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Compound Parabolic Serpentine Collector

Mr.Sekhar Vidhya Sagar
M.Tech Student
Department of Mechanical Engineering
Malla Reddy Engineering College (Autonomous)
Maisammaguda, Dhulapally, Secunderabad, TS.

Mr.V. Siva Rama Krishna
Assistant Professor
Department of Mechanical Engineering
Malla Reddy Engineering College (Autonomous)
Maisammaguda, Dhulapally, Secunderabad, TS.

ABSTRACT:

Compound Parabolic Concentrators (CPC) the main aim of this project is to fabricate a Compound Parabolic Concentrating Collector. The Compound Parabolic Concentrating Collector is non-imaging like a flat plate collector. The concentration ratio up to 10 can be achieved in the non-tracking mode easily. Thus it leads to cost savings. It can be 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 main difference in the concentrator being designed is the piping system, which uses a serpentine design. Serpentine collectors consist of a flow duct that is bonded to the absorber plate in a serpentine or zigzag fashion. Serpentine piping for the collector ensures the absorption of heat over a wide area, when compared to a Harp collector. Hence making it more efficient type of piping system for a solar collector. The project brings both the ideas together into one collector and also compare the resulting collector with the conventional flat plate collector.

INTRODUCTION

SOLAR THERMAL ENERGY

Solar Thermal Energy (STE) is a technology for harnessing solar energy for thermal energy (heat) requirement in industries, residential sector and commercial setup. Solar thermal collectors are classified as low-,medium-,or high-temperature collectors. Low-temperature collectors are flat plates generally used to heat swimming pools. Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use. Most air heat fabricators and some water heat manufacturers have a completely flooded absorber consisting of two sheets of metal which the fluid passes between. Because the heat exchange area is greater they may be marginally more efficient than traditional absorbers. Sunlight passes through the glazing and strikes the absorber plate, which heats up, changing solar energy into heat energy.

High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements up to 300oC / 20 bar pressure in industries, and for electric power production. However, there is a term that used for both the applications. Concentrated Solar Thermal (CST) for fulfilling heat requirements in industries and Concentrated Solar Power (CSP) when the heat collected is used for power generation. CST and CSP are not replaceable in terms of application. The solar collectors absorb the sun’s rays, convert them to heat and transfer the heat to a heat-transfer fluid. (The heat-transfer fluid is typically a glycol and water mixture in regions where seasonal freezing in a concern.) The heat-transfer fluid is then pumped into a heat exchanger located inside the water storage tank where it heats the water. After releasing its heat via the heat exchanger, the heat-transfer fluid flows back to the collectors to be reheated. The controller keeps the heat-transfer fluid circulating whenever there is heat available in the solar collectors. In the winter, a boiler serves as an alternate heat source. Solar thermal systems can be integrated into existing hot water systems with relative ease.

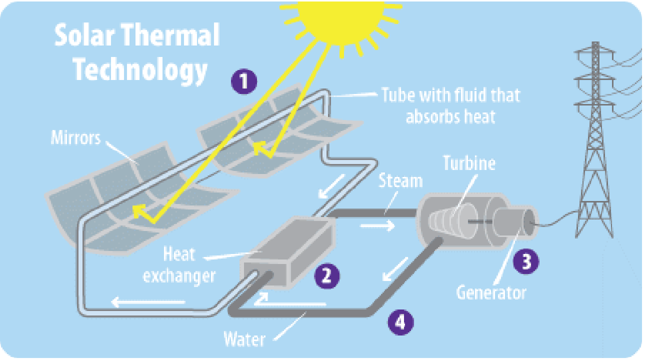


Fig 1 . Solar Thermal Power Plant

Solar thermal energy can be useful for drying wood for construction and wood fuels such as wood chips for combustion. Solar is also used for food products such as fruits, grains, and fish. Crop drying by solar means is environmentally friendly as well as cost effective while improving the quality. The less money it takes to make a product, the less it can be sold for, pleasing both the buyers and the sellers. Technologies in solar drying include ultra low cost pumped transpired plate air collectors based on black fabrics. Solar thermal energy is helpful in the process of drying products such as wood chips and other forms of biomass by raising the temperature while allowing air to pass through and get rid of the moisture. Solar cookers use sunlight for cooking, drying and pasteurization. Solar cooking offsets fuel costs, reduces demand for fuel or firewood, and improves air quality by reducing or removing a source of smoke.The simplest type of solar cooker is the box cooker first built in 1767. A basic box cooker consists of an insulated container with a transparent lid. These cookers can be used effectively with partially overcast skies and will typically reach temperatures of 50–100 °C.

Concentrating solar cookers use reflectors to concentrate solar energy onto a cooking container. The most common reflector geometries are flat plate, disc and parabolic trough type. These designs cook faster and at higher temperatures (up to 350 °C) but require direct light to function properly. The Solar Kitchen in Autryville, India uses a unique concentrating technology known as the solar bowl. Contrary to conventional tracking reflector/fixed receiver systems, the solar bowl uses a fixed spherical reflector with a receiver which tracks the focus of light as the Sun moves across the sky. The solar bowl's receiver reaches temperature of 150 °C that is used to produce steam that helps cook 2,000 daily meals.[22]

Flat Plate Collector

Flat-plate collectors, developed by Hottel and Whillier in the 1950s, are the most common type. Solar Thermal Flat Plate collectors are some of the oldest proven technology available on the market today. A flat-plate collector consists of an absorber, a transparent cover, a frame, and insulation. Usually a low iron safety glass is used as a transparent cover as it lets trough a great amount of the radiation from the sun. Simultaneously, only very little of the heat emitted by the absorber escapes the cover (greenhouse effect). In addition, the transparent cover prevents wind from cooling the absorber. Together with the frame, the cover protects the absorber from adverse weather conditions.

The absorber consists of a thin absorber sheet (of thermally stable polymers, aluminum, steel or copper, to which a matte black or selective coating is applied) often backed by a grid or coil of fluid tubing placed in an insulated casing with a glass or polycarbonate cover. In water heat panels, fluid is usually circulated through tubing to transfer heat from the absorber to an insulated water tank. This may be achieved directly or through a heat exchanger. The insulation on the back of the absorber and on the side walls lessens the heat loss through conduction. Insulation on better quality panels are usually mineral fiber insulating materials like glass wool or rock wool. Their principle of operation is relatively simple, but there have been advances in the construction technology, materials and absorber surface that are used by different manufacturers. All have a collector box, usually made of steel or aluminum sheet. The absorber plate, with tubes attached for a heat transfer fluid to pass through, placed within the box. Beneath the absorber plate is insulation to prevent the loss of heat out through the bottom of the box. Above the plate is a transparent collector cover, usually glass, which is designed to trap solar radiation and convert it to heat in the absorber plate.

WORKING PRINCIPLE OF A FLAT PLATE COLLECTOR

As Explained in the previous chapter, the main element of a flat-plate collector is the absorber plate. It covers the full aperture area of the collector and must perform three functions: absorb the maximum possible amount of solar irradiance, conduct this heat into the working fluid at a minimum temperature difference, and lose a minimum amount of heat back to the surroundings. Absorption, Solar irradiance passing through the glazing is absorbed directly on the absorber plate without intermediate reflection as in concentrating collectors. Surface coatings that have a high absorptance for short-wavelength (visible) light, are used on the absorber. Usually these coatings appear dull or "flat," indicating that they will absorb radiation coming from all directions equally well. Either paint or plating is used, and the resulting black surface will typically absorb over 95 percent of the incident solar radiation.

The second function of the absorber plate is to transfer the absorbed energy into a heat-transfer fluid at a minimum temperature difference. This is normally done by conducting the absorbed heat to tubes or ducts that contain the heat-transfer fluid. The heat-transfer fluid may either be a liquid (water or water with antifreeze) or gas (air). The important design criterion here is to provide sufficient heat transfer capability that the difference between the temperature of the absorber surface and the working fluid is not excessive; otherwise, the heat loss from the absorber would be excessive. High heat-transfer rates are usually accomplished at the expense of pumping power and absorber plate material.

When a liquid is used as the heat-transfer fluid as is most often the case, special problems occur in transferring the heat absorbed on the absorber surface into the fluid. Liquid collector absorber plates often consist of a flat sheet of metal with tubes spaced 10-25 cm (4-10 in.) apart and attached to it in some fashion (integral, brazed or press fitted). The sheet of metal absorbs most of the solar irradiance and acts as a fin to bring the absorbed heat into the fluid. The following are important points in designing a good ‘tube and sheet’ absorber:

1. The absorber sheet must he made of a material with high thermal conductivity.
2. The fin should be thick to minimize the temperature difference required to transfer heat to its tube.
3. Tubes should not be spaced too far apart; otherwise, a higher temperature difference between the tip of the absorber and the base will result.
4. Tubes should be thin-walled and of a high-thermal -conductivity material.
5. The tube should be brazed or welded to the absorber sheet to minimize thermal contact resistance.
6. The tube and absorber sheet should be of similar material to prevent galvanic corrosion between them.

When air is the heat-transfer fluid, often the back side of the absorber plate usually forms one surface of a duct and heat is transferred through the absorber sheet to the air over the entire back surface of the absorber. A thin, rather than thick, absorber sheet of high-thermal-conductivity material will enhance this heat-transfer process. The internal air passage must be designed to provide a sufficiently high airflow velocity past the back of the absorber to give adequate heat transfer without producing a high pressure drop across the collector. Low heat-transfer rates cause the absorber plate to become significantly hotter than the heat-transfer fluid, which increases heat loss. On the other hand, a large pressure drop across the collector causes high pumping power consumption by the fans supplying the air.

Because the temperature of the absorber surface is above ambient temperature, the surface re-radiates some of the heat it has absorbed back to the surroundings. This loss mechanism is a function of the emittance of the surface for low-temperature, long-wavelength (infrared) radiation. The dilemma is that many coatings that enhance the absorption of sunlight (short-wavelength radiation) also enhance the long wavelength radiation loss from the surface. This is true for most dull black paints.

A class of coatings, mostly produced by metallic plating processes, will produce an absorber surface that is a good absorber of short-wavelength solar irradiance but a poor emitter of long-wavelength radiant energy.. Flat-plate absorbers that have selective surfaces typically lose less heat when operating at high temperature, as will be seen in However, the absorptance of selective coatings is seldom as high as for non-selective coatings, and a tradeoff must be made based on whether the increased high-temperature performance overshadows the reduced low-temperature performance and expense of the selective coating. The absorber is usually covered with one or more transparent or translucent cover sheets to reduce convective heat loss. In the absence of a cover sheet, heat is lost from the absorber as a result of not only forced convection caused by local wind, but also natural convective air currents created because the absorber is hotter than ambient air. The cover sheet forms a trapped air space above the absorber, thereby reducing these losses. However, convective loss is not completely eliminated because a convective current is set up between the absorber and the cover sheet, transferring heat from the absorber to the cover sheet. External convection then cools the cover sheet, producing a net heat loss from the absorber. In addition, heat loss is reduced because of the thermal resistance of the added air space.

The number of cover sheets on commercial flat-plate collectors varies from none to three or more. Collectors with no cover sheet have high efficiencies when operated at temperatures very near ambient temperature. This is because incoming energy is not lost by absorption or reflection by the cover sheet. When no cover sheet is used, however, a considerable amount of the incident energy is lost during operation at temperatures much above ambient or at low solar irradiance levels. A typical application for an uncovered flat-plate collector is for swimming pool heating, where temperatures less than 10ºC (18ºF) above ambient are required.

Plastic cover sheets are sometimes used for the second cover sheet when two sheets are required. Installation of the plastic sheet beneath the glass protects the plastic from the environment. Glass also does not transmit UV radiation and thus protects the plastic, which is usually sensitive to this portion of the solar spectrum. Rigid sheets of acrylic-or fiberglass-reinforced polymers are in use, as are stretched films of polyvinyl fluoride. Some of these plastic cover sheets have a transmittance approaching that of low iron glass. A major drawback of this scheme is the potential for overheating the plastic sheet at collector stagnation (no-flow) temperatures.

ADVANTAGES OF FLAT PLATE COLLECTORS:

Flat-plate collectors will absorb energy coming from all directions above the absorber (both beam and diffuse solar irradiance). Because of this characteristic, flat-plate collectors do not need to track the sun. They receive more solar energy than a similarly oriented concentrating collector, but when not tracked, have greater cosine losses.

- Lower cost of production. :
  The main advantage of flat-plate solar collectors over evacuated-tube ones is their price. And though recent trends in evacuated-tube technology closed part of the gap, flat-plate solar collectors are still a cheaper solution. As all the materials used in the production of a Flat Plate Collector are cheap, and can be easily found, it makes it easy to produce and decreases the cost of production as well.
- Horizontal or vertical mounting is possible:
  Flat Plate collectors can be oriented and mounted depending on the requirement. This is possible due to its simple design and versatility

- Can be more easily integrated with the fabric of the building (roof integrated / facade integrated).

DISADVANTAGES OF FLAT PLATE COLLECTORS

By studying the working principle and the properties of the material used in Flat Plate collector we can say that the flat plate collector also has its share of disadvantages. Some of the disadvantages of the Flat Plate Collector are as mentioned below

- Lower performance through conduction, convection and radiation therefore need for more surface area of collector
- Higher wind load requirements (they act like a sail and catch the wind)
- Glass and absorber can get dirty and effect performance
- Needs more maintenance
- Higher volume content equated to larger component sizes. i.e. expansion vessel
- It is not as efficient in lower light, like in bright light.

INTRODUCTION TO CONCENTRATING COLLECTORS

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.

Concentrating, or focusing, collectors intercept direct radiation over a large area and focus it onto a small absorber area. These collectors can provide high temperatures more efficiently than flat-plate collectors, since the absorption surface area is much smaller. However, diffused sky radiation cannot be focused onto the absorber. Most concentrating collectors require mechanical equipment that constantly orients the collectors toward the sun and keeps the absorber at the point of focus. Therefore; there are many types of concentrating collectors.

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. In the following chapter, 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.

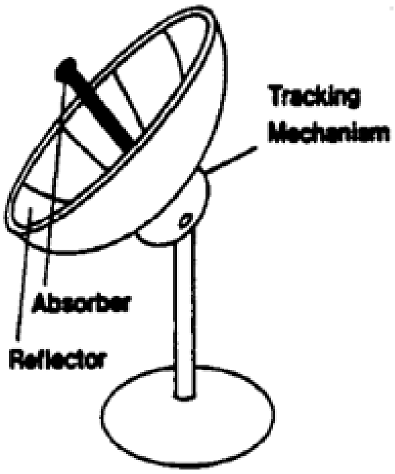


Fig 2. Concentrating Collectors (a)

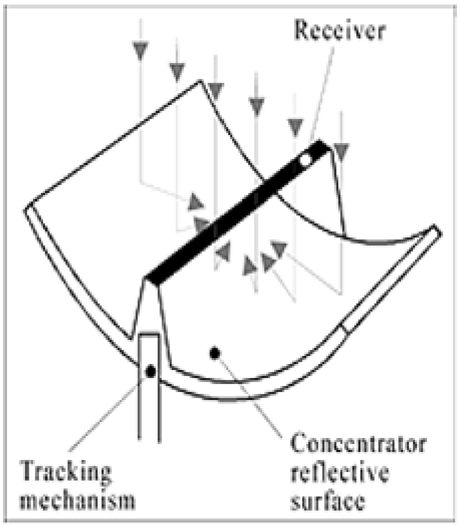


Fig 3. Concentrating Collectors (b)

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.

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.

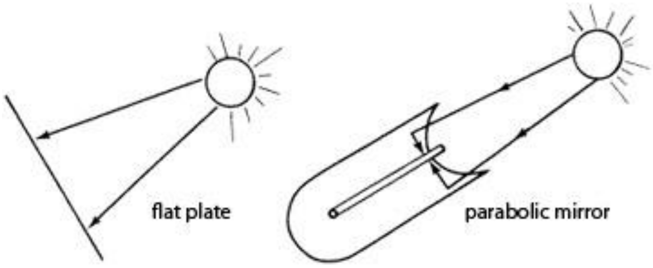


Fig 4. Non-Focusing Collector vs Focusing Collector

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.

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. The CPC(or Winston Collector) is trough like arrangement of two facing parabolic mirrors. Unlike the single parabolic trough reflector described earlier, the CPC is non-focusing, but solar radiation from many directions is reflected towards the bottom of the trough.

Fig 5. Compound Parabolic Concentrator

Because of this characteristic, a large proportion of solar radiation, including diffused (scattered) radiation, entering the trough opening is collected (and concentrated) on a small area. In addition to collecting both direct and diffused radiation, an advantage of the CPC is that it provides moderately good concentration, although less than that of the focusing type of collectors, in an east-west direction without(or only seasonal) adjustment for sun tracking. It is possible to concentrate solar radiation by a factor of 10 without diurnal tracking, using this type of collector.

CPC reflectors can be designed for any absorber shapes. For example,
a) Flat one-sided absorber,
b) Flat two-sided absorber (fin),
c)Wedge-like absorbers, or
d)Tubular absorbers.

For Economic as well as for thermal reasons tubular and fin type of absorbers are preferable. The concentric tubular absorber with an evacuated jacket, temperatures of about 200oC are achievable with Winston collectors.

They are suitable for the temperature range of 100oC – 150oC even if the absorber is not surrounded by the bio vacuum. It is claimed that Winston collectors are capable of competitive performance at high temperatures of about 300oC required for power generation, if they are used with selectively coated vacuum enclosed receivers which decrease thermal losses from the collector.

Construction and working of CPC

The geometry of a CPC is shown in figure. 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.

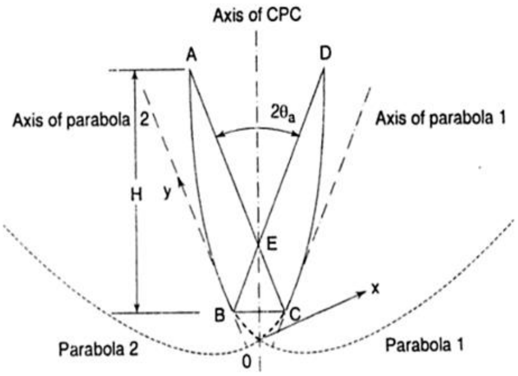


Fig 6: Geometry of a Compound Parabolic Concentrator

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.

HEAT TRANSFER ANALYSIS

Modes of Heat Transfer

Conduction

Heat transfer, a dissipative process, describes the exchange of thermal energy between physical systems and/or within a system. Heat conduction, also called diffusion, is the direct microscopic exchange of kinetic energy of particles either within a system or through the boundary between two systems. When an object is at a different temperature from another body or its surroundings, heat flows until thermodynamic equilibrium is established with the maximum entropy attainable, as described by the second law of thermodynamics, and there is thus no further net transfer of thermal energy across the boundary between the systems, or across any internal boundary.

The law of heat conduction, also known as Fourier's law, states that the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows. We can state this law in two equivalent forms: the integral form, in which we look at the amount of energy flowing into or out of a body as a whole, and the differential form, in which we look at the flow rates or fluxes of energy locally. Newton's law of cooling is a discrete analog of Fourier's law, while Ohm's law is the electrical analogue of Fourier's law.

The differential form of Fourier's Law of thermal conduction shows that the local heat flux density, $\vec{q}$, is equal to the product of thermal conductivity, k, and the negative local temperature gradient, $-\nabla T$. The heat flux density is the amount of energy that flows through a unit area per unit time.

$$\vec{q} = -k\nabla T$$

where (including the SI units)

- $\vec{q}$ is the local heat flux density, W·m^{-2}
- k is the material's conductivity, W·m^{-1}·K^{-1},
- ∇T is the temperature gradient, K·m^{-1}.

The thermal conductivity, k, is often treated as a constant, though this is not always true. While the thermal conductivity of a material generally varies with temperature, the variation can be small over a significant range of temperatures for some common materials. In anisotropic materials, the thermal conductivity typically varies with orientation; in this case k is represented by a second-order tensor. In non-uniform materials, k varies with spatial location. For many simple applications, Fourier's law is used in its one-dimensional form. In the x-direction,

$$q_x = -k\frac{dT}{dx}$$

By integrating the differential form over the material's total surface S, we arrive at the integral form of Fourier's law:

$$\frac{\partial Q}{\partial t} = -k \oint_S \vec{\nabla} T \cdot \vec{dA}$$

where (including the SI units):

- $\frac{\partial Q}{\partial t}$ is the amount of heat transferred per unit time (in W), and
- $\vec{dA}$ is an oriented surface area element (in m^2)

The above differential equation, when integrated for a homogeneous material of 1-D geometry between two endpoints at constant temperature, gives the heat flow rate as:

$$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$$

Where ,

A is the cross-sectional surface area,
ΔT is the temperature difference between the ends,
is the distance between the ends.

This law forms the basis for the derivation of the heat equation.

Convection

Heat convection occurs as diffusion of kinetic energy at the molecular level and/or as advection which is when bulk flow of a fluid (gas or liquid) carries heat along with the flow of matter in the fluid. So called "natural convection" may be triggered by an excess of thermal energy, such as when the Sun heats the Earth's surface, or (in gravitational fields) by buoyancy forces, such as when water gas molecules rise through nitrogen and oxygen molecules which are heavier. Another form of convection is forced convection or advection. In this case the fluid is forced to flow by use of a pump, fan or other mechanical means.

Convection-cooling is sometimes called "Newton's law of cooling" in cases where the heat transfer coefficient is independent or relatively independent of the temperature difference between object and environment. This is sometimes true, but is not guaranteed to be the case (see other situations below where the transfer coefficient is temperature dependent).Newton's law, which requires a constant heat transfer coefficient, states that the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings. The rate of heat transfer in such circumstances is derived below:

Newton's cooling law is a solution of the differential equation given by Fourier's law:

$$\frac{dQ}{dt} = h \cdot A(T(t) - T_{\text{env}}) = h \cdot A\Delta T(t)$$

Where,

Q is the thermal energy in joules

h is the heat transfer coefficient (assumed independent of T here) (W/m^2 K)

A is the surface area of the heat being transferred (m^2)

T is the temperature of the object's surface and interior (since these are the same in this approximation)

T_{env} is the temperature of the environment; i.e. the temperature suitably far from the surface

$\Delta T(t) = T(t) - T_{\text{env}}$ is the time-dependent thermal gradient between environment and object.

The heat transfer coefficient **h** depends upon physical properties of the fluid and the physical situation in which convection occurs. Therefore, a single usable heat transfer coefficient (one that does not vary significantly across the temperature-difference ranges covered during cooling and heating) must be derived or found experimentally for every system analyzed. Formulas and correlations are available in many references to calculate heat transfer coefficients for typical configurations and fluids. For laminar flows, the heat transfer coefficient is rather low compared to turbulent flows; this is due to turbulent flows having a thinner stagnant fluid film layer on the heat transfer surface.[5] However, note that Newton's law breaks down if the flows should transition between laminar or turbulent flow, since this will change the heat transfer coefficient **h** which is assumed constant in solving the equation.

Newton's law requires that internal heat conduction within the object be large in comparison to the loss/gain of heat by convection (lumped capacitance model), and this may not be true (see heat transfer). Also, an accurate formulation for temperatures may require analysis based on changing heat transfer coefficients at different temperatures, a situation frequently found in free-convection situations, and which precludes accurate use of Newton's law. Assuming these are not problems, then the solution can be given if heat transfer within the object is considered to be far more rapid than heat transfer at the boundary (so that there are small thermal gradients within the object). This condition, in turn, allows the heat in the object to be expressed as conduction.

Radiation

Thermal radiation is electromagnetic radiation generated by the thermal motion of charged particles in matter. All matter with a temperature greater than absolute zero emits thermal radiation. When the temperature of the body is greater than absolute zero, interatomic collisions cause the kinetic energy of the atoms or molecules to change. This results in charge-acceleration and/or dipole oscillation which produces electromagnetic radiation, and the wide spectrum of radiation reflects the wide spectrum of energies and accelerations that occur even at a single temperature. Examples of thermal radiation include the visible light and infrared light emitted by an incandescent light bulb, the infrared radiation emitted by animals and detectable with an infrared camera, and the cosmic microwave background radiation. Thermal radiation is different from thermal convection and thermal conduction—a person near a raging bonfire feels radiant heating from the fire, even if the surrounding air is very cold.

Sunlight is part of thermal radiation generated by the hot plasma of the Sun. The Earth also emits thermal radiation, but at a much lower intensity and different spectral distribution (infrared rather than visible) because it is cooler. The Earth's absorption of solar radiation, followed by its outgoing thermal radiation are the two most important processes that determine the temperature and climate of the Earth.

If a radiation-emitting object meets the physical characteristics of a black body in thermodynamic equilibrium, the radiation is called blackbody radiation. Planck's law describes the spectrum of blackbody radiation, which depends only on the object's temperature. Wien's displacement law determines the most likely frequency of the emitted radiation, and the Stefan–Boltzmann law gives the radiant intensity.

Thermal radiation is one of the fundamental mechanisms of heat transfer. Thermal radiation occurs through a vacuum or any transparent medium (solid or fluid). It is the transfer of energy by means of photons in electromagnetic waves governed by the same laws. In a solar collector the mode of all the three modes of heat transfer (as explained) takes place. The radiative heat transfer from one surface to another is equal to the radiation entering the first surface from the other, minus the radiation leaving the first surface.

- For a black body

$$\dot{Q}_{1\to2} = A_1 E_{b1} F_{1\to2} - A_2 E_{b2} F_{2\to1}$$

Using the reciprocity rule, $A_1 F_{1\to2} = A_2 F_{2\to1}$, this simplifies to:

$$\dot{Q}_{1\to2} = \sigma A_1 F_{1\to2} (T_1^4 - T_2^4)$$

where σ is the Stefan–Boltzmann constant and $F_{1\to2}$ is the view factor from surface 1 to surface 2.

- For a grey body with only two surfaces the heat transfer is equal to:

$$\dot{Q} = \frac{\sigma (T_1^4 - T_2^4)}{\dfrac{1-\epsilon_1}{A_1\epsilon_1} + \dfrac{1}{A_1 F_{1\to2}} + \dfrac{1-\epsilon_2}{A_2\epsilon_2}}$$

Where ϵ are the respective emissivities of each surface. However, this value can easily change for different circumstances and different equations should be used on a case per case basis. Thermal radiation power of a black body per unit area of radiating surface per unit of solid angle and per unit frequency ν is given by Planck's law as:

$$u(\nu, T) = \frac{2h\nu^3}{c^2} \cdot \frac{1}{e^{h\nu/k_B T} - 1}$$

Or, in terms of wavelength

$$u(\lambda, T) = \frac{\beta}{\lambda^5} \cdot \frac{1}{e^{hc/k_B T\lambda} - 1}$$

Where, β is a constant.

This formula mathematically follows from calculation of spectral distribution of energy in quantized electromagnetic field which is in complete thermal equilibrium with the radiating object. The equation is derived as an infinite sum over all possible frequencies. The energy, $E = h\nu$, of each photon is multiplied by the number of states available at that frequency, and the probability that each of those states will be occupied.

Integrating the above equation over ν the power output given by the Stefan–Boltzmann law is obtained, as: $P = \sigma \cdot A \cdot T^4$

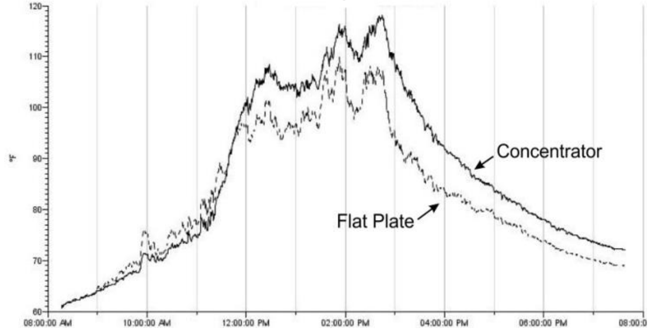
where the constant of proportionality σ is the Stefan–Boltzmann constant and A is the radiating surface area.

RESULTS & OBSERVATIONS

As mentioned earlier, the Compound Concentrating Collector built was tested for its heat transfer efficiency versus the conventional flat plate collector. The heat transfer analysis of the CPC was done as mentioned in Chapter 5. For a graphical representation of the performance of the collector, the collector was for the observed for the increase in the temperature of the water circulating in through the serpentine piping. For a obtaining comparison, a flat plate collector was also made to operate under the same condition.

And from Our common knowledge we know that, the collector with the better performance heats the water in its reservoir to a higher temperature, and the difference in final temperatures in the two reservoirs is an indicator of how much better one collector performed than the other.

The collectors were operated during the monsoon season with ambient temperature of 22°C. The results were tabulated for the data obtained for two days of observation, and the following results were obtained.

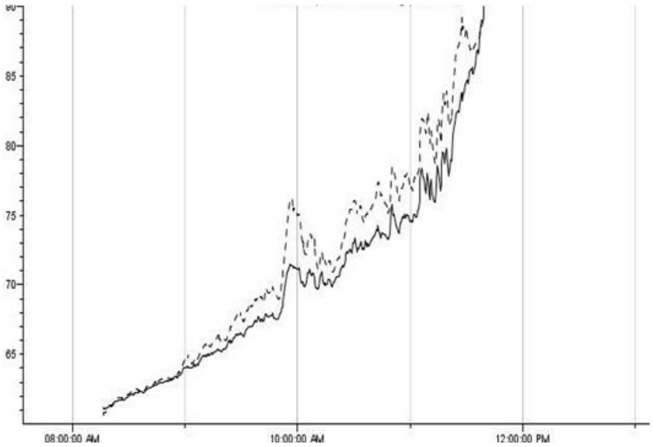


The dotted line in the graph represents the temperature of the water exiting the Flat plat collector, and the solid line represents the temperature of the water exiting the Concentrator.

	Time	Concentration Temperature (°F)	Flat Plate Collector Temperature (°F)
1	08:00:00 AM	60	60
2	10:00:00 AM	71	77
3	12:00:00 PM	103	95
4	02:00:00 PM	115	105
5	04:00:00 PM	90	80
6	06:00:00 PM	77	70
7	08:00:00 PM	70	65

It is important to notice that, the temperature of the concentrator exceeds the flat plate by almost 12 degrees Fahrenheit, at any given point of time.

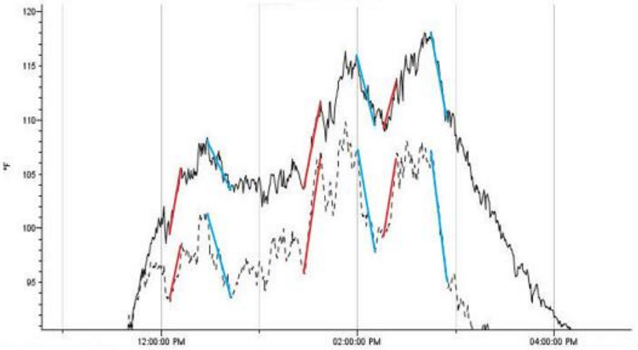
Let us now analyse the graph above in three different sections, one section representing the beginning of the day, one for the period where the heating of the water is in peaks, and the other is the cooling down period. The observation from the beginning of the day seems interesting because flat plate heats faster than the concentrator. It is due to the larger metallic surface of the flat plate picking up heat from the air more readily than the much smaller collector tube of the concentrator. Once the concentrator could lock onto the rising sun, the concentrator heated quickly, from the graph we can see that both heat rapidly once the sun is visible.



The above mentioned graph depicts the same observation; the flat plate collector reaches a temperature of 75°F, by 10:00 AM, where as the concentrator reached only at a temperature of 68°F.

And it's worth noting that due to the higher concentrating factor of the CPC, the heat is trapped at a much higher rate, as at 11:30AM both the collectors where at a temperature of 87°F.

When we notice the area of the graph which represents the mid-day time period, we can find the rate at which both these collectors heat and as well as the rate at which they cool down. The two slope lines, red and blue in color, represent the slope of the temperature graphs that is the rate of heating and the rate of cooling respectively.



CONCLUSION

In this thesis, the design and development of 2-dimensional non-imaging type CPC with flat plate absorber and having two parabolic reflectors is attempted. It seems to be far better than flat plate collector and the focusing type collector like simple parabolic concentrator. It can be concluded that the fabricated CPC has an efficiency of 10-15% more than the conventional collectors. Also, the amount of temperature levels of the water obtained by the use of CPC is much higher than its counterparts.

Following advantages are concluded for 2-D CPC:
1. There are many practical applications where moderate temperature (not very high or low) is required. Such applications are water heating, steam generation, industrial process heating, pumping of ground water, power generation and many more. The temperature needed for such application is about 100ºC. CPC is most suitable for this purpose. Even when it is non-evacuated and without any selective surface coating, it can attain the temperature up to 100oC and higher.

2. Flat plate collector may attain the temperature up to 90ºC. This puts the limitations on most of the moderate temperature applications.

3. CPC can also attain higher temperatures up to 200ºC to 300ºC at higher concentration ratio or when it is evacuated between absorber and envelope and the selective coating is applied on absorber surface or by using some special modifications.

4. Focusing type simple parabolic concentrator needs a continuous tracking of the sun, so the costly arrangement for tracking device is required, whereas for CPC, no continuous tracking is needed. It requires only a few tilt adjustments per year.

5. No diffuse radiation is accepted by simple parabolic concentrator, while a significant fraction (= 1/C) of diffuse radiation is accepted by CPC.
6. Due to smaller size of absorber in CPC, loss coefficient and hence losses are less as compared to that in FPC.

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