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An investigation on the performance characteristics of solar flat plate collector with different selective surface coatings

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Abstract
In the present work, investigations are made to study performance characteristics of solar flat plate collector with different selective surface coatings. Flat plate collector is one of the important solar energy trapping device which uses air or water as working fluid. Of the many solar collector concepts presently being developed, the relative simple flat plate solar collector has found the widest application so far. Its characteristics are known, and compared with other collector types, it is the easiest and least expensive to fabricate, install, and maintain. Moreover, it is capable of using both the diffuse and the direct beam solar radiation. For residential and commercial use, flat plate collectors can produce heat at sufficiently high temperatures to heat swimming pools, domestic hot water, and buildings; they also can operate a cooling unit, particularly if the incident sunlight is increased by the use of reflector. Temperatures upto 70 ^{o}C are easily attained by flat plate collectors. With very careful engineering using special surfaces, reflectors to increase the incident radiation and heat resistant materials, higher operating temperatures are feasible.

Keywords: Selective surface coatings; Solar flat plate collector; Collector performance.

1. Introduction

Solar water heaters play a vital role in low temperature applications especially in domestic sector [1]. Solar collector absorbs the incoming solar radiation, converting it into thermal energy at the absorbing surface, and transferring the energy to a fluid flowing through the collector. The fluid may be used for various purposes such as to heat the building and to dry the agricultural products etc. The solar energy has two main factors in its favor. Firstly, unlike fossil fuel and nuclear power it is environmentally clean source of energy. Secondly, it is free and available in adequate quantities in almost all parts of the world where people live. However there are many problems associated with the use of solar energy. The solar radiation flux available in the hottest regions on earth rarely exceeds 1 kW/sq-m; these are low values from the point of view of technological utilization. Hence large collecting areas are required. The second problem is that its availability varies widely with time, because of the day night cycle and also seasonally because of earth's orbit around the sun.

The flat plate collector forms the heart of any solar energy collection system designed for operation in the low temperature range, from ambient to 60 ^{o}C, or the medium temperature range, from ambient to 100 ^{o}C. Currently, the use of solar water heaters in households is becoming more prevalent due to their low electrical cost as compared to conventional electric heaters [2]. The principle behind a flat plate collector is simple. If a metal sheet is exposed to the solar radiation, the temperature will rise until the

rate at which energy is received is equal to the rate at which heat is lost from the plate; this temperature is termed as equilibrium temperature. If the back of the plate is protected by a heat insulating material, and exposed surface of the plate is painted black and is covered by one or two glass sheets, then the equilibrium temperature will be much higher than that for the simple exposed sheet. This plate may be converted into a heat collector by adding a water circulating system, either by making it hollow or soldering metal pipes to the surface, and transferring the heated liquid to a tank for storage. Flat plate collectors are useful in supplying thermal energy at moderate temperatures up to the normal boiling point of water 100 °C [4]. This is precisely the operating range required for these applications. They are durable and effective. Flat-plate collectors are in wide use for domestic household hot-water heating and for space heating, where the demand temperature is low. Many excellent models of flat-plate collectors are available commercially to the solar designer. Flat-plate collectors fall into two basic categories: liquid and air. In a liquid collector, solar energy heats a liquid as it flows through tubes which are adjacent to the absorber plate. For this type of collector, the flow tubes are attached to the absorber plate so the heat absorbed by the absorber plate is readily conducted to the liquid. Air collectors are simple, flat-plate collectors used primarily for space heating. The absorber plates in air collectors can be metal sheets, layers of screen, or nonmetallic materials. The air flows past the absorber by natural convection or when forced by a fan. Because air conducts heat much less readily than liquid does, less heat is transferred between the air and the absorber than in a liquid collector.

An energy efficient solar collector should absorb incident solar radiation, convert it to thermal energy and deliver the thermal energy to a heat transfer medium with minimum losses at each step. It is possible to use several different design principles and physical mechanisms in order to create a selective solar absorbing surface [6]. Two types of special surfaces, of great importance in solar collector system are selective and reflective surfaces. Selective surfaces combine a high absorptance for radiation with a low emittance for the temperature range in which the surface emits radiation. This combination of surface characteristics is possible because 98 per cent of the energy in incoming solar radiation is contained within wavelengths below 3μm, whereas 99 per cent of the radiation emitted by black or gray surfaces at 400 K is at wavelengths longer than 3 μm. Almost all black selective surfaces are generally applied on the metal base which provides low emittance for thermal radiation and simultaneously good heat transfer characteristics for photo thermal applications. Solar radiation may be collected as shown in Figure 1 (a) where most of the energy is absorbed and a small amount of energy reflected and radiated by the surface. Such a surface is called good selective surface. However if the particular surface does not have good enough selectivity, it may be enhanced by adding one or more filters as shown in Figure 1 (b). This will allow the incoming solar energy to hit the absorbing surface but will prevent the energy radiated from this surface from escaping. Similarly a reflector may be added which will reflect the energy towards the absorbing surface and thus prevent it from escaping as shown in Figure 1 (c). This arrangement can be repeated any number of times and the surfaces can be stacked one on the top of the other. Selective absorbing coatings can be divided into various classes depending upon the mechanism associated with the functional performance.

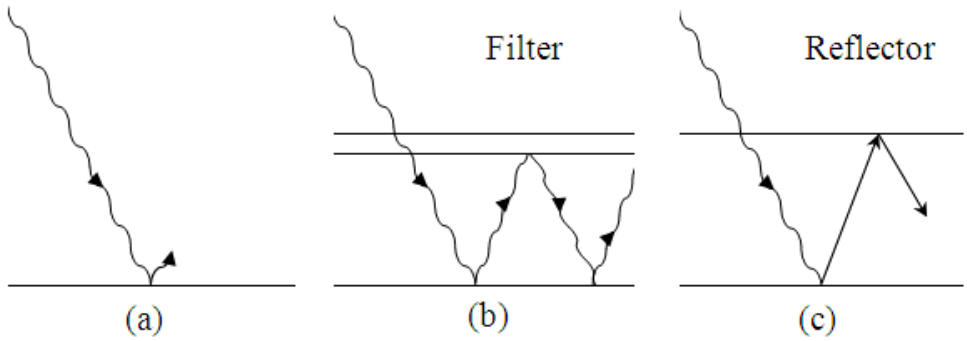

Figure 1. Various mechanisms for absorption of photo thermal energy [3]

A surface that has a high absorptance and is a good absorber of solar radiation usually has a high infrared emittance as well and is a good radiator of heat. A flat-black paint that absorbs 96% of the incoming solar energy will also reradiate much of the energy as heat, the exact amount depending on the

temperature of the absorber plate and the glazing. Ideally, one would like a surface to be selective, absorbing all the solar wavelengths and emitting none of the heat wavelengths, so that more heat could be transferred to the working fluid; for such a surface, $\alpha = 1$ and $\varepsilon = 0$. Selective absorbers can be manufactured to approach this ideal, and several are available commercially. Selective absorbers often consist of a very thin black metallic oxide on a bright metal base. The oxide coating is thick enough to act as a good absorber, with $\alpha = 0.95$, but it is essentially transparent to longer wavelength heat radiation, neither absorbing nor emitting much of the 3 to 30 micron radiation. On the other hand, the bright metal base of the absorber surface has a low infrared emittance and radiates very little heat. The combination, in effect, gives a surface that is a good absorber but a poor radiator. As a result, the efficiency of the collector is greater when this type of surface is used [3].

2. Types of Black Selective Coatings

Selective coating of the heating panel has been suggested to increase the energy absorbing properties. By way of example, a solar heating panel may be coated with black paint which is expensive and absorbs a great amount of solar energy. However, it has been found that paint flakes, chips, and it is not very durable. Black paint also enables much of the absorbed energy to be lost by emittance.

Selective surface coatings can be prepared by using the following techniques:

1. Vacuum evaporation
2. Vacuum sputtering
3. Ion exchange
4. Chemical vapour disposition
5. Chemical oxidation
6. Dipping in chemical baths
7. Electroplating
8. Spraying
9. Screen printing, and
10. Brass painting method, etc.

Black nickel has also been used as a coating for solar heating panels. Black nickel is good heat conductor, but coatings of this material are vulnerable to moisture. Various attempts have been made to improve the black nickel coatings. For example, a substrate is first coated with bright nickel and then overlaid with a layer of black nickel. However this bright-black nickel selective coating has been difficult to control in the deposition of black nickel coating in order to achieve the desired optimum properties and coating thickness. As the black nickel is being deposited, the substrate cannot be removed from the plating bath without the requirements for stripping the black nickel and restarting the deposition process again. Also, the black nickel, as deposited, is still subject to corrosion from the atmosphere and other sources. These problems have been solved by the present invention where in black chrome is utilized as the selective solar coating. The black chrome deposit has a high absorptivity in the visible range and a low emissivity in the infrared range when the coating is between about 0.5 micron and about 2.5 microns.

The nickel black coating over shining metal substrate is produced by electro deposition which is used commercially in solar water heaters. The metal base on which the nickel black coating is to be obtained is first perfectly cleaned and dried as per standard chemical cleaning techniques. The black coating is then obtained by immersing the substrate as a cathode in an aqueous electrolytic bath containing 75 gm nickel sulphate ($NiSO_4$), 28 gm zinc sulphate ($ZnSO_4$), 24 gm ammonium sulphate ($(NH_4)2SO_4$), 75 gm nickel sulphate ($NiSO_4$), 28 gm zinc sulphate ($ZnSO_4$), 17 gm ammonium thiocynate (NH_4SCN) and 2gm citric acid ($C_6H_8O_7$) per litre.

The most successful and stable selective surfaces developed so far is black chrome. It is made by electroplating a layer of bright nickel on absorber plate, then electrodepositing an extremely thin layer of chromium oxide (black chrome) on the nickel substrate. Black chrome coatings have been extensively investigated and recommended even for very high temperature applications. Black chrome coatings were applied on copper substrate. The coatings have average solar absorptance of 0.93 and thermal emittance of 0.10 and good humidity resistance. Black chrome on copper shows good selectivity and humidity resistance but is not feasible because of the high cost of copper substrate. Bath composition per liter is 400 gm chromium oxide (CrO_3), 60 gm sodium hydroxide (NaOH), 0.5 gm hexafluorosilicic acid ($H_2Si F_6$), 2.5 gm sucrose ($C_{12}H_{22}O_{11}$) and 7.5 gm barium carbonate ($BaCO_3$).

Black copper oxide coating on copper or aluminium is the most commonly used selective surface and is extensively commercialized in solar collector industries. Before blackening, the copper is buffed to remove dirt and oxide layer to yield a clean bright surface. After being degreased in a boiling bath of metal cleaner, it is washed in clean water and rubber with a soft wire brush to remove gritting particles. It is then dipped for different times in the blackening bath containing the followings per liter of water, at a solution temperature of 140-145°C 100 gm sodium hydroxide (NaOH) and 50 gm sodium chlorite ($NaClO_2$).

Cobalt oxide selective surface can be produced on bright nickel-plated steel substrate by electroplating techniques. The coating is obtained by immersing this plate as a cathode in an aqueous electrolytic bath at 400 ^oC containing per liter 450 gm cobalt sulphate heptahydrate ($CoSO_4$ $7H_2O$), 45 gm Cobalt chloride hexahydrate ($CoCl_2$ $6H_2O$) and 40 gm boric acid (H_3BO_3).

Solchrome is manufactured by electrochemically cleaning the copper sheets after which they are electroplated with nickel. Subsequently, black chrome is electrochemically deposited over the nickel coating in a continuous process. Subsequent to the nickel application the copper is rinsed again before the black chrome solar selective coating is applied and thereafter the surface is subjected to a series of chemical rinses after which it undergoes an extensive drying period.

Table 1. shows properties of some important selective coatings. The objective of the design of a solar collector is to maximize the absorption of solar radiation but minimize thermal loss from the plate to the surroundings due to radiation. Solar radiation is concentrated at relatively low wavelengths because it is emitted by a high temperature source, the sun. However, the collector the plate emits radiation at relatively high wavelengths because it is (by comparison to the sun) cold. Therefore, an ideal solar collector surface has an absorptivity (which, according to Kirchoff's Law, is equal to the emissivity) that is high at low wavelengths in order to capture the solar irradiation and an emissivity that is low at high wavelengths in order to minimize radiation heat loss. These types of selective surfaces are important for achieving high collector efficiency.

Table 1. Properties of selective coatings [5]

Selective coatings	**α**	**ε**	**α/ε**
Black Chrome	0.93	0.10	9.3
Black Nickel on polished Nickel	0.92	0.11	8.4
Black Nickel on galvanized Iron	0.89	0.12	7.4
CuO on nickel	0.81	0.17	4.7
Co_3O_4 on silver	0.90	0.27	3.3
CuO on Aluminium	0.93	0.11	8.5
CuO on anodized Aluminium	0.85	0.11	7.7
Solchrome	0.96	0.12	8.0
Black paint	0.96	0.88	1.09

3. Experimental Program and Procedure

The Indian standard procedure for testing solar flat plate collectors and reporting the performance was proposed by Bureau of Indian Standards (IS: 12933: 2003, Part 5, Second Revision). Many solar heat collectors employ tubes of copper or other metals to convey heat transport liquid which is heated by contact with the tube walls. Aluminum is desirable as a plate material because of its low cost and high thermal conductivity, while copper is desirable as a tube material owing to its relative freedom from corrosion when used with untreated water. The construction of a flat-plate collector is shown in Figure 2. The basic parts noted are a absorber, transparent or translucent cover sheets, and an insulated box. The absorber is usually a sheet of high-thermal-conductivity metal with tubes or ducts either integral or attached. Its surface is painted or coated to maximize radiant energy absorption and in some cases to minimize radiant emission. The cover sheets, called glazing, let sunlight pass through to the absorber but insulate the space above the absorber to prohibit cool air from flowing into this space. The insulated box provides structure and sealing and reduces heat loss from the back or sides of the collector. In the Table 2 specifications of the fabricated flat plate collector are shown.

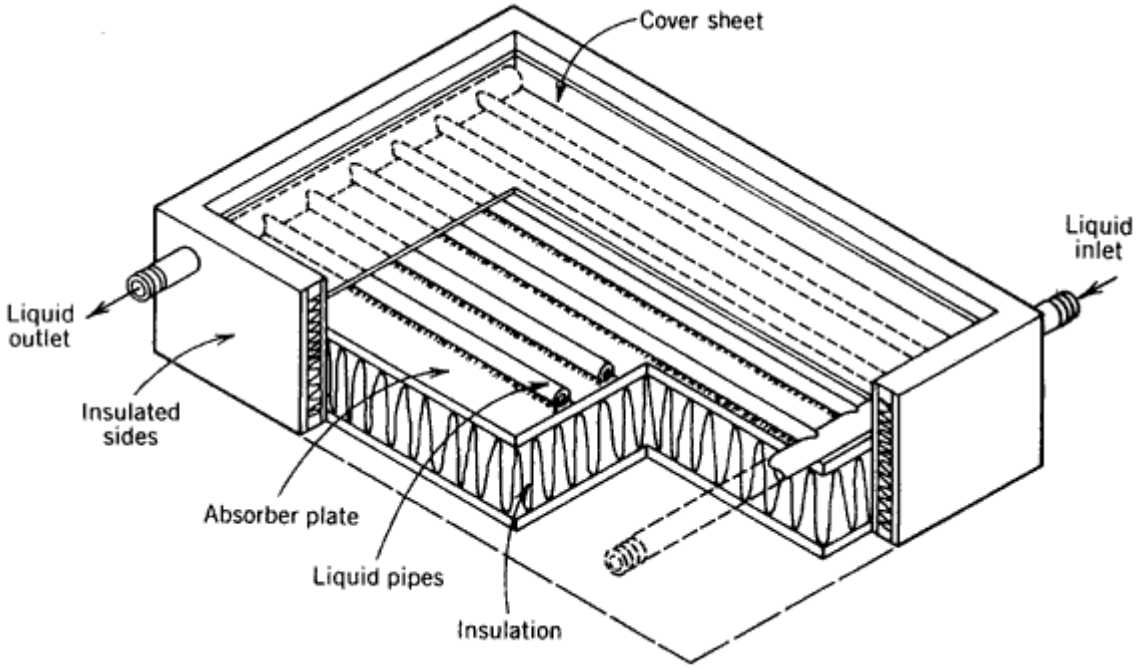

Figure 2. A typical liquid flat-plate collector.

Table 2. Specifications of the fabricated flat plate collector

Description	**Specification**
Collector dimensions (Length x Width x Thickness)	2 m x 1 m x 0.12 m
Collector type	Flat plate
Number of glass covers	1
Glass cover emissivity/absorptivity	0.85
Refractive index of glass relative to air	1.5
Cover material	Low iron glass
Cover thickness	5 mm
Cover transmission	94%
Absorber plate dimensions (Length x Width)	1.85 m x 0.81 m
Absorber plate material	Copper
Thermal conductivity of the plate material	386 W/m °C
Density of the plate material	8954 kg/m^3
Construction type	Fin and tube
Plate thickness	26 gauge
Header material	Copper
Header material thickness	22 gauge
Absorber area	1.5 m^2
Header tuber size	Φ25 mm
Riser material	Copper
Riser tuber size	Φ12.5 mm
Number of riser tubes used	6
Insulation material	Rockwool
Thermal conductivity of insulating material	0.035 W/m °C
Insulation thickness	30 mm
Sheet Material of collector tray	Galvanized iron sheet
Location of collector tray	Davanagere (14.3l° N,75.58°E)

The following are important points in designing a good 'tube and sheet' absorber:

- The fin (absorber sheet) must be made of a material with high thermal conductivity.
- The fin should be thin to minimize the temperature difference required to transfer heat to its base.
- Tubes should not be too spaced to avoid higher temperature difference midway between the tubes.
- Tubes should be thin-walled and of a high-thermal -conductivity material.
- The tube should be brazed or welded to the absorber sheet to minimize thermal contact resistance.
- The tube and absorber sheet should be of similar material to prevent galvanic corrosion between them.

4. Experimental setup and test procedure

The water heater uses a flat plate collector connected to a plastic water tank. Cold water from the overhead tank enters the plastic hot water storage tank. A number of vertical tubes called risers connected to the header. Water from the hot water storage tank enters the flat plate collector through header and vertical tubes. Water gets heated in the risers of the flat plate collector and its density will decrease the lighter density water move up and stored in the hot water storage tank. Higher density water from the bottom of the tank again enters the flat plate collector and gets heated and moves up and stored in the hot water storage tank and vice-versa. Hot water can be drawn from the hot water storage tank for further application. This type of collector is hard to make because it requires the tubes to be accurately drilled and soldered together. The other type, the serpentine collector, uses a single piece of pipe that winds back and forth across the collector as it rises. In this work, we have used three such header and riser arrangement with three different absorber coatings namely Solchrome, Matt black and Black chrome. These three coatings are used for comparing their effect on the performance (solar heat absorption) of flat plate collector. Each arrangement consists of five riser tubes brazed to header tubes with separate inlet and outlet pipes. These three arrangements are enclosed in a galvanized iron box with a cover plate of 5 mm thickness along with rock wool insulation within the enclosure. The inlet and outlet pipes of each arrangement of the collector box are connected to the separate storage tanks of 20 liters capacity with the help of rubber hose pipes. The storage tanks used are made of thick plastic material. For pilot experiments, insulation are not provided on the storage tanks since plastic is a bad conductor of heat. This collector box is fixed to the stand which is made of mild steel, the stand is provided with some inclination adjustment so that the collector box can be inclined with different angles for experimental purpose. Schematic diagram of experimental setup is shown in Figure 3. The inlet of cold water is connected to the bottom header pipe and the outlet is connected to the top header pipe.

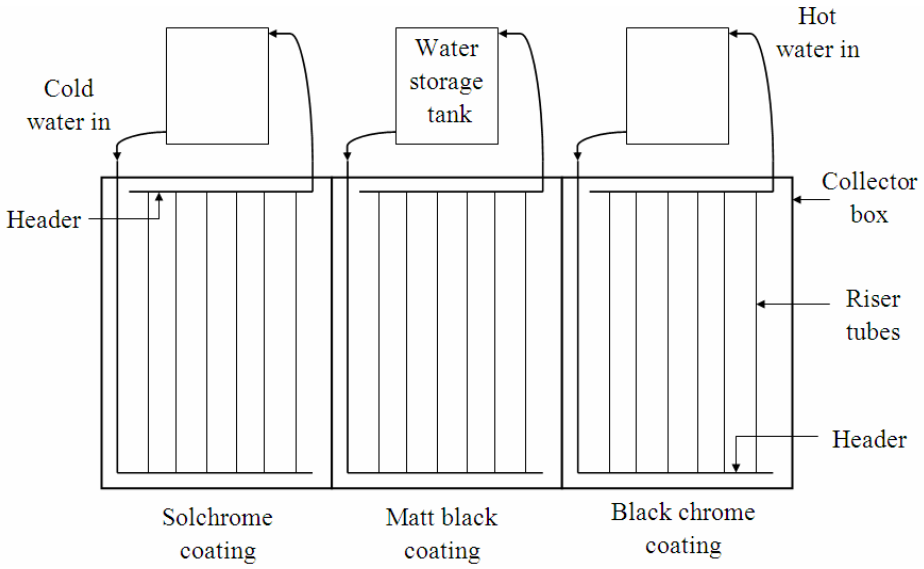

Figure 3. A typical liquid flat-plate collector.

Water is circulated with the help of thermosyphon action throughout the pipe and tank arrangement. The temperature of cold inlet water and hot water in the storage tank were tabulated with the help of thermometer for every 30 minutes from 8.00 am to 4.00 pm.

5. Results and discussions

The useful energy collected from a collector can be obtained from the following formula.

$$\eta = \frac{Q_u}{A_c I_T} = F_R(\tau\alpha) - F_R U_L\left(\frac{T_i - T_a}{I_T}\right) \quad (1)$$

Since the values of F_R, $(\tau\alpha)$ and U_L are essentially constant, it is seen from equation (1) that if η is plotted against heat loss parameter $(T_i - T_a)/I_T$ than a straight line with negative slope would be obtained. The intercept on y-axis (intersection of the line with the vertical efficiency axis) would give the value of $FR(\tau\alpha)$, while the slope of the line i.e. the efficiency difference divided by the corresponding horizontal scale difference would give the value of FR_{UL}.

If experimental data on collector heat delivery at various temperatures and solar conditions are plotted, with efficiency as the vertical axis and heat loss parameter as the horizontal axis, the best straight line through the data points correlates collector performance with solar and temperature conditions. The intersection of the line with the vertical axis is where the temperature of the fluid entering the collector equals the ambient temperature, and collector efficiency is at its maximum. At the intersection of the line with the horizontal axis, collector efficiency is zero. This condition corresponds to such a low radiation level, or to such a high temperature of the fluid into the collector, that heat losses equal solar absorption, and the collector delivers no useful heat. This condition, normally called stagnation, usually occurs when no fluid flows in the collector.

For an understanding of the performance evaluation of the collector, Figures 4, 5 and 6 gives the variation of the water temperature in storage tanks for different absorber selective surface coatings and for 30°, 45° and 60° collector tilt angles. From these figures it is clear that maximum temperature of water is observed for black chrome coating followed by the matt black and solchrome coatings. The experimental results may slightly vary if experiment is conducted on different dates.

Davangere is located at 14.31° N 75.58° E with more than 300 bright sunny days in a year. The water temperatures in the storage tank are measured and recorded for different angles of collector. Experiment was conducted from 8.00 am to 4.00 pm on four different days for a particular collector angle such as 30°, 45° and 60°.

Figure 7 shows the variation of difference between hot water outlet temperature and cold water inlet temperature versus time for different tilt angles for collector with an absorber coated with black chrome. From this plot it is evident that higher temperature difference between hot water outlet and cold water inlet is observed for 30° tilted collector with black chrome coated selective surface absorber.

Figure 8 shows the comparison between collector efficiency for three different tilt angles for collector with an absorber coated with black chrome. It is observed from the Figure 8 that efficiency is maximum for 30° tilted collector having an absorber coated with black chrome.

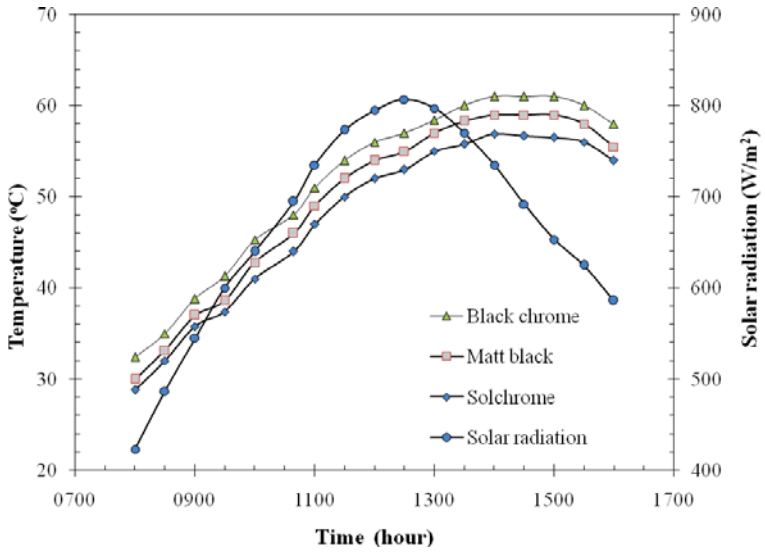

Figure 4. Variation of water temperature in storage tank for 30° collector tilt

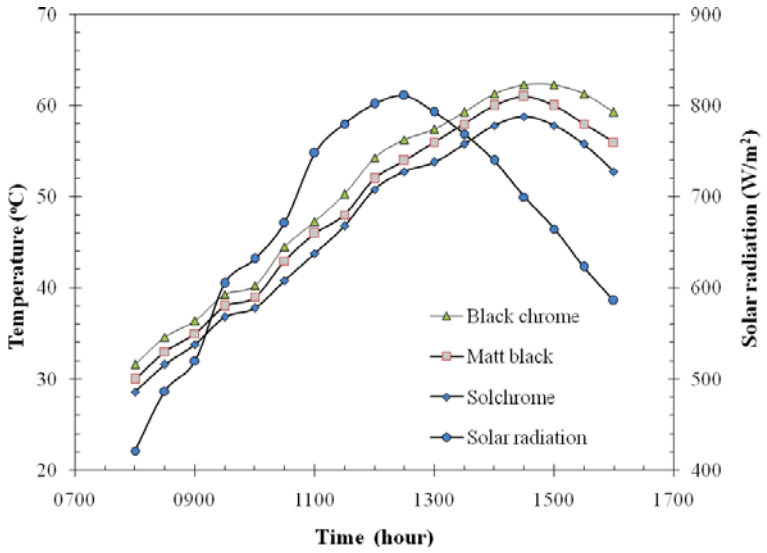

Figure 5. Variation of water temperature in storage tank for 45° collector tilt

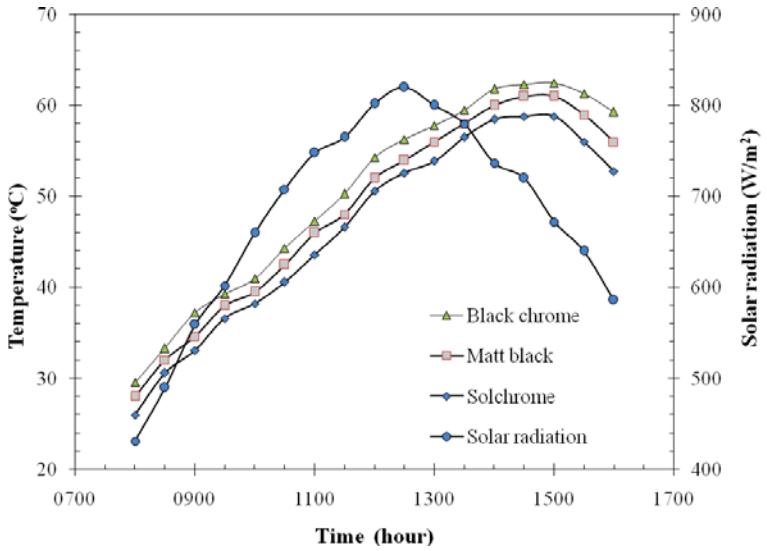

Figure 6. Variation of water temperature in storage tank for 60° collector tilt

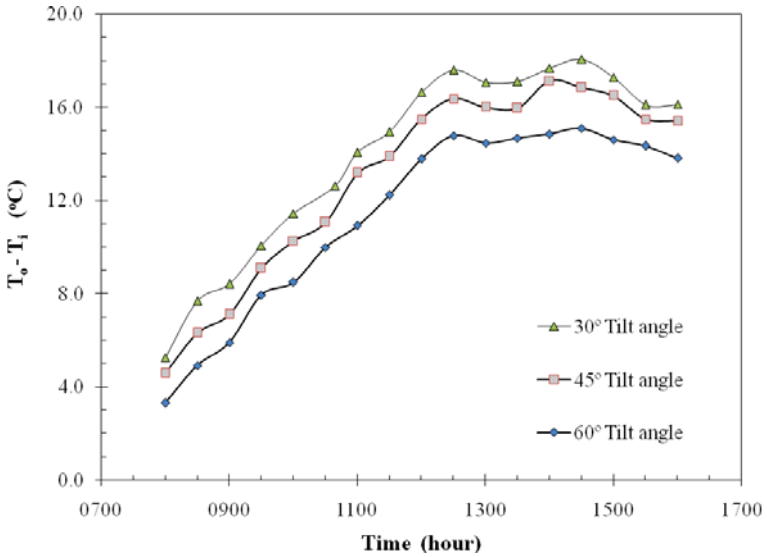

Figure 7. Variation of water inlet and outlet temperature for different collector tilt angles with an absorber coated with black chrome

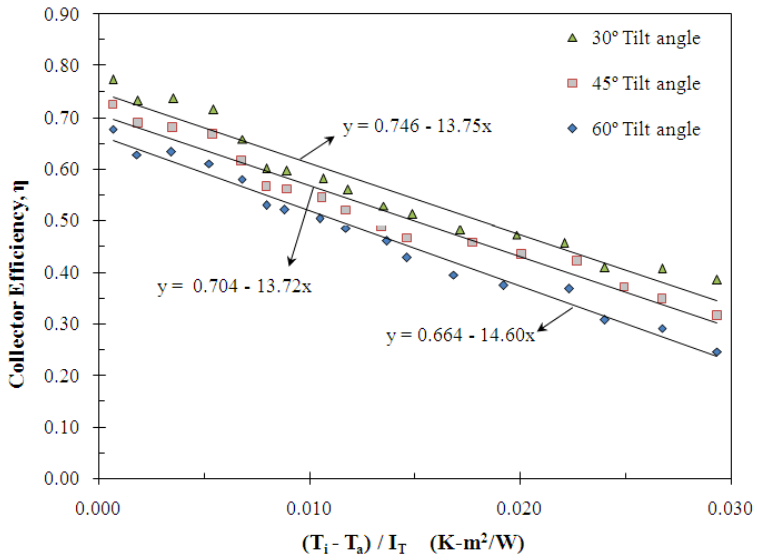

Figure 8. Thermal efficiency versus (Ti – Ta)/IT for different collector tilt angles with an absorber coated with black chrome

5. Conclusions

In this project work three different coatings for solar flat plate collectors are used and water temperature in the storage tank are recorded. The main use of this technology is in residential buildings where the demand for hot water has a large impact on energy bills. In the last few years, significant advances have been made in the development of flat plate collectors. In summary, it can be said that selection of appropriate absorber coating influences the absorber temperature and hence the water temperature in the collector.

- Selection of absorber coatings has influence on the performance of flat plate collectors.
- Maximum temperature of hot water in the storage tank is obtained for black chrome coating when compared to other two coatings which are used in this work.
- Higher temperature of water is observed for black chrome coating followed by the matt black and solchrome coatings.
- The thermal efficiency of collector is highest for black chrome coating. It is clear that, for 30^o tilt angle, the intercept is about 0.746 and the slope 13.75.
- Difference in temperature of hot water outlet and cold water inlet is maximum for black chrome during experimentation for a collector tilted at an angle of 30^o.
- Performance of solar thermal absorber can be improved by change of absorber materials and coating thickness.

Nomenclature:

A_c	Collector gross area (m^2)
F_R	Heat removal factor
I_T	Incident solar radiation (W/m^2)
Q_u	Rate of useful energy gained (W)
T	Temperature (K)
U_L	Heat loss coefficient (W/m^2 K)
α	Absorptivity
ε	Emissivity
η	collector efficiency
τ	transmissivity

Subscripts

a	Air or ambient
i	Inlet
o	Outlet

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