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Solar Thermal Energy Utilization using Metal Fiber Reinforced Concrete (MFRC) Collector for Producing Hot Water in Sultanate of Oman

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Abstract**:** ***Conventional flat plate collectors makes use of a large amount of metals such as Copper, Aluminium and Galvanised iron or steel for the collection and transport of solar thermal energy for useful heat gain. Studies on the energy inputs required for the production of these different materials indicate that a large amount of fossil fuel energy is required for their production at different stages. Absorber plate for conventional FPC requires comparatively more metal when compared to other parts of the system. In the present paper it is replaced using cheap material such as concrete reinforced with waste metal fibres. Three metal fibres namely copper (Cu), mild steel (MS) and aluminium (Al) of average size 3 mm have been added with volume fraction varying from 0.0011 to 0.0068. Thermal conductivity of the metal fibre reinforced concrete increase more significantly with addition of copper, when compared to MS and Al. Plate thickness of 25 mm has been fixed based on collector efficiency factor analysis for flat plate collector of size 2 m x 1 m. Experiments conducted revealed that hot water at 50-60ºC at 60 kg/hr with daily average efficiency of 55 – 65 % can be supplied from FPC in winter season.***

Keywords**:** ***Metal Fiber Reinforced Concrete (MFRC), Flat Plate Collector (FPC), Solar Energy.***

I. INTRODUCTION

The importance of renewable energy sources in any future energy scenario is generally accepted. Solar energy is one of the major source of renewable energy in the tropical regions of Sultanate of Oman [11]. It has the advantage of being available free of cost and in abundance. In addition, unlike fossil fuels it is an environmentally clean source of energy. However the main problem is that it is a dilute source of energy. Consequently, large collecting areas are required, resulting in high costs. Thus, the real challenge in utilizing solar energy as an alternative source of energy is of an economic nature [13]. One has to strive for the development of cheaper methods of collection, so that the large initial investments required in most applications are reduced.

Various types of collectors are employed for the utilization of solar energy. Among them, flat-plate collectors are simple to construct and easy to operate. They are, therefore, widely used over the world for numerous applications such as water heating, air heating and industrial process heating. Conventional flat-plate collectors (FPC) manufactured presently makes use of a large amount of metal (e.g. Cu, Al, and galvanized iron or steel) for the collection and the transport of solar energy. But studies on the energy inputs required for the production of different materials indicate that metals need a large amount of fossil fuel energy for their production [2] [7]. Furthermore, in case of FPCs individual collector modules are connected to form a large array to meet the required energy demand. Thus the solar systems form a separate entity and consequently, to build and install a solar heating system requires an "up-front" investment of fossil fuel. It may take quite a few years to recover these investments from the insolation collected by a solar system. By that time, the system itself may need replacement. So as long the energy cost of a solar system is comparable with the insolation they collect, they can hardly be regarded as a "solution" to our energy problems, on an overall basis. However, this does not mean that the solar heating systems are impracticable. On the other hand, an important factor that needs to be considered in the design and fabrication of solar collectors is the investment of energy. One must avoid using materials which requires a great deal of energy in their production. Instead, efforts need to be made to develop collectors from relatively low energy cost materials such as concrete, ceramics, etc. Furthermore, it would seem desirable that solar collectors be made an integral part of building elements like the roof and walls. Consequently the separate solar system investment would be partially merged in to the building construction investment. The present paper gives the performance analysis for solar flat plate collector made out of metal fibre reinforced concrete as absorber for providing hot water. Such FPCs when integrated with the building structures are likely to be more cost effective than the conventional systems having metal absorber plates. Moreover when integrated with building rooftop, they will reduce the solar thermal load on the air-conditioning systems installed in the buildings of Sultanate of Oman.

II. CONCEPT OF ENERGY SPENT

Solar thermal collectors use a large amount of energy intensive materials such as Cu, Al, galvanized iron, etc. Table 1 gives the average energy required in the form of heat to make various raw materials and products.

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It is a little startling to realize that a large quantity of energy is used in the case of metals. On the other hand there are materials like concrete and bricks which consume far less energy in their production.

Table 1 Energy Requirement for Some Materials [6] [9]

Materials	Energy Required MJ / kg
Titanium	560.6
Aluminium	283.8
Copper	130.3
Low-density polystyrene	123.2
High-density polystyrene	111.8
Polystyrene	74.2
Polyvinyl chloride	56.8
Plate glass	28.4
Glass wool	28
Steel slabs	27.9
Paper	25.4
Glass	15
Portland cement	8.9
Fireclay brick	4.9
Common brick	4.1
Concrete	1.3
Sand & gravel	0.08
Lumber	0.00105

Based on this information, Payne [7] [8] has estimated the total quantity of energy put in before a collector is ready for use. Though his calculations for the energy invested in materials for the production and maintenance of a flat-plate solar collector system are not exhaustive, they are precise enough to conclude that resulting energy payback time for solar flat-plate collectors could be quite high.

It would therefore be appropriate to look for less energy intensive materials like concrete. Moreover due to higher specific heat capacity thick concrete slabs behaves as heavier thermal mass when compared with thin copper plates as absorber plates; this could be advantageous when employed for solar collectors. Additionally, it would also be desirable to integrate the solar collectors into the building elements like the roof and wall panels appropriately so that the separate solar system investment would be included partially in the investment for the building construction.

III. THERMAL CONDUCTIVITY OF METAL FIBRE REINFORCED CONCRETE (MFRC)

Absorber plates used for solar collectors should have higher thermal conductivity, is one of the requirement for solar flat plate collectors. Concrete thermal conductivity varies from 1.2 to 2.5 W/mK [3] which is very low when compared to metals. Addition of metal fibres improves the thermal conductivity of the concrete along with the strength due to the effect of reinforcement [4]. Waste metal fibres from machining are reinforced into concrete mixture during the preparation for improving its thermal conductivity. Three different materials namely copper, steel and aluminium and their mixtures have been considered for mixing. Thermal conductivity of a composite material is calculated using Voigt Rule of Mixture (ROM) as mentioned below [5],

$$K = \phi K_d + (1-\phi) K_m \qquad (1)$$

K, K_d and K_m are the thermal conductivity of the composite, metal fibres and concrete respectively. ϕ is the volume fraction of metal fibres added.

Fig. 1 shows the variation of concrete thermal conductivity (K_composite) with addition of metal fibres namely copper (Cu), aluminium (Al) and mild steel (MS) for same volume fractions. As expected, thermal conductivity of composite material (MFRC) increases with addition of the metal fibres.

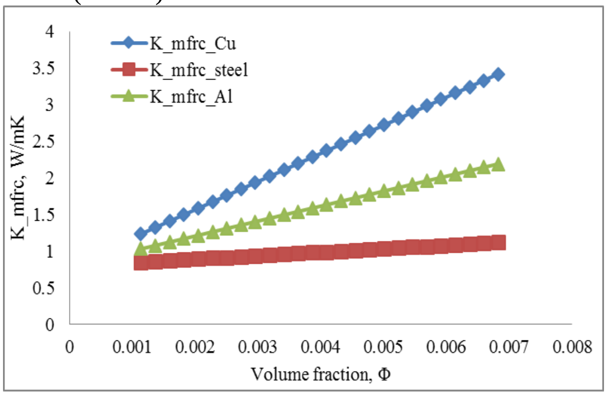

Fig. 1. Variation of thermal conductivity of concrete with copper, steel and aluminium for same volume fraction

For same volume fraction ratio for metal fibres added, thermal conductivity of composite (MFRC) material increases at higher rate with copper. This is due to the highest thermal conductivity of copper when compared to mild steel and aluminium. Thus copper fibres are selected for mixing with concrete as the dispersed medium to improve the thermal conductivity of the MFRC. These fibres are mixed with concrete in the top layer (which is 1/3rd of the total thickness of the plate) such that the thermal conductivity will reduce from top layer to bottom.

An overall thermal conductivity of 3.42 W/mK for MFRC with 0.68 % volume fraction for copper fibres of overall 3 mm average diameter has been considered for further analysis.

IV. MFRC FLAT PLATE COLLECTOR

Collector efficiency factor (F') and heat removal rate (F_R) are important factors in the design of flat plate collectors that signifies the effective useful heat gain and the resistance encountered by absorbed solar radiation in reaching collector fluid respectively.

These factors are affected by plate thickness, tube pitch and the mass flow rate of the fluid for the given value of overall heat transfer coefficient (Ul). The collector efficiency (F') and heat removal (FR) factors calculation has been carried using the following relations [10],

$$F' = \frac{1}{WU_l\left[\frac{1}{U_l\left[(W-D_o)\phi + D_o\right]} + \frac{1}{C_B} + \frac{1}{\pi D_i h_f}\right]} \qquad (2)$$

Where,

$$\text{Fin effieciency factor}(\phi) = \frac{\tanh\left[m(W-D_o)/2\right]}{\left[m(W-D_o)/2\right]} \qquad (3)$$

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$$m = \sqrt{\frac{U_l}{k\delta}} \quad (4)$$

C_B is the adhesive bonding coefficient and $1/C_B = 0$ as no adhesives are used for attaching the tubes to the absorber plate. δ is the plate thickness.

$$F_R = \frac{\dot{m}C_p}{U_l A_p}\left[1 - \exp\left\{-\frac{F'U_l A_p}{\dot{m}C_p}\right\}\right] \quad (5)$$

$\dot{m}$ is the mass flow rate of the water through the tubes. The useful heat gain (Q_{useful}) can be calculated as,

$$Q_{useful} = \dot{m}C_p\left(T_{fo} - T_{fi}\right) \quad (6)$$

The incident solar radiation (S) on the collector is calculated as below,

$$I_T = I_b r_b + I_d r_d + \left(I_b + I_d\right) r_r \quad (7)$$

$$S = I_T \; x \; A \quad (8)$$

A is the absorber surface area in m^2. r_b, r_d, r_r are the tilt factors beam, diffused and reflected radiations. These factors are calculated [10] as shown below.

$$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\phi - \beta) + \cos\delta\cos\omega\cos(\phi - \beta)}{\sin\phi\sin\delta + \cos\delta\cos\omega\cos\phi} \quad (9)$$

$$r_d = \frac{1 + \cos\beta}{2} \quad (10)$$

$$r_r = \rho\left(\frac{1 + \cos\beta}{2}\right) \quad (11)$$

ρ is the ground reflectivity which is assumed as 0.2 for the analysis [10]. δ, ϕ, ω and β are declination angle, location latitude, hour angle and inclination angle for the collector.

The declination angle (δ) for n^{th} day of the year is calculated using the following relation [10],

$$\delta = 23.45\sin\left[\frac{360}{365}(284 + n)\right] \quad (12)$$

The instantaneous efficiency is then calculated using the following relation:

$$\eta_{inst} = \frac{Q_{useful}}{S} x100\ \% \quad (13)$$

A. Effect of design parameters

Effect of design parameters: plate thickness, tube spacing outside coil diameter, the mass flow rate of the water and overall heat transfer coefficient on the performance of the collector in terms F', Ø, and F_R has been considered for the analysis. Final dimensions are finalized based on the analysis.

1. Effect of plate thickness

Plate thickness affects the performance parameters of the collector. Fig. 2 below shows the effect of plate thickness on the performance parameters F', Ø, and F_R.

The tube diameter, tube spacing and the flow rate are kept constant for the analysis. F', Ø, and F_R have least values at lower plate thickness. As plate thickness increases, these factors increases and tends to become constant with plate thickness of 0.04 m. The dimensionless parameter *m* (that affects the heat transfer through the collector), decreases with the plate thickness. This increases the fin efficiency factor Ø causing further increase in F' and F_R. Moreover, increasing the plate thickness also increases the conduction resistance for heat transfer through the base, reducing the heat losses. Additionally, the bottom layer for the absorber is made of plain concrete having large heat capacity. This layer stores the heat loss from the absorber/basin and supplies it back to the working fluid, which in turn increases the overall collector efficiency.

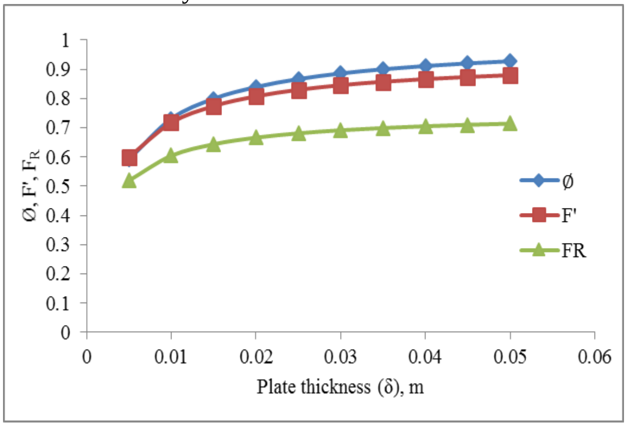

Fig. 2. Effect of plate thickness on FR, F' and Ø

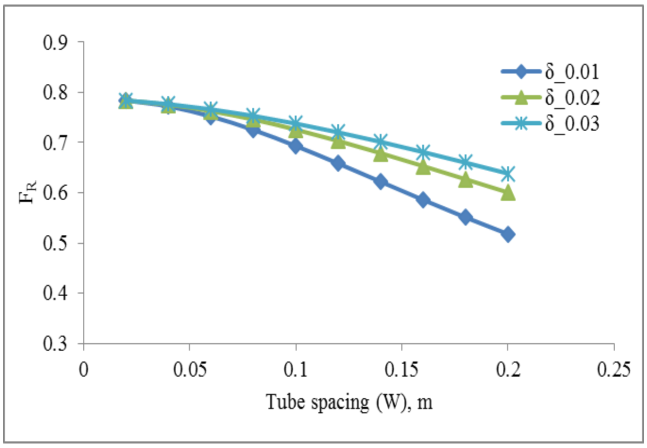

Fig. 3. Effect of tube spacing on FR for different plate thickness

2. Effect of tube spacing (pitch)

Fig. 3 shows the effect of tube spacing on heat removal factor F_R for different plate thickness. The tube diameter, overall heat transfer coefficient and water flow rates are considered constant. As the tube spacing increases F_R values decrease continuously for all the plate thicknesses. The path for heat conduction increases with increase in pitch, causing the decrease in F_R values. For lower plate thickness, F_R decreases more rapidly with tube spacing.

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3. Effect of tube diameter

The tube spacing, water flow rate and the overall heat transfer coefficient are kept fixed for the analysis. As the tube diameter increases, the fin effectiveness of the collector increases for all the plate thickness. The path for conduction heat transfer decrease with increasing tube diameter which increases the effectiveness of the collector.

The effectiveness increases sharply when the plate thickness is increased from 0.01 to 0.02 m. Higher values of effectiveness are observed for 0.03 m of plate thickness. Fig. 4 below shows the variation of the collector effectiveness with tube diameter.

4. Effect of mass flow rate

The tube spacing, overall heat transfer coefficient and tube diameter are kept fixed for the analysis. As shown in Fig. 5, with increasing mass flow rates of water through the tube, the collector heat removal factor increases for all the plate thickness. Increasing the flow rates increases the convective heat transfer coefficient inside the tube, causing the increased heat removal rate.

This also decreases the collector surface temperature decreasing the top loss from the surface to the surroundings. This increases the collector efficiency. But this decreases the outlet temperature of the water from the collector. F_R values are almost independent of plate thickness for all the flow rates.

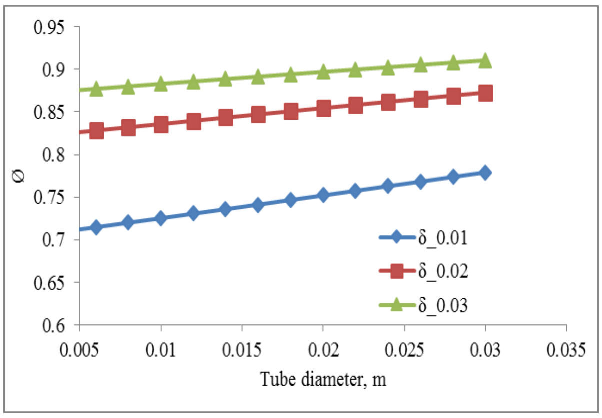

Fig. 4. Effect of tube diameter on Ø for different plate thickness

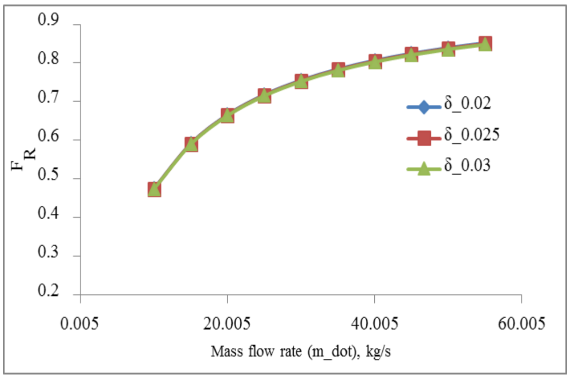

Fig. 5. Effect of mass flow rate on F_R for different plate thickness

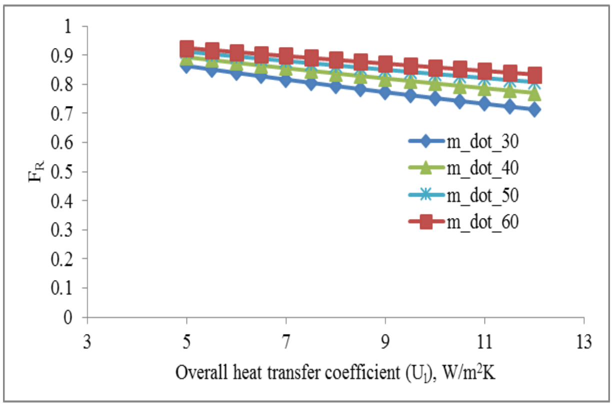

Fig. 6. Effect of Overall heat transfer coefficient on FR for different flow rates

5. Effect of overall heat transfer coefficient

For the fixed values of plate thickness, tube spacing and coil diameter, as the overall heat transfer coefficient increases, the heat losses increases and hence the heat removal factor decreases for all the flow rates of water. Fig. 6 shows the variation.

B. Final design

Following are the final specifications estimated for the MFRC collector based on the analysis and the literature reviewed in Table 2 as below,

Table 2 Final specifications estimated for the MFRC collector

Cement to sand ratio	1:4
Water to sand ratio	0.7
Maximum size of the fine aggregate	3.46 mm
Metal fibres used	Copper
Percentage of metal fibres used	0.68 %
Average size of the metal fibres	3 mm
Average thermal conductivity of MFRC	3.42 W/mK
Absorber plate thickness	0.03 m
Tube arrangement	Serpentine type
Tube outer diameter	0.0127 m
Tube spacing	0.15 m
Number of glass covers used	1
Water flow rate	60 kg/hr
Collector size (length x width)	2 m x 1 m
Absorber coating	Black board paint
Overall heat transfer coefficient	10 W/m²K
Insulation	Wood (plywood)
Collector orientation	North-south (facing south)
Tilt angle	24°
Latitude - Muscat	23.5859°
Longitude - Muscat	58.4059°
Standard time longitude	60°

Fig. 7 & 8 shows the system layout and the pictorial view of the MFRC flat plate collector at the site.

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C. Performance testing and analysis

Fig. 9 and 10 below shows the hourly variation of (Tg – Ta), (Tfo - Tfi), solar radiation incident on the collector surface and the instantaneous efficiency for the MFRC collector for the day at 60 kg/hr.

Tg, Ta, Tfi, and Tfo are glass surface, ambient, water inlet and water outlet temperatures respectively. Ap is the absorber area in m^2. Compared to conventional flat plate collectors MFRC collectors have higher thermal mass.

Due to this the initial temperature difference between Tfo and Tfi is lower as some time needs to be elapsed for heating up to the operating conditions.

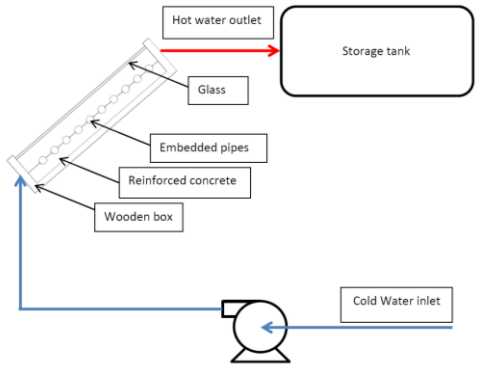

Fig. 7. System layout

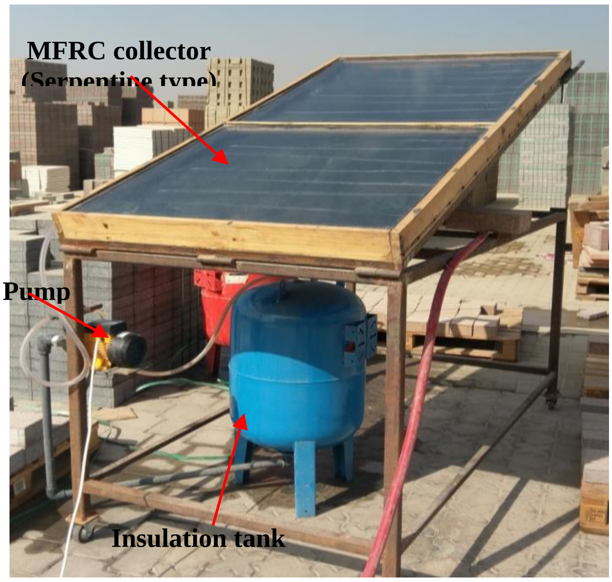

Fig. 8. Pictorial view of MFRC flat plate collector system

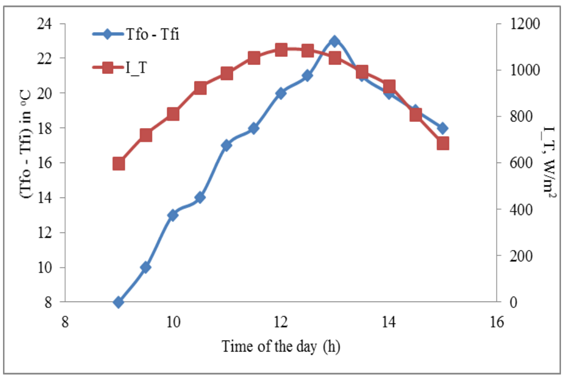

Fig. 9. Hourly variation of solar radiation incident on collector surface and (Tfo – Tfi) at 60 kg/hr

Thereafter the difference increases with hour of the day. A phase difference is observed between the highest temperature difference and the highest solar insolation on the surface of the collector.

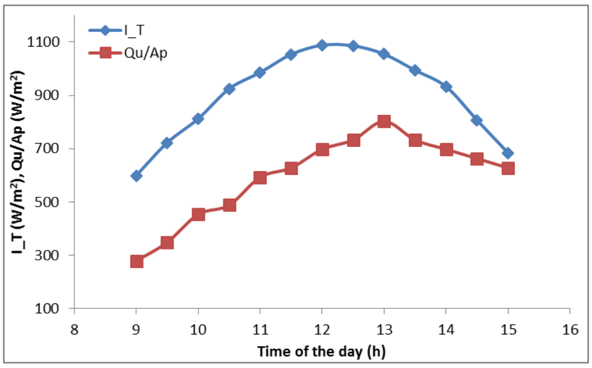

Fig. 10. Hourly variation of solar radiation incident on collector surface and the useful heat gain from the collector at 60 kg/hr for a day

The useful heat gain from the collector increases with increasing solar insolation incident on the collector surface. Unlike conventional collectors, the phase difference of 50-60 minutes is observed between the useful highest heat gain and highest value of I_T. This is due to the higher thermal mass of the collector that delivers higher temperatures after the highest value I_T. Furthermore, due to the same reason collector can deliver useful energy for some time after the sunset. The daily average temperature of the water collected in the insulation tank at the end of the day varies between 50 – 60°C depending on the solar insolation for the fixed temperature and mass flow rate for the inlet water. The average daily efficiency for the collector varies from 55 % to 65%.

V. CONCLUSION

In the present work, the metal absorber plate for FPC has been replaced using metal fiber reinforced concrete (MFRC). Three different waste metal fibers namely steel, aluminum and copper have been considered for the reinforcement of the concrete during the analysis. From the analysis, for same volume fraction ratio, copper fibers improve concrete thermal conductivity significantly and thus selected for further analysis. Based on the performance testing and analysis of the results following conclusions are cited:

- Performance of the MFRC system is comparable with conventional metallic solar flat plate collector systems.
- It is possible to supply hot water at moderate temperatures between 50-60°C with average daily efficiency of 55-65% in day time.
- Due to high thermal lag, this collector could provide hot water even after the sun set for some time.

These collectors can be further integrated with roof top through slight modification to provide hot water at moderate temperatures offering a low cost passive solar water heating system in the building itself. Additionally these roof integrated systems will also reduce the thermal load on the air conditioning systems installed in the building.

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