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A review of Solar Flat Plate Thermal Collector

Group: **E2**

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Abstract:

Thermal applications and power generation from solar radiation are emerging vary rapidly as the world continues to thrive for energy sources of future, other than the conventional sources. Solar thermal collector is one of the basic needs to convert sun's energy to our useable forms. Broadly, these collectors are divided into two groups, non-concentrating solar thermal collectors and concentrating solar thermal collectors. This report aims to review the 'Solar Flat Plate Thermal Collector' which falls under the non-concentrating thermal collectors. It achieves the target by walking through a brief history of the solar thermal collectors, brief descriptions of various collector types, details construction and thermal performance, with pointing out the areas where improvement can be done.

Introduction:

The fundamental source of energy on the Earth's surface is the sun. The sun radiates huge amount of energy which incidents on the Earth surface. This energy received by the sun is the solar energy. Despite being an enormous energy radiator, the low density and intermittency of solar energy calls for the storage and collection of this energy. As this radiant energy needs to be harnessed and stored, several devices have been invented and studied upon. (Kalogirou, 2004)

One of such devices which converts the radiation of the sun into usable form is the solar collector. Figure shows a solar collector. A solar collector absorbs sun's radiant energy and converts it to thermal energy for diversified use. This thermal or heat energy is then transferred to the working substance either air or fluid. (John A. Duffie, 2006) A solar collector varies according to its design. A flat plate solar collector has the same intercepting area as its absorbing area whereas a concentrated or curved surface collector has a smaller receiver area compared to the interceptor area.(Chowdhury and Salam, 2019) A solar collector works on the greenhouse effect principle. It absorbs the radiation of shorter wavelength and keeps it trapped to heat the collector plate. The long wave radiation is usually reflected back or remains unabsorbed. (Zondag, 2008; Tian and Zhao, 2013)

The present world energy condition focuses on the development of various renewable energy. The most easily and readily available energy on the Earth is the radiation energy of the sun. This radiant energy is harnessed by solar collectors and used for various domestic or household purposes, even for a few industrial sectors. The use of solar energy not only puts less pressure on the current sources of energy present but also shows a light of hope in solving the current energy crisis. Solar water heating or solar energy usage is on rise mainly for three reasons-firstly, the increase of price of available fossil fuels like oil, gas etc. secondly, the world is getting concerned over the fact that fossil fuel is gradually being replenished from the Earth and thirdly, the use of renewable energy reduces pollution as well as demand on electricity.(Kalogirou, 2004; Luo *et al.*, 2018)

In this report, a review of the solar flat plate collector is provided which is organised as follows:

- A brief introduction about the types of solar collectors' present.
- The construction, working procedure and application of a flat plate solar collector.
- Thermal analysis and performance improvement of flat plate collector.

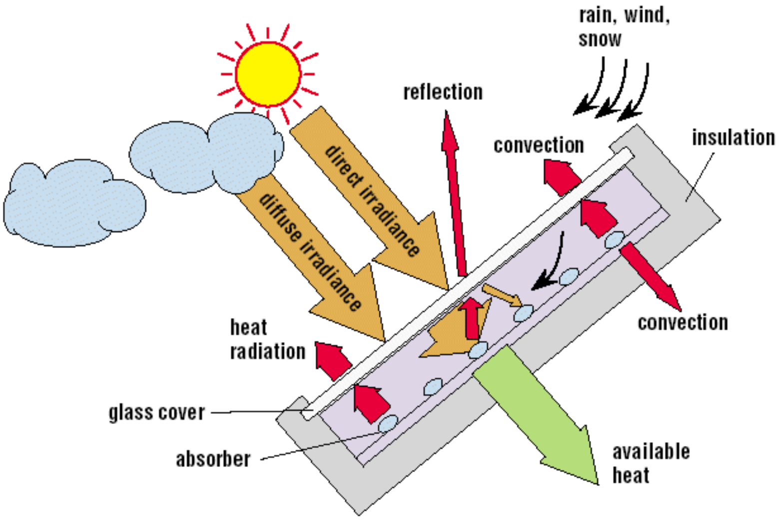


Figure: A typical solar flat plate collector (complet, 2019)

History of Solar Collector:

The use of solar energy or solar radiation was evident since the beginning of mankind. The primary uses were related to drying clothes or other household items, but with the progress of time major breakthroughs came since 1700s.

In 1767, Swiss scientist Horace-Benedict de Saussure created the first solar collector. He used an insulated box which was covered with three glass layers to absorb sun's energy. William J. Baileys, in 1908, built a copper collector using copper coils and boxes. In the 1950's, he first accurate model of flat plate solar collectors was developed by Hottel and Willier. From then, people have been working for improvement and development of the solar collectors. Recent studies show much improvement of efficiency of solar collectors. Further researches and studies are in progress for more development in this sector. (Kalogirou, 2004; Zondag, 2008)

Types of Collectors:

A solar collector's main purpose is to absorb solar radiation of the sun and convert it into heat energy by transferring heat to the working fluid. There are mainly two types of solar collectors: -

1. Non-concentrating solar collectors
2. Concentrating solar collectors (Kalogirou, 2004)

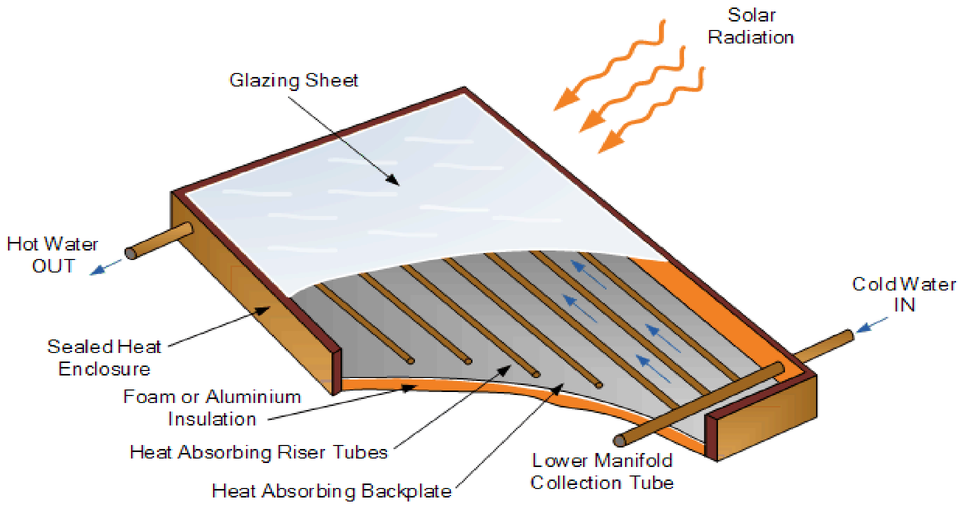
1. **Non-concentrating Solar Collectors:** Non-concentrating solar collectors are usually used for low temperature applications. These collectors consist of flat surface which absorbs heat from the sun. The efficiency of non-concentrating collectors is comparatively less but in terms of cost and maintenance these are much feasible. There are a few types non-concentrating solar collectors. (Kalogirou, 2004; Tian and Zhao, 2013)

i. **Flat Plate Solar Collector:** Flat plate solar collector is a very basic type of solar collector. It has a flat rectangular surface as an absorber. It is very efficient and convenient for temperatures up to 100°C. (John A. Duffie, 2006) These collectors are classified as liquid type and air type based on their heating application. Flat plate collector is usually set up in the top of a building or a structure or in an open field and it uses both beam and diffused solar radiation for heating up. Figure (a) shows a flat plate collector. Several types of flat plate collectors have been designed since the 1900s by using different types of materials for improvement of performance as well as making it cheaper and more long-lasting. In the later section of this report detailed discussion about flat plate collectors is done.(Kalogirou, 2004; Jesko, 2008; Amrutkar, 2012; Tian and Zhao, 2013; Chowdhury and Salam, 2019; Fudholi and Sopian, 2019)

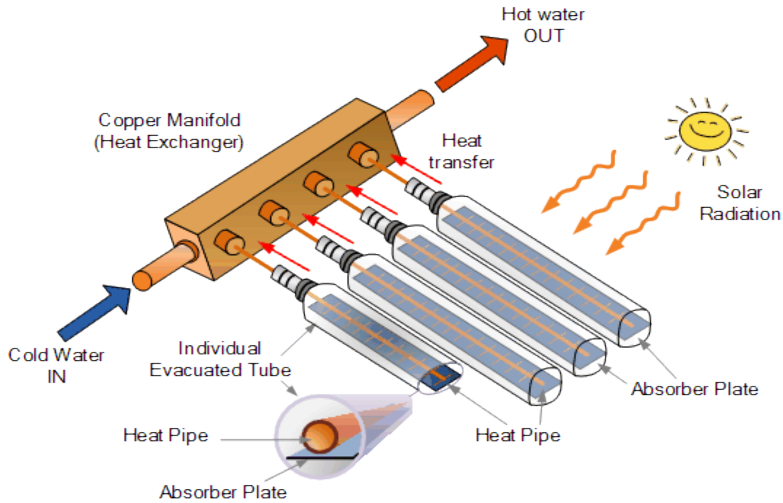
ii. **Evacuated Tube Collector:** Evacuated tube collector differs from the flat plate collector in construction and operation. Figure (b) shows a flat plate collector. Evacuated collectors are used in climates with high temperature or where the temperature is too high for flat plate collector to work efficiently. Evacuated tube collectors consist of a heat pipe inside a vacuum sealed tube. The heat pipe is made of copper for high heat absorbance. In these collectors, liquid-vapour phase change materials are used for high efficiency heat transfer. (Yogi Goswami D., 2000) Another type of collector is present which consists of two concentric annealed glass tube with vacuum between the layers. The glass tubes are usually made of borosilicate glass. The inner tube works as the absorber of the solar radiation which is coated with selective absorber coating. The vacuum, by creating isolation between the tubes helps to reduce the heat losses by convection and conduction and hence increases the efficiency of the collector. It acts by the principle of a thermos flask. Evacuated tube collector can absorb both beam and diffused radiation.(Kalogirou, 2004; Jesko, 2008; Tian and Zhao, 2013)

iii. **Solar Pool Collector:** Solar pool collectors are the collectors used for heating the water directly using sun’s radiation. These collectors work in a similar way as that of flat plate collectors but are unglazed, not covered with glass. Figure (c) shows a flat plate collector. Solar pool collectors cannot work in freezing temperature. They are mostly used for heating swimming pool water to 20°-25°C.(Jesko, 2008)

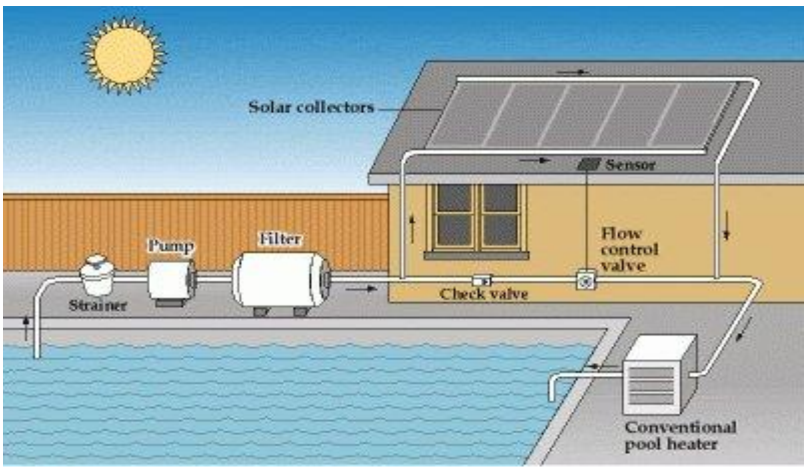
iv. **Tank-type Collector:** Tank-type collectors are similar to flat plate collectors in working. They are used for heating water in a tank for domestic and household purposes. Figure (d) shows a flat plate collector. These collectors are set in the tank where water is to be heated and heats the water to a temperature near 50°-60°C.(Jesko, 2008)


Solar
Radiation
Glazing Sheet
Hot Water
OUT
Cold Water
IN
Sealed Heat
Enclosure
Foam or Aluminium
Insulation
Heat Absorbing Riser Tubes
Heat Absorbing Backplate
Lower Manifold
Collection Tube

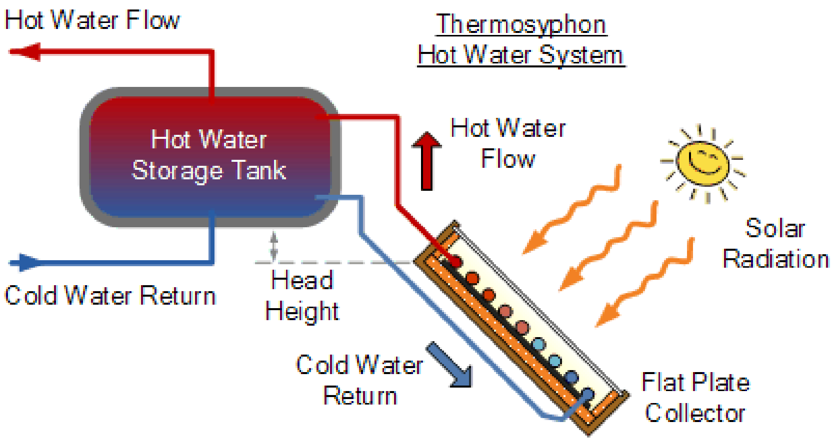
(a)


Hot water
OUT
Copper Manifold
(Heat Exchanger)
Heat
transfer
Solar
Radiation
Cold Water
IN
Individual
Evacuated Tube
Absorber Plate
Heat Pipe
Heat Pipe
Absorber Plate

(b)


Solar collectors
Sensor
Flow
control
valve
Pump
Filter
Strainer
Check valve
Conventional
pool heater

(c)



(d)

Figure: (a) Flat plate solar (Anon., 2020), (b) Evacuated tube collector (Anon., 2020) (c) Solar pool heaters (Solar Swimming Pool Heaters, 2020) and (d) Tank type collector (Anon., 2020)

2. **Concentrating Solar Collectors:** Concentrating solar collectors are usually used for high temperature applications more than 100°C. Concentrating collectors may be reflectors or refractors. Wide variation is present in their design-parabolic, circular, cylindrical, convex or concave etc. Concentrating collectors focuses sunlight using lens and mirrors. The collectors maybe glazed or unglazed depending on the requirement. There are both sun tracking system as the sun's position changes with time as well as non-tracking system. It is also divided in two types as line focusing and point focusing. A few types of concentrating collectors are present.(Kalogirou, 2004; Jesko, 2008; Tian and Zhao, 2013)

   i. **Parabolic Trough Collector:** Parabolic trough collector is a line focusing type of solar collector where the radiation of the sun is focused along the focus of the parabolic trough. Parabolic collectors are made by bending a reflective sheet into parabolic shape. An absorber pipe covered with glass tube to protect it from dust and moisture which reduces reflectivity is placed along the focal line and working fluid usually water flows through it. The sun rays are reflected and falls on the absorber tube which heats the working fluid (John A. Duffie, 2006). The absorber or receiver tube is coated with material of high solar radiation absorptance and the glass layer helps in reduction of thermal losses by convection and radiation. By the use of one-axis tracking device, which tracks the sun position in one direction only, either east-west or north-south, the position and focus of the solar radiation changes with the elevation of the sun. The collector pipe or the trough are rotated along the axis of the absorber pipe continuously. Temperature up to 400°C can be obtained using this collector. Parabolic trough collectors are the most advanced solar collector technologies and mainly used for solar thermal electricity generation.(Kalogirou, 2004; Zondag, 2008; Tian and Zhao, 2013) (Kreider JF, 1991)

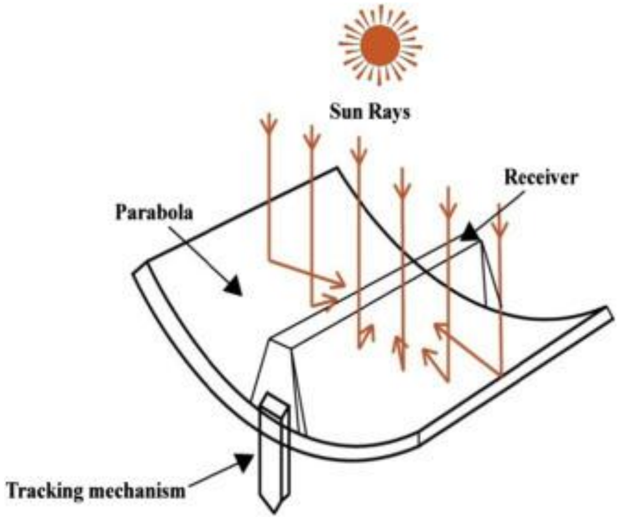


Figure: Parabolic Trough Collector (M.U.H. Joardder, 2017)

ii. **Parabolic Dish Collector:** It is a point focusing type of solar collector. The receiver is placed at the focus of the concentrator or dish. The sun's radiation is collected at the receiver. (Winston, 1974) It uses two axis sun tracking system. It is used for high temperature works above 1500°C. Working fluid circulates through the receiver. Dish collector is mainly used for small electricity generation using sunlight. It is the most efficient among all collectors.(Kalogirou, 2004; Tian and Zhao, 2013)

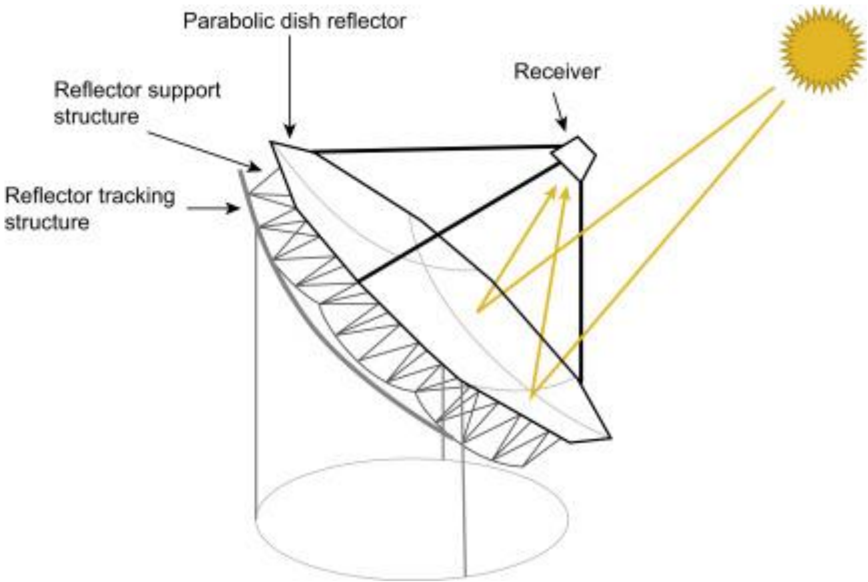


Figure: Parabolic Dish Collector (Manuel J. Blanco, 2017)

iii. **Heliostat Field Collector:** It consists of a number of flat mirrors called heliostats spread over a large region. Altazimuth mounts are used for setting up the mirrors.

The heliostats focus the sun's radiation to a common tower usually 500m long. The collector or receiver is placed in the central tower which consist of vertical tubes of flowing water. Up to 1500°C temperature is achievable using this collector. The heliostats are controlled by automated tracking device to change position with respect to the sun. Heliostat collectors are used for power generation using high temperature steam generated from heating the working fluid.(Kalogirou, 2004; Tian and Zhao, 2013) (Kalogirou, 1991)

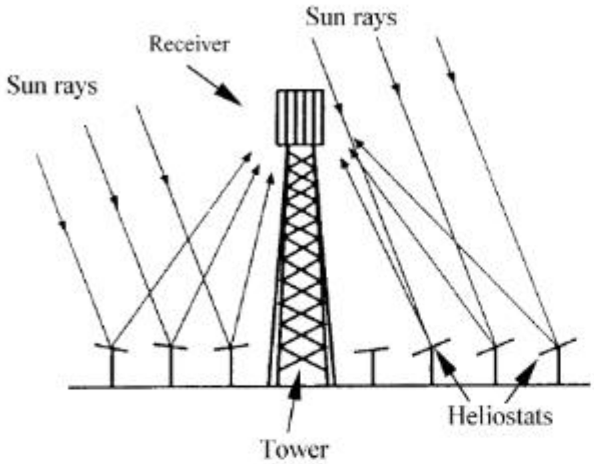
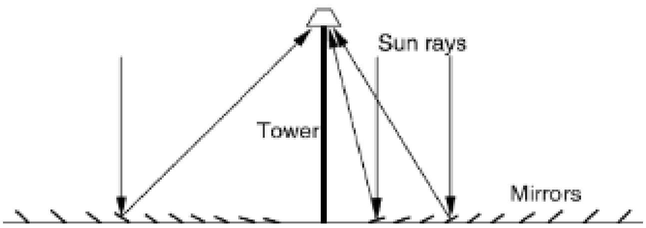
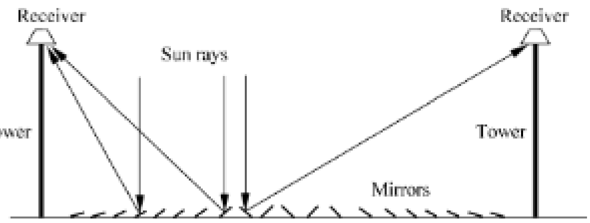


Figure: Heliostat Field Collector (Kalogirou, 2004)

iv. **<u>Fresnel Lens Concentrating Collector:</u>** In this collector Fresnel lens is used. Fresnel lens is flat on one side and provided with linear grooves on the other side. The grooves possess optical quality for which the behave like a common lens. The absorber tube is oriented in such a way that the radiation after refraction through the lens is focused at the tube. (Lorenzo E, 1986) Another type of collector is the linear Fresnel reflector which consists of a linear arrangement of flat or curved elastic mirrors focusing light on a receiver mounted on the top a linear tower.(Kalogirou, 2004; Tian and Zhao, 2013)



(a)



(b)

Figure: (a) Linear Fresnel Reflector, (b) Compact Linear Fresnel Reflector (Kalogirou, 2004)

Construction:

A typical flat plate solar collector consists of a glazed absorber plate, tubes, thermal insulation, cover strip, insulated casing. Flat plate collectors are usually permanently fixed on a roof top or an open field and doesn't require any sun tracking system. The collectors are to be oriented directly towards the equator, facing south in the northern hemisphere and north in the southern. The optimum tilt angle of the collector must be equal to the latitude of the location with angle variations of 10–15° more or less depending on the application. A short description of the parts of a typical flat plate collector is given here. (Yogi Goswami D., 2000) (John A. Duffie, 2006) (Kalogirou, 2004)

a) **Absorber Plate:** The absorber plate is a rectangular sheet made of high heat conducting material, especially copper or aluminium because of their high heat conductivity. It is usually painted in black and coated with absorptive material to get the maximum absorption of solar radiation. (John A. Duffie, 2006) This thin layer is highly absorbent to shortwave solar radiation but comparatively translucent to long wave radiation. Another thin layer is provided below the coating with high reflectance to long wave radiation. The absorber plate absorbs the sun's heat energy and transfer that to the working fluid with minimum heat loss.(Kalogirou, 2004; Ibrahim *et al.*, 2011; Amrutkar, 2012; Tian and Zhao, 2013) (John Twidell, 2015)

b) **Headers:** Tubes of large diameter are placed at the top and bottom of the absorber plate for the entrance and discharge of fluid. The header pipes are made of copper for maximum heat conduction from the absorber plate. (John A. Duffie, 2006) These header pipes are connected to the copper tubes by welding.(Kalogirou, 2004; Ibrahim *et al.*, 2011; Amrutkar, 2012; Michael, S and Goic, 2015)

c) **Tubes:** Several tubes made of copper are placed on the absorber plate. The working fluid flows through the tubes where they are heated. The copper tubes are positioned parallelly on the absorber plate. (John Twidell, 2015)The liquid tubes are connected at both ends by large diameter header tubes. These are soldered and brazed to the absorber plate so that smooth heat transfer takes place between them by getting maximum surface contact. (John A. Duffie, 2006) (Kalogirou, 2004; Ibrahim *et al.*, 2011; Amrutkar, 2012; Tian and Zhao, 2013)

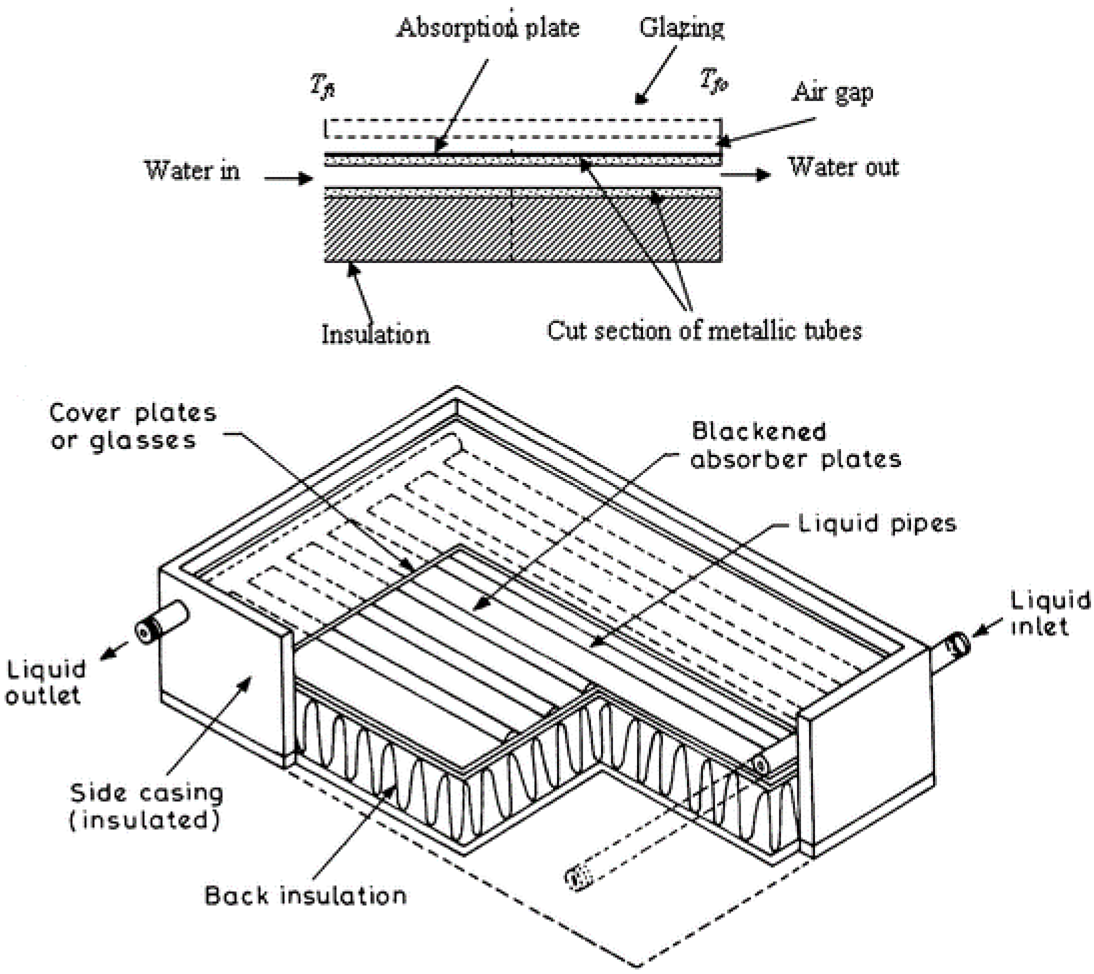


Figure: Parts of a Flat Plate Collector

d) **<u>Glazing:</u>** Glazing refers to covering with glass or plastic having radiative properties. A flat plate collector has single, double or multiple layers of glazing above the blackened absorber plate. Low iron glass is mainly used for glazing having high transmissivity of short-wave radiation and low or zero transmissivity of long-wave radiation. (John A. Duffie, 2006) The main purpose of glazing is to allow as much as solar radiation possible and create an insulation of the absorber plate with the environment by entrapping radiation to reduce convective losses as well as radiative losses. Transmission of short-wave radiation can also be increased by antireflective coating and surface texture. The glazing materials doesn't absorb heat like absorber plate.(Kalogirou, 2004; Amrutkar, 2012; Tian and Zhao, 2013)

e) **<u>Insulation:</u>** Insulation is provided to the sides and bottom of the flat plate collector to reduce heat loss. Different insulating materials like rubber, cotton, wool is used for this purpose. Insulating substances decrease heat loss from the absorber plate and helps in heating the tubes as well as the plate.(Kalogirou, 2004; Amrutkar, 2012)

f) **Casing:** A steel or wooden casing is used to hold the parts together. In the casing a layer of insulation is provided at the bottom. The absorber plate is placed after that with copper tubes incorporated in it. The sides are also insulated for the reduction of heat loss through convection. (John A. Duffie, 2006) Finally, the glazing is done with glass to provide air gap between absorber and the atmosphere. All the parts are soldered, brazed or welded properly to get maximum surface contact and high heat transfer. Casing protects the parts from environmental influences like dust particles, rainfall, moisture etc.(Amrutkar, 2012; Tian and Zhao, 2013)

Working:

A solar collector works as a water heater and is based on the transformation of the absorbed solar radiation to thermal energy. In general, solar collector works by absorbing solar radiation which incidents on the collector plate passing through the glazed glass. The absorbed heat is then transferred to the working fluid flowing through the connected copper tubes with minimum heat loss. The heated fluid is then moved to the place of its use or to a storage tank for later use. (John A. Duffie, 2006)

A solar collector heating system is two types- active or direct and passive or indirect.

Active or direct solar collector is basically an open-loop system. In this system, a differential temperature sensor is used to compare the temperature of the water to be heated. The heat collected by the collector is transferred to the working fluid which goes directly to the storage tank and then supplied to the household needs. A heat pump is used which draws cold water from the bottom of the storage tank and circulates it through the solar collector. As a result, the heated water is circulated through the tanks directly from the collector (Kalogirou, 2004; Tian and Zhao, 2013; Jamar *et al.*, 2016).

Open-loop system is of two types- drain-down system and the recirculating system.

In the drain-down system a valve is used to allow the solar collector to fill with water when the collector reaches a certain temperature.

In the recirculating system water is pumped through the collector when the temperature in the storage tank reaches a certain critical value.

Passive or indirect system is a closed-loop system. In this system, a heat transfer fluid called glycol is used to circulate through the solar collector. Glycol after absorbing radiant heat from the collector is passed to a heat exchanger where it heats the working fluid through heat transfer. Glycol works as anti-freezing substance and can operate efficiently at freezing temperature. The working fluid after being heated from the heat exchanger is transferred to a storage tank for after use. (Bhowmik and Amin, 2017; Pandey and Chaurasiya, 2017)

Thermo-siphon system is a kind of passive system which consists of an insulated storage tank set above the collectors. The heated fluid moves to the storage tank by convective process and stored there. In response, the cold fluid circulates to the collector and gets heated up. In this system, flow of fluid is slow. This system is simple and uses no energy and requires comparatively low maintenance.(Zondag, 2008; Luo *et al.*, 2018)

Air flat plate collectors works on the same principle but is used for conditioning of household or commercial premises. It works by natural or forced convection of depending on absorbed heat. In air heating systems, boiler is used to heat the air before using for space heating. Blower or fan may also be used for forced flow of air in other applications. (Gordon, 2001)

Applications:

Solar collectors are primarily used for heating water for household purposes to reduce the usage and of energy and fossil fuel. Typical application of flat plate solar collector includes the following: (Anon., 2017) (John A. Duffie, 2006) (John Twidell, 2015) (Kalogirou, 2004)

- Water heating for household and residential use like washing clothes, bathing, washing other equipment as well as drinking warm water is done by solar collectors
- Industrial application of solar water heating includes the use of warm water in leather industry, textile industry, food and beverage industry etc.
- Laundry shops use warm water for washing clothes by using either active or passive collector
- Water of swimming pool is heated using solar collector
- Solar collectors are used in desalination plants for evaporation of water by heating it to high temperature
- Solar concentrators are used for solar distillation by heating copper boilers filled with water
- Solar powered electricity is generated from the radiant energy of the sun using solar collectors
- Air heater is used for space heating in household and commercial zones
- Crop drying for agriculture industry is done by forced flow of air using air heaters

Thermal Analysis:

Classical analysis on the basis of thermodynamic principles of a flat plate collector are discussed in this section. The basic aspect of thermal analysis of a flat plate collector is the thermal efficiency of the collector. (Özil and Yaşar, 1987; Kalogirou, 2004; Farahat, Sarhaddi and Ajam, 2009; Amrutkar, 2012; Luo *et al.*, 2018; Fudholi and Sopian, 2019) (John A. Duffie, 2006) (John Twidell, 2015) (Yogi Goswami D., 2000)

I. **Energy balance for a flat plate collector:** Thermal efficiency is defined as the ratio of the delivered useful energy in the working fluid to the incident solar energy on per unit collector or absorber area in a specific time period. Under steady conditions, the useful energy delivered by the collector is given by (John A. Duffie, 2006) (John Twidell, 2015) (Özil and Yaşar, 1987)

$$Q_u = I_t A_c (\tau\alpha)_{\text{eff}} - Q_l \tag{1}$$

or,

$$Q_u = S A_c - Q_l \tag{2}$$

where,

I_t = incident solar radiation on a collector surface

A_c = area of the absorber or collector

$(\tau\alpha)_{eff}$ = effective solar cover(s) transmittance and absorber plate surface absorptance product.

S = the difference between the incident solar radiation and the optical losses

Q_l = heat loss to the surroundings from the collector plate

If the conditions remain constant, the instantaneous efficiency of a flat plate collector is given by

$$\boldsymbol{\eta = \frac{Q_u}{Q_a} = \frac{Q_u}{I_t A_c}} \qquad (3)$$

Where,

Q_u = useful thermal energy provided by the collector

Q_a = the total absorbed solar energy by the collector

II. **Overall Heat Loss Coefficient (U_L):** The efficiency of a flat plate collector can be fully explained and studied if we know all the terms of the equation. For that, we need to know the overall heat loss coefficient (U_L) which is the collector heat loss conductance. If the overall heat loss coefficient (U_L) is known then by knowing the average collector plate temperature (T_P), the total heat loss by the collector to the surroundings (Q_l) can be found. This loss of thermal energy per unit area from the collector to the surroundings by conduction, convection and infrared radiation can be represented as the product of overall heat loss coefficient (U_L) times the difference between the average absorber plate temperature (T_P) and the ambient temperature of the surroundings (T_∞).

$$\boldsymbol{Q_l = U_L A_c (T_P - T_\infty)} \qquad (4)$$

The overall heat loss coefficient (U_L) can be calculated if we know the design parameters of a flat plate collector. Let us consider the thermal network of a two-cover system as shown in figure. At any location the plate temperature is (T_P) and the absorbed solar radiation compensating the optical losses is (S). This absorbed energy (S) is distributed to thermal losses through the top, bottom and side and to useful energy gain. (John A. Duffie, 2006) (Özil and Yaşar, 1987; Amrutkar, 2012)

a) **Top loss coefficient (U_t):** Since the top portion of a flat plate collector remains covered with glass, the energy loss from this portion is mainly due to convection and radiation between the parallel plates. The steady-state energy transfer between the plate at T_P and the first cover at T_{c1} is the same as between any other two adjacent covers and is also equal to the energy lost to the surroundings from the top cover. (Agarwal, 1981) (Özil and Yaşar, 1987)

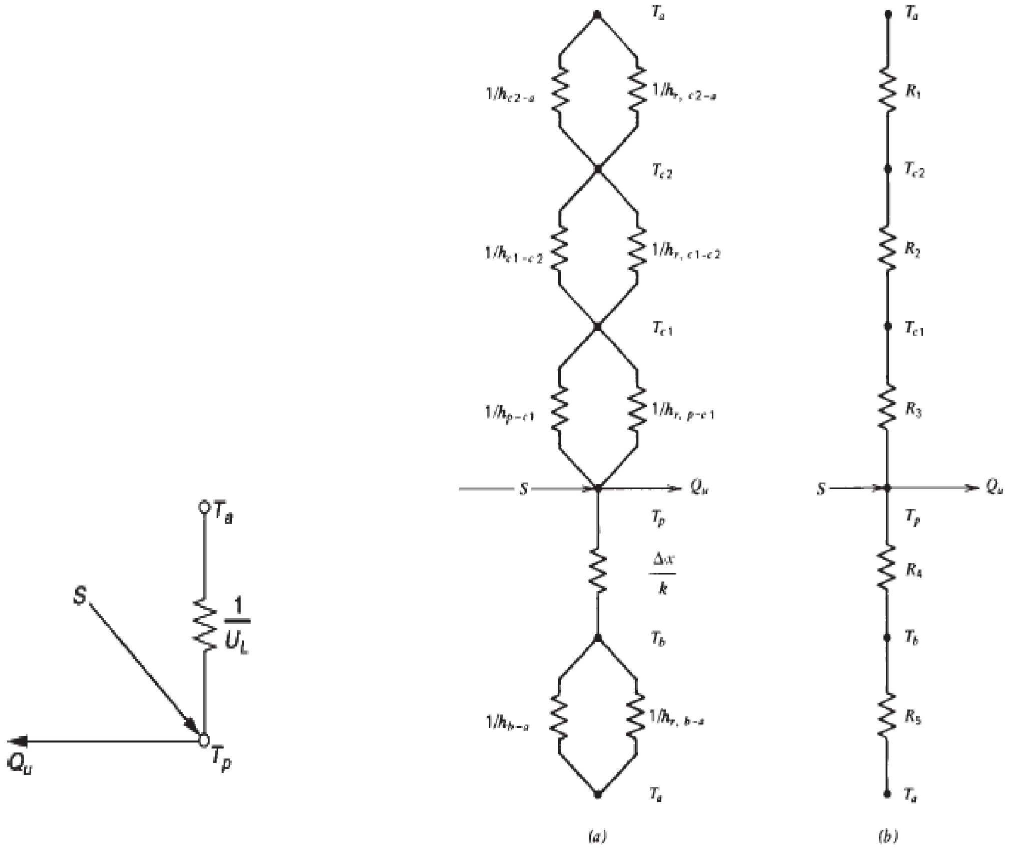


Figure : Solar Resistance (John A. Duffie, 2006)

The loss through the top per unit area is then equal to the heat transfer from absorber plate to the first cover:

$$\boldsymbol{q_{loss} = h_{c,p-c1}(T_P - T_{c1}) + \frac{\sigma(T_P^4 - T_{c1}^4)}{\frac{1}{\varepsilon_P} + \frac{1}{\varepsilon_{c1}} - 1}} \qquad (5)$$

where $\mathbf{h_{c,p\text{-}c1}}$ is the convection heat transfer coefficient between two inclined parallel plates. If the radiation heat transfer coefficient is used then the heat loss becomes

$$\boldsymbol{q_{loss} = (h_{c,p-c1} + h_{r,p-c1})(T_P - T_{c1})} \qquad (6)$$

where

$$h_{r,p-c1} = \frac{\sigma(T_P + T_{c1})(T_P^2 + T_{c1}^2)}{\frac{1}{\varepsilon_P} + \frac{1}{\varepsilon_{c1}} - 1} \quad (7)$$

So, the resistance R_3 can be expressed as

$$R_3 = \frac{1}{h_{c,p-c1} + h_{r,p-c1}} \quad (8)$$

For the resistance R_2, similar expression of equation (8) can be as mentioned earlier, the heat transfer being equal. Thus, theoretically there can be as many covers as desired but practical limit is two and the most used is a single cover collector.

The resistance from the top cover to the surroundings has the same form as equation (8) but there is the effect of wind induced convection heat transfer coefficient (h_w). The radiation resistance from the top cover accounts for radiation exchange with the sky at temperature (T_s). For convenience, we reference this resistance to the ambient temperature (T_∞), so that the radiation heat transfer coefficient can be written as

$$h_{r,c2-\infty} = \frac{\sigma\varepsilon_c(T_{c2} + T_s)(T_{c2}^2 + T_s^2)(T_{c2} - T_s)}{(T_{c2} - T_\infty)} \quad (9)$$

The resistance to the surrounding R_1 is then written as

$$R_1 = \frac{1}{h_w + h_{r.c2-\infty}} \quad (10)$$

For this two-cover system, the top loss coefficient (U_t) from the collector plate to the environment is (John A. Duffie, 2006)

$$U_t = \frac{1}{R_1 + R_2 + R_3} \quad (11)$$

(Hottel, 1942) and (Klein, 1975) have developed the following correlation for an FPC with all-glass covers:

$$U_t = \frac{1}{\frac{N}{T_P - T_\infty} + \frac{1}{h_{c2}}} + \frac{\sigma(T_P - T_\infty)(T_P^2 - T_\infty^2)}{\frac{1}{\varepsilon_p + 0.0425(1-\varepsilon_p)} + \frac{2+f-1}{\varepsilon_g} - 1} \quad (12)$$

where

f = $(1 - 0.04\ h_{c,\infty} - 0.0005\ h^2_{c,\infty})\ (1 - 0.058\ N)$

N = number of covers

$\boldsymbol{\varepsilon_p, \varepsilon_g}$ = infrared emittance of absorber plate and cover respectively.

When the collector inclination angle is not 45°, a correction for (U_t) is needed:(Özil and Yaşar, 1987)

$$\frac{U_t(\varphi)}{U_t(45°)} = 1 - (\varphi - 45)(0.00259 - 0.00144\varepsilon_p) \tag{13}$$

Where,

$\boldsymbol{U_t(\varphi)}$ = the angle at which collector is inclined

b) **Bottom loss coefficient (U_b):** In order to find the energy loss through the bottom, there are two series resistance R_4 and R_5, where R_4 represents the heat loss through the insulation and R_5 represents the heat loss by convection and radiation to the environment. It can be assumed that R_5 is zero because all heat loss takes place through the insulation. The coefficient of heat loss through the bottom (U_b) can be approximated as: (John A. Duffie, 2006) (Özil and Yaşar, 1987)

$$U_b = \frac{1}{R_4} = \frac{k}{L} \tag{14}$$

Where,

k = thermal conductivity of the insulating material

L = thickness of the insulation

c) **Side loss coefficient (U_s):** The evaluation of the heat loss through the edges and sides of the collector is usually complicated. But the side loss being small it is unnecessary to calculate it will good accuracy in a well-designed system. If the edges have the same insulation thickness as that of the bottom, the side loss can be estimated as one-dimensional sideways heat flow across the perimeter of the collector plate. (Özil and Yaşar, 1987)
If the edge loss coefficient-area product is $(U/A)_{edge}$, then the side loss coefficient based on the collector area (A_c) is

$$U_s = \frac{(UA)_{edge}}{A_c} \tag{15}$$

In any case, the overall heat loss coefficient of a collector is expressed as the of the losses in top, bottom and sides, (John A. Duffie, 2006) (Özil and Yaşar, 1987)

$$\boldsymbol{U_L = U_t + U_b + U_s} \quad (16)$$

III. **Absorber Plate Efficiency:** Let us consider a finned tube collector shown in figure. The factors influencing the amount of heat transferred from the absorber plate to the transport fluid under the steady state conditions are:

- the absorber plate temperature
- the transport fluid bulk temperature
- the overall heat transfer coefficient between the plate and the fluid.

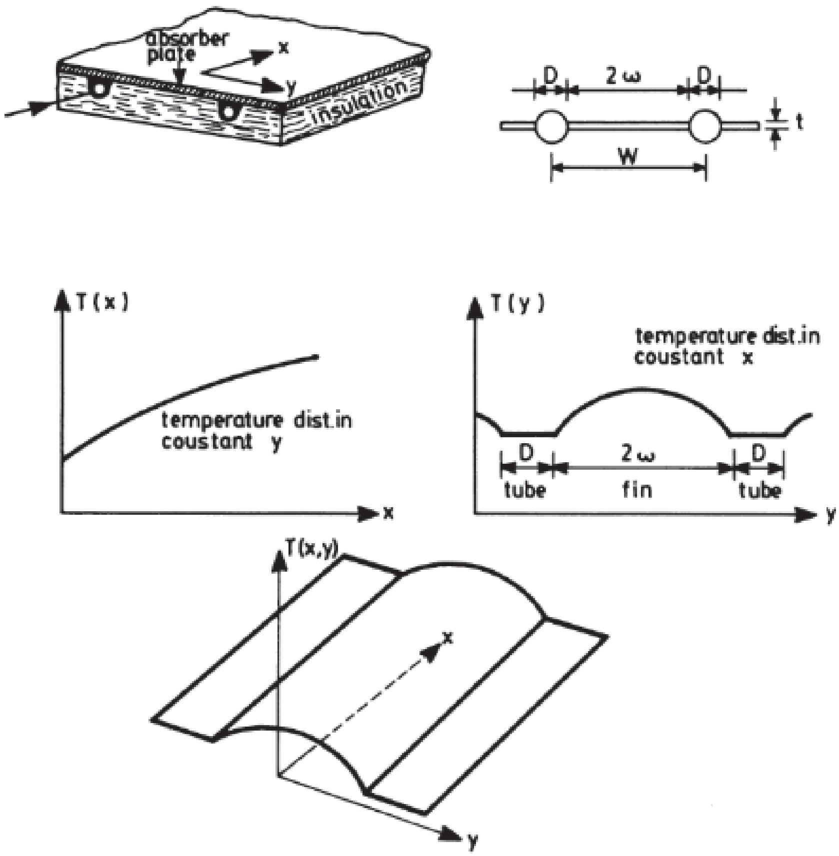


Figure : Plate temperature distribution in a typical finned tube collector (Özil and Yaşar, 1987)

Making use of the heat transfer relationships for the finned surfaces and assuming a fin of length (ω) with the tube being the base at a temperature T_b, we can write the following equation: (Özil and Yaşar, 1987)

$$m = \sqrt{\left(\frac{U_L}{k_p t}\right)} \quad (17)$$

$$\eta_p = \frac{1}{m_\omega}\tanh(m_\omega) \quad (18)$$

Where,

k_p = the absorber plate's thermal conductivity

t = thickness respectively

n_p = the absorber plate efficiency

IV. **Collector Efficiency Factor (F'):** The collector absorbs solar energy which is transferred to the working fluid flowing through the tubes. The thermal energy is removed by conduction process to the working fluid which is the useful energy gain. The heat energy which is transferred mainly depends on two factors: (John A. Duffie, 2006) (Cruz-Peragon *et al.*, 2012)

- convective heat transfer coefficient between the tube wall and the fluid (h_f)
- thermal resistance (bond conductance) between the tube wall and the fin (C_b).

The overall heat gain to the working fluid is expressed as:

$$Q' = \frac{T_b - T_f}{\frac{1}{h_f \pi D} + \frac{1}{C_b}} \quad (19)$$

Where,

T_f = local temperature of the working fluid

D = internal diameter of the tube

C_b = bond conductance

For better performance of collector, the bond conductance needs to be of a minimum value. (Whillier A., 1963) concluded that good metal to metal contact is needed so that bond conductance is greater than 30W/m°C or else there would be a significant loss of performance of the collector. (John A. Duffie, 2006) The bond conductance is defined by bond thermal conductivity (k_b), average bond thickness (γ) and bond width (b).

$$C_b = \frac{k_b b}{\gamma} \quad (20)$$

Now, eliminating T_b from equation (19), we get,

$$Q' = WF'\left[S - U_L(T_f - T_\infty)\right] \tag{21}$$

The term F' in the equation is the collector efficiency factor.

$$F' = \frac{{}^{1}/_{U_L}}{W\left[\frac{1}{U_L[D + (W - D)F]} + \frac{1}{C_b} + \frac{1}{h_f \pi D}\right]} \tag{22}$$

Where,

W = the distance between the tubes

D = the diameter of the tube

F = fin efficiency parameter

At a particular location, F' represents the ratio of the actual useful energy gain to the useful gain that would result if the collector surface had been at the local fluid temperature. F' physically represents the ratio of thermal resistance between the collector surface and ambient air to the thermal resistance between the working fluid and surroundings. Thus, F' is the ratio of two heat transfer coefficients.

$$F' = \frac{U_O}{U_L} \tag{23}$$

For any collector design and fluid flow, the collector efficiency factor (F') remains constant. It is a function of overall heat loss coefficient (U_L) and h_f. Both parameters are dependent on temperature but not a strong function of temperature. Another factor on which F' depends is the fin efficiency factor F which has a strong dependence on temperature. F' varies inversely with the overall heat loss coefficient. (John A. Duffie, 2006) (Özil and Yaşar, 1987; Luo *et al.*, 2018)

V. **<u>Collector Heat Removal Factor (F_R):</u>** The expressions for η_p and F' were both derived with the basic assumption that the transport fluid temperature T_f remained constant within the collector. But practically T_f increases along the length of the tube. The quantity which relates the useful energy gain by the collector to the energy gain if the collector surface were at the fluid inlet temperature is the collector heat removal factor F_R. (John A. Duffie, 2006) (Özil and Yaşar, 1987)

$$F_R = \frac{\dot{m}C_P(T_{fo} - T_{fl})}{A_c[S - U_L(T_{fl} - T_\infty)]} \tag{24}$$

Now, removing the T_f from the equation and using F', we obtain:

$$F_R = \frac{\dot{m}C_P}{A_c U_L}\left[1 - exp\left(-\frac{A_c U_L F'}{\dot{m}C_P}\right)\right] \tag{25}$$

Where,

m = the mass flow rate of the working fluid

$\mathbf{C_P}$ = the heat capacity of the fluid

VI. **<u>Collector Flow Factor (F''):</u>** The collector flow factor F'' is the ratio of the F_R to F'. The collector flow factor is a function single variable dimensionless quantity, the collector capacitance rate. (John A. Duffie, 2006) (Özil and Yaşar, 1987; Cruz-Peragon *et al.*, 2012)

$$F'' = \frac{F_R}{F'} = \frac{\dot{m}C_P}{A_c U_L F'}\left[1 - exp\left(-\frac{A_c U_L F'}{\dot{m}C_P}\right)\right] \tag{26}$$

The quantity F_R is the ratio of the actual heat transfer to the maximum possible heat transfer. The maximum rate of heat transfer from a collector occurs when the collector surface remains at the temperature of the inlet fluid. The loss to the surrounding becomes minimum then. The actual useful energy obtained is then given as the product of the collector heat removal factor (F_R) and the maximum possible heat energy obtained. (John A. Duffie, 2006)

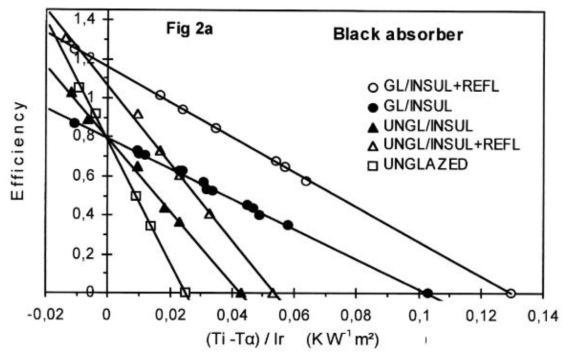
$$Q_u = A_c F_R[S - U_L(T_i - T_\infty)] \tag{27}$$

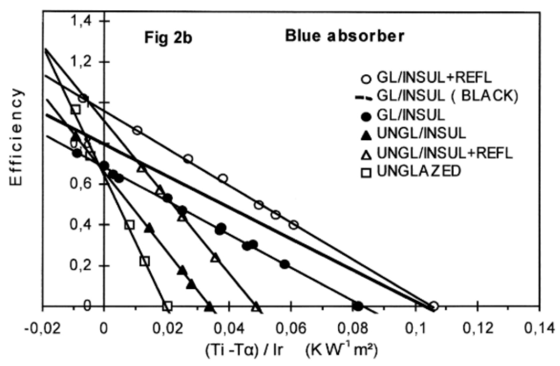
<u>Improvement of Performance:</u>

Performance of solar flat plate collectors is always of the highest priority. Researchers across the globe are working relentlessly to make the collectors more efficient and cost effective. A significant amount of improvements of solar flat plate collector can be done but the priority should be maximum increment of annual heat collection with minimum cost. Before going into details of the performance analysis, first, we need to define some parameters based on which we can discuss the improvements. Typically, a flat plate thermal collector is made of glazing covers, plates for absorbing heat, insulating layers, pipes filled with working fluid and other components as well. Every component has some very specific tasks which contribute to the overall system efficiency. Improvement in the performance will be discussed upon these factors with details examination of different materials to build the components.

Glazing can be made of glass and can be of single layer or multiple layers. It can also be made of other materials which behave transparent to short wave radiation but blocks the long wave radiation. The task of a glazing is to reduce convection loss as well as to reduce irradiation losses. Low-iron glass is a great candidate for the glazing material. It has a transmittance of approximately 0.85-0.87 for solar radiation and a zero transmittance for radiation between 5µm-50 µm.(Khoukhi and Maruyama, 2005) It is founded that Teflon film or Teflon honeycomb structure used as a second glazing can increase the performance of the thermal collector. An overall performance increase of 5.6% is observed at 50 ºC operating temperature whereas a 12.1% increase is seen at the same operating temperature by using Teflon honeycomb (reduces convection loss). Antireflection coating is another option to increase overall performance. At 50ºC operating temperature 6.5% increase in performance can be achieved by using antireflection treatment.(Hellstrom *et al.*, 2003).

Mostly, the absorber plate is coated with black surfaces so that maximum heat can be absorbed. "Desirable selective surfaces usually consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to long-wave thermal radiation, and a thin lower layer that has a high reflectance and a low emittance for long-wave radiation." (Tian and Zhao, 2013). Different color coatings have also been proposed. In the experiment blue and red-brown color absorbers are inspected. Efficiency of the collector is close to that of using a black observer but color paints of black tone is a requirement. These observers are efficient in variety range of operating temperature. The results are shown below:





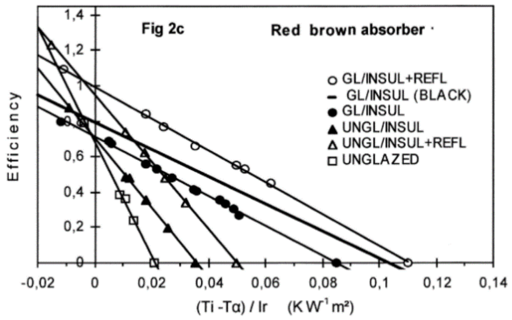


Fig. 2. Steady state efficiency results of the tested collector models.

Figure: Comparison of coating of absorber plate using different color (Tripanagnostopoulos, Souliotis and Nousia, 2000)

Another proposed and examined type of absorber plate is nickel pigmented aluminium-oxide. By using this absorber net collective flux was increased highly when absorptivity goes high with constant emissivity but the conversion efficiency increased a little. (Wazwaz *et al.*, 2002)

To get an optimal performance, not only thermal performance improvement is necessary but also it is needed to reduce losses form absorber plates. A honeycomb structure made of transparent material and inserted into the air gap between the glazing and the absorber is beneficial to prevent heat loss form the absorber plate. (Francia G., 1961)

System overheating is one of the main problems of a solar flat plate collector which needs to be addressed. One of the easiest ways to prevent system overheating is transferring of the heat energy, absorbed by the absorber, rapidly to system's work fluid (Slaman and Griessen, 2009). Good heat transfer is a must in solar receivers (Tian and Zhao, 2013). Introduction of porous insertion significantly affect the heat transfer of solar receivers. With this insertion heat transfer improves but it introduces a pressure drop as a penalty. "The heat transfer was augmented in all receivers due to increase in heat transfer area, thermal conductivity and turbulence. The maximum heat transfer coefficient is achieved in top half porous disc receiver with H = 0.5di, w = di at h =30° with reasonable drag. The percentage increases in Nusselt number for optimum receiver configuration is 64.2% compared to tubular receiver at Reynolds number of 31,845 with the pressure drop of 457 Pa. There is a scope to optimize the receiver configuration with other working fluids, materials different porosity values of the receiver." (Ravi Kumar and Reddy, 2009) The heat transfer from the solar collectors can be improved significantly by introducing oscillating laminar flow of working fluid inside the recuperating pipes. Oscillating flow increases the thermal diffusivity of the working fluid which contributes to overall increase in thermal efficiency (Lambert, Cuevas and del Río, 2006). Another way of increasing efficiency is employing a recycle type double pass device for solar receiver. This method works by increasing velocity of the working fluid. The system takes advantages of premixing and recycle effects to increase the inlet temperature leading to an improved thermal performance. Performance of solar collector is improved basically for higher fluid velocity and higher heat transfer co-efficient. A penalty of this system is decreasing of temperature difference based on which heat transfer takes place. (Ho, Yeh and Wang, 2005).

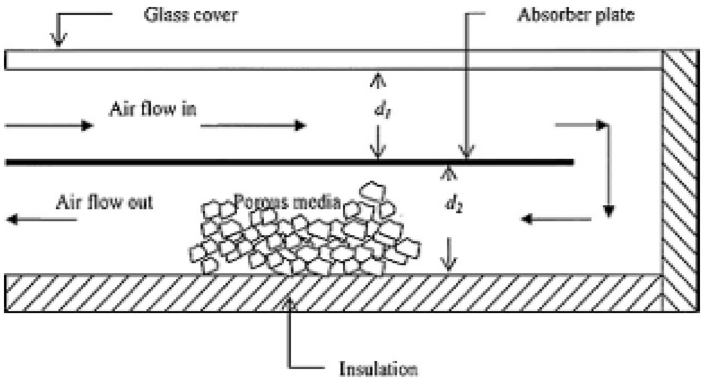


Figure: Schematic of double passage solar collector with porous media in the second channel (Sopian *et al.*, 2009).

In the figure d1 is the upper channel depth and d2 is the lower one. This experiment investigated the variable d1 and d2 in order to find an optimal one.(Tian and Zhao, 2013)

Sopian et al., (2009) proved if there is a porous media in the second channel then the outlet temperature increases as a result overall thermal efficiency of the system improves. Another study suggests that using different fins thermal performance can be increased. “The overall panel heat transfer increases when the fin pitch (or the fin angle) is decreased, when the fin thickness is increased, and when the thermal conductivity ratio is increased. The streamwise pressure drop increases with decreasing fin pitch (or fin angle) and increasing fin thickness. For a fixed fin thickness, the selection of a small fin pitch (or fin angle) over the range studied results in a higher heat transfer enhancement per unit pumping power.” (Ackermann, Ong and Lau, 1995) Polycarbonate honeycombs can be implemented to obtain better heat transfer rate. CFD modelling was used to determine the effects and confirmed with the theoretical results (Martinopoulos *et al.*, 2010). Exergetic study shows that, “By increasing the incident solar energy per unit area of the absorber plate, the exergy efficiency increases. The exergy efficiency decreases rapidly when the ambient temperature and the wind speed increase. Since these parameters change during the day, for having the maximum exergy efficiency other parameters and the solar collector operating conditions should change during the day and the design of solar collector should be based on the daily average of these parameters. The design parameters such as pipes’ diameter have a little effect on the exergy efficiency.” (Farahat, Sarhaddi and Ajam, 2009)

“In addition, Selmi et al. (2008) simu- lated heat transfer phenomena in flat-plate solar collectors using commercial CFD codes by considering the mixed heat transfer modes of conduction, convection and radiation between tube sur- face, glass cover, side walls and insulating base of the collector, and their results achieved good agreement with test data.”(Selmi, Al-Khawaja and Marafia, 2008) (Tian and Zhao, 2013).

Conclusion:

Details description of the solar flat plate collector is presented in this paper, including mechanism of construction and working principle, mathematical background to evaluate its performance, applications as well as a qualitative approach to find out the areas where research can be done to enhance the performance. Improvement of performance are described mostly based on thermal performance enhancement. Different materials are examined for making the components like absorber plate, glazing etc. to maximize efficiency.

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