of diffused radiation that can be collected is given by 1 /CR. The general Concentration Ratio for a CPC is around 3 – 10, while that for PTC and Parabolic Dish Collector is more than 1000. Thus the advantage of a CPC is that it can collect diffuse radiation too. Thus its performance is satisfactory in cloudy atmosphere too.

2.3 Different Absorber Shape[4]

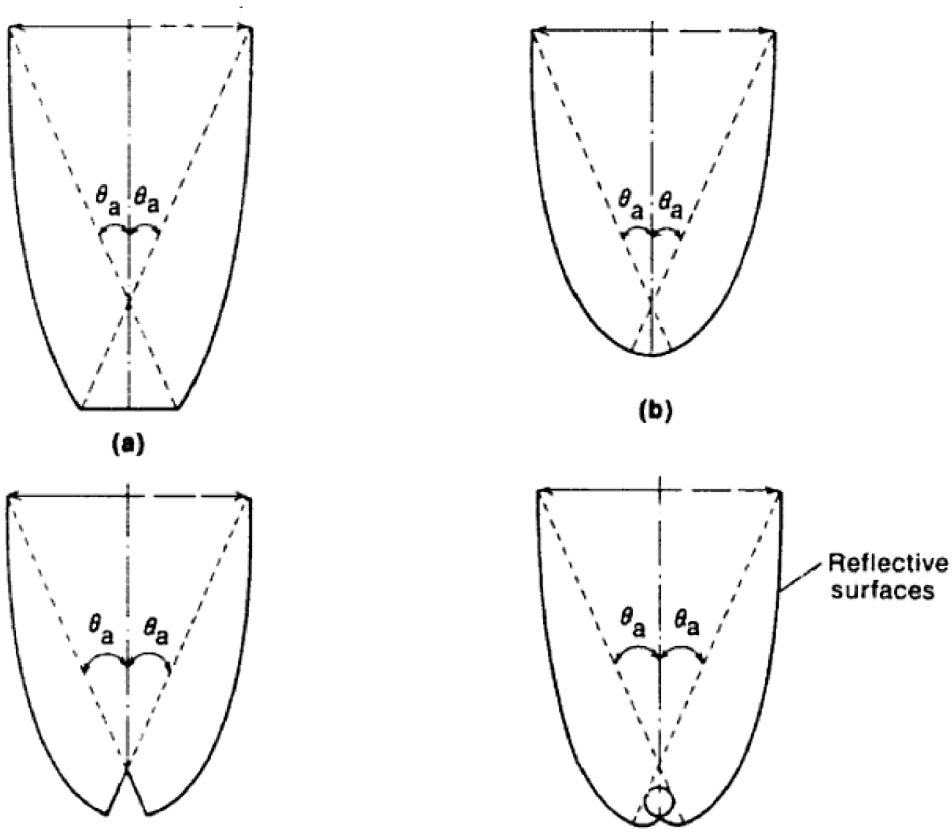

Fig 5: Different absorber shape (a) basic CPC, (b) fin receiver, (c) bifurcated fin receiver, and (d) tubular receiver[2]

2 Solar Power Engineering by B S Magal

Now for a particular desired temperature, the height and aperture area of CPC are determined from the available equation. Now even if CPC is truncated to half of the size, the collector efficiency won't suffer much, as the edge of the CPC were nearly parallel to the axis of the collector. The different absorber shapes that are presently used with a CPC are shown in the figure.

2.4 Second Stage Concentrator[5]

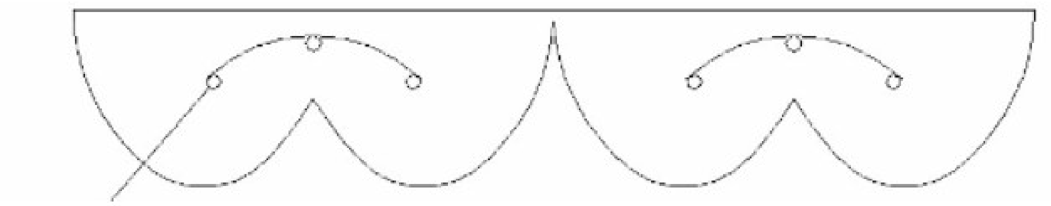

Fig 6: Second stage Concentrator

Compound Parabolic Concentrators are mostly used in two stages concentrating devices. Two stage concentration means that solar energy concentrated from another collector as heliostat or parabolic dish is further concentrated by CPC to increase the Concentration Ratio up to 40,000. Two stages concentrator is generally used in the following places:

1. Solar Tower: The solar energy concentrated by Heliostat located in the area of $2km^2$ is further concentrated by the CPC so that the concentration ratio becomes very high along with the increase in collector efficiency.
2. In industries to increase the efficiency of CPC, they are used in conjunction with parabolic collector as shown in figure. The solar rays are hence accurately focused on a very infinitesimal area thus increasing the efficiency.
3. Also asymmetric CPC are used with flat absorber such that all of the reflected radiation is absorbed at the bottom of the absorber.

Thus 2-Stage Concentrator is used where collector efficiency, not the capital, is the requirement.

CHAPTER 3: COMPARISON WITH OTHER COLLECTORS

3.1 Application of Compound Parabolic concentrator

CPC found their application in the following field

1. In solar still (water pasteurization) – to remove impurity or microbes from the water[6]
2. In solar water heating – for domestic water heating purpose in buildings
3. In power generation – in photovoltaic cells
4. In solar cooking

The figure shows the general working of compound parabolic concentrator as solar water distillation.

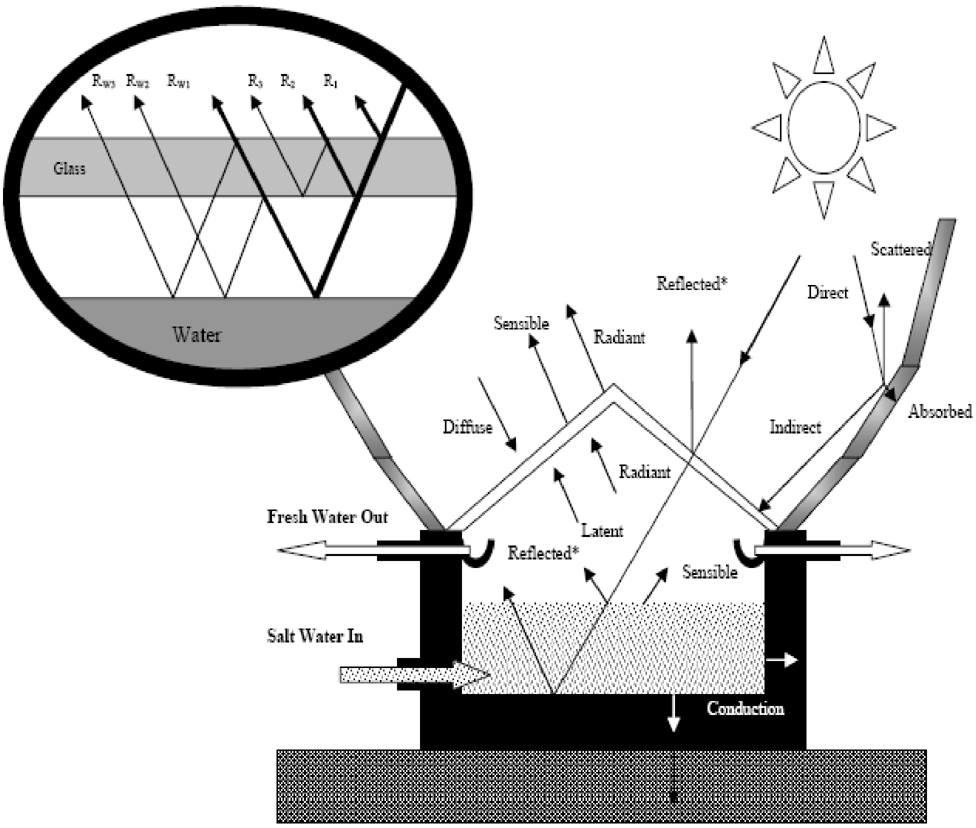

Fig 7: CPC used in Solar Still Plant[1]

1 Numerical Simulation of the direct application of Compound Paraboloic Concentrators to a single effect solar still basin by Joshua Pearce and David Denkenberger

3.2 Tracking of CPC[5]

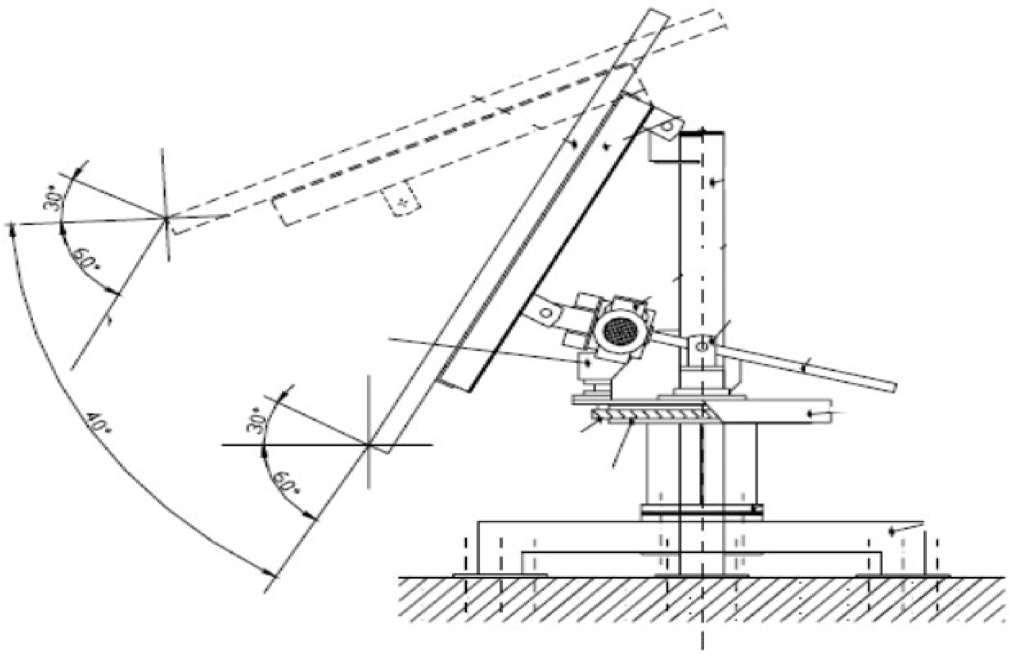

Fig 8: Tracking of a CPC through hydraulic circuit[2]

Tracking of a CPC as discussed earlier may not be required if the CPC has concentration ratio of 3 – 5, and high acceptance angle. Also CPC are generally oriented in the East – West direction with south facing aperture area, so that the maximum sunlight is utilized. However for application where the concentration ratio is very high or the acceptance angle is less, than tracking is to be provided to ensure that sunlight falls continuously on the CPC.

A tracking device for a CPC is shown in the figure. The tracking is done by hydraulic circuits and is single axis tracking. The CPC in the figure is used for domestic water heating purpose in buildings. The efficiency was found to increase by providing tracking and the maximum efficiency attained was 72%.

The tracking that can be provided for a CPC can be continuous or intermittent. Intermittent tracking is required when the acceptance angle is large and the tracking is required only due to the change in inclination of the earth.

2 Solagua, a Non-static Compound Parabolic Concentrator for Residential Buildings by P. Gata Amaral, E. Ribeiro, R. Brites and F. Gaspar.

3.3 Comparisons with Flat Plate Collector[7]

1. Both are generally used without solar tracking.
2. Receiver area reduces for the same output temperature desired. The cost per unit area of solar collecting surface hence decreases. Also the insolation intensity increases.
3. Heat storage costs are less due to the higher temperature achievable.
4. Temperature up to 300ºC - 350ºC can be obtained using CPC with vacuum coating. The flat plate collector can deliver heated water up to 90ºC.
5. Hence FPC is generally used for domestic solar water heating, while the application of CPC lies even in industrial process and power generation.
6. The radiation losses are less in case of CPC, but optical losses like intercept loss, reflectance losses are present
7. Collector efficiency increase due to reduction in absorber size.
8. Difficult to fabricate and also the maintenance costs are higher as CPC needs frequent cleaning.

3.4 Comparisons with other Concentrating Collectors[7]

1. CPC can concentrate diffused radiation, other concentrating collectors as parabolic trough and parabolic dish only concentrates the beam radiation component on the solar radiation. The component of diffused radiation that can be collected is given by 1 / CR. As the concentration ratio for CPC is lower, it can concentrate diffused radiation.
2. Generally the CPC are of larger acceptance angle and are oriented in the east-west direction. Hence only intermittent tracking every 15 days or even up to every 2 months (for concentration ratio 3 – 5) is needed. For good performances of parabolic trough and parabolic dish, a continuous tracking is required.
3. Parabolic dish collector can deliver temperature up to 500ºC
4. Hence CPC are economical as compared to the other concentrating collectors.

CONCLUSION

From the different referred Technical Papers, it can be concluded that

1. CPC is generally used for medium pressure steam delivery, at around 150°C - 200ºC. These operating temperature are easily achieved by CPC as compared to FPC or PTC.

2. CPC are used in Solar Still Plant and Water Pasteurization, they make the process very economical.

3. For CPC with larger acceptance angle, tracking may not at all be required. However intermittent tracking from 2 days period to 2 months period may be required for applications requiring higher Concentration Ratio

4. For domestic water heating too CPC is an alternate option. The high initial cost can be balanced if the hot water requirements are very high and all through the year, ie in the polar region and in buildings

5. Comparison with Cylindrical Parabolic Collector and Parabolic Dish Collector[1]

Type of Concentrator: **Parabolic Dish Collector**	Type of Concentrator: **Parabolic Trough Collector**	Type of Concentrator: **Winston Collector (CPC)**
Type of Focus : Point	Type of Focus : Line	Type of Focus : Line
Lens or Mirror : Mirror	Lens or Mirror : Mirror	Lens or Mirror : Mirror
Sun's Concentration : > 1000	Sun's Concentration : 100	Sun's Concentration : 3-6
Tracking : Yes	Tracking : Yes	Tracking : No
Temperature (C) : >2638	Temperature (C) : 538	Temperature (C) : 121
Typical Application : Electricity	Typical Application : Electricity, Heat	Typical Application : Heat
Comments : Small-scale applications	Comments : Small or Large Systems	Comments : Concentration decreases as acceptance angle increases

Table 1: Comparison of various parameters for different Collectors[1]

1 Understanding Solar Collector by George Kaplan

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