Effect of Dimples on Solar Concrete Plate Collectors and its Comparison with Other Domestic Water Heating Systems

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Abstract- Though solar water heater is an environment-friendly and a well-established effective method of heating water, yet it is not used on a large scale in a country like India where abundant solar energy is available for most of the year. A large proportion of population prefers the use of electric geysers or stoves over solar water heaters as they have cheaper initial costs. Thus with an objective of low-cost solar collector water heater, an investigation is conducted on concrete as collector plate. In order to improve the efficiency of concrete plate collector, a serpentine tube is used instead of parallel tubes, with the addition of metal fibers in concrete mixture to improve its thermal conductivity and dimples are created on the serpentine tube to enhance heat flow from tube to water flowing through it. In order to calculate the exact effect of dimples on concrete plate collector, dimpled tube collector is compared with smooth tube collector. It is observed that dimples lead to an increase in outlet water temperature and improved efficiency for all water flow rates. Also in this paper, comparison of concrete plate collector with existing systems of domestic water heating for the bathing purpose is presented.

Keywords- Solar water heater; concrete plate collector; metal fibers; serpentine tube; dimpled tube.

1. Introduction

Most of the people use conventional methods like burning of wood, electric geyser, gas geyser to heat water for domestic purposes especially for bathing instead of SWH (solar water heater) despite it being an environment-friendly method. The reasons behind this uneven usage distribution between SWH and conventional methods is a very high difference in initial cost, long payback periods, SWH acquires ample space for its setup, forms dead load on building structure, needs daily sunlight and in the absence of adequate sun rays, it requires a conventional method backup. On the other hand, though conventional methods have low initial cost, their usage leads to the production of air pollutants and greenhouse gasses either directly or indirectly accompanied by fossil fuel consumption which then leads to increase in imports and energy shortage. Besides domestic use, such conventional methods are also used heedlessly in many small scale industries and commercial purposes for hot water applications. Therefore to achieve energy and environmental security it is need of the hour to make optimum utilization of available renewable energy resources, also in domestic water heating purposes by using SWH, as billions of people daily needing hot water bath makes this application of significant importance. Also, the geographical location of India stands to its benefit for generating solar energy.

As the primary reason for lesser usage of SWH is its high initial cost, so an alternative SWH of lower cost made of concrete absorber plate with heat augmentation technique on tube carrying water is designed, fabricated and tested. Concrete is used because of following reasons – low cost, ease of availability, high heat storage capacity, good heat absorbing capacity if painted dark, resistant to thermal and environmental stresses and long life. Some noteworthy works have been conducted on solar concrete plate collectors (CPC) earlier by J. K. Nayak et al. [1] in 1989, Chaurasia [2] in 2000 and V. Krishnavel et al. [3] in 2014. By studying previous works and implementing dimple technique on tubes, a more efficient solar CPC is presented in this paper. Dimples are fabricated on copper tubes carrying water to increase the heat transfer rate from concrete to copper pipe and from pipe to water flowing through it. The effectiveness of dimples has been proved earlier by many investigations conducted by A. García et al. [4], Z. Huang et al. [5], Juin Chen et al. [6], Johann Turnow et al. [7], Pedro G. Vicente et al. [8] and Michele Ciofalo and Massimiliano Di Liberto [9]. Dimpled surfaces cause an increase in heat transfer coefficient with a consequential increase in the friction factor as a result of an increase of the degree of turbulence due to interruption of the development of the boundary layer, rotating and/or secondary flows generation and an increase in effective heat transfer area. Also, no extra material or much additional cost is needed to fabricate dimples on the tube. In addition to dimples, additional turbulence is created due to the serpentine tube which allows mixing of water uniformly, and also they cover maximum collector area absorbing more heat from concrete. In order to calculate the exact effect of the dimpled tube on CPC another identical CPC is fabricated with smooth tube and both are tested simultaneously.

One of the most important aspects of this CPC is that in future, this dimpled tube CPC can be integrated into roof slab of buildings while their construction, acting as SWH as investigated in works of Rangsit Sarachitti et al. [10] Majdi Hazami et al. [11]. Thus it will eliminate dead loads on buildings and make them energy efficient.

2. Fabrication

CPC with a top surface area of 2m×1m and thickness 3.5cm is fabricated in a wooden box which is covered with aluminum foil on inside surface to reflect solar rays on the concrete slab. A serpentine copper tube (copper used for its high thermal conductivity) of inner diameter 8mm, thickness 1mm and spacing 8cm is hammered with a tool to create circular dimples of diameter 3mm and depth 1mm. The dimples are fabricated on four sides of the pipe and with a spacing of 5cm as shown in figure 1. This dimpled serpentine tube tied to wire mesh is then embedded in concrete slab during its fabrication such that half tube is immersed in concrete and the remaining half is in air gap as shown in figure 2. The copper grid is arranged in such a manner because solar radiations will directly fall on it and also stored heat from concrete will be passed on to tubes. In order to improve the thermal conductivity of concrete, metal fibers are added to the concrete mixture. The CPC is then painted black to increase its absorptivity to 95% [12]. The box is covered from the top by a toughened transparent glass to trap solar radiations inside the box. The CPC in the box is then inclined at the latitude of place to have maximum insolation throughout the year [13] by placing it on a mild steel stand as shown in figure 4.

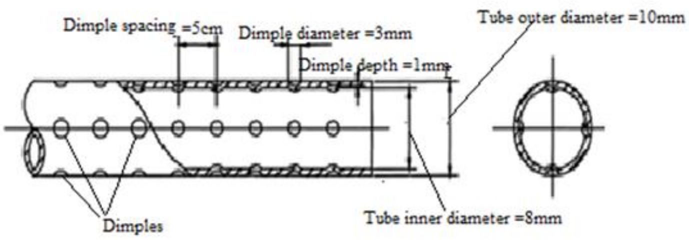

Fig. 1. Dimpled tube with dimensions

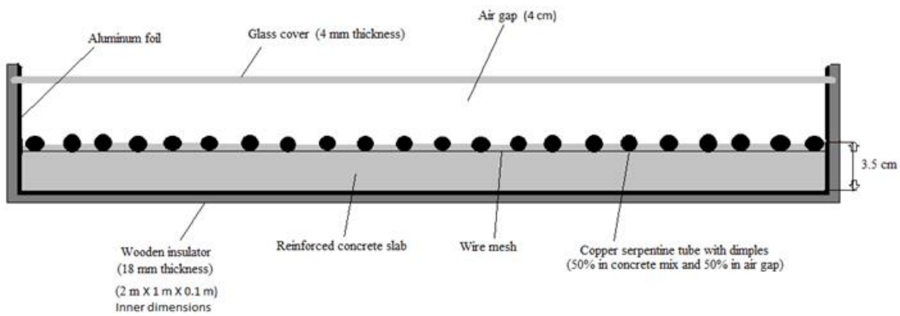

Fig. 2. Cross-section of concrete plate collector

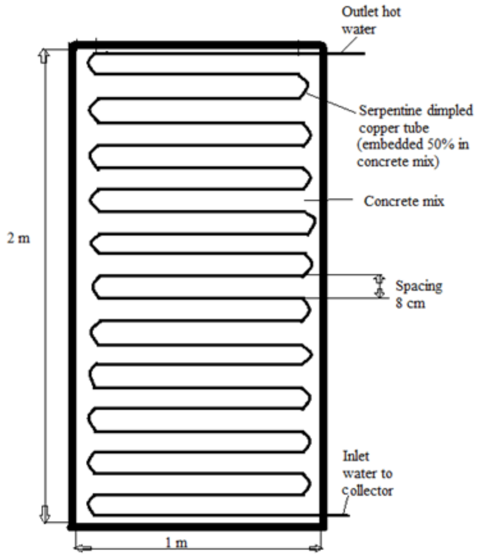

Fig. 3. Top view of concrete plate collector

Fig. 4. Photo of comparison of smooth tube and dimpled tube concrete plate collectors

3. Testing Results

Tests are taken during the summer season for 4 different mass flow rates – 20lph (liters per hour), 25lph, 30lph and 35lph; where water is flowing through both collectors continuously for 5 hours from 11:00 am to 4:00 pm for particular water flow rate ($\dot{m}$) per day. Atmospheric temperature (T_a), inlet water temperature (T_i), outlet water temperature (T_o) and solar insolation (I_t) are noted every 30 min. Then Q_u (total useful heat gained by water) and η (Instantaneous collector efficiency) are calculated to measure the effect of the dimpled tube.

$$Q_u = \dot{m}\times C_p\times(T_o-T_i) \quad (1)$$

and$Q_u/2$ is useful heat gain per square meter

$$\eta = Q_u/(A_p\times I_t) \quad (2)$$

Testing results show that inlet water temperature is higher than atmospheric temperature due to the heat absorbed by pipe material connected between water supply and collector inlet. Temperature is maximum at the start as water is flown in unutilized collector so more heat is absorbed by water at the start, thus giving maximum efficiency. Solar insolation goes on decreasing after 1.00pm but efficiency of collector increases thereafter due to heat storage capacity of concrete, thus giving hot water till 4.00pm.

Table 1 depicts that total 100 liters of water above 75˚C is collected at 4.00pm for 20 lph flow rate. Dimple effect on outlet water temperature is seen in the range of -1 to 3 C˚ with an average increase of 1.1˚C and average efficiency increase of 1.2%.

Table 1. Readings for water flow rate 20 liters per hour

Time of day	T_a (˚C)	T_i (˚C)	$(T_o)_1$ (w/o dimple) (˚C)	$(T_o)_2$ (with dimples) (˚C)	I_t (W/m^2)	$(Q_u)_1$ (w/o dimple) (W)	$(Q_u)_2$ (with dimples) (W)	η_1 (w/o dimple) (%)	η_2 (with dimples) (%)
11.00	37	42	83	86	912.4	953.7	1023.5	52.3	56.1
12.00	39	48	74.5	77	1038.7	616.4	674.6	29.7	32.5
13.00	39.5	50	76.5	78	1076.1	616.4	651.3	28.6	30.3
14.00	41.5	50	76	76	955.2	604.8	604.8	31.7	31.7
15.00	42	48	74	75	765.5	604.8	628	39.5	41
16.00	40	46	64	63	385.4	418.7	395.4	54.3	51.3
Total quantity of water collected = 100 liters									
Average outlet water temperature = 74.7 ˚C (w/o dimple) & 75.8 ˚C (with dimples)									
Average efficiency = 39.3 % (w/o dimple) & 40.5 % (with dimples)									

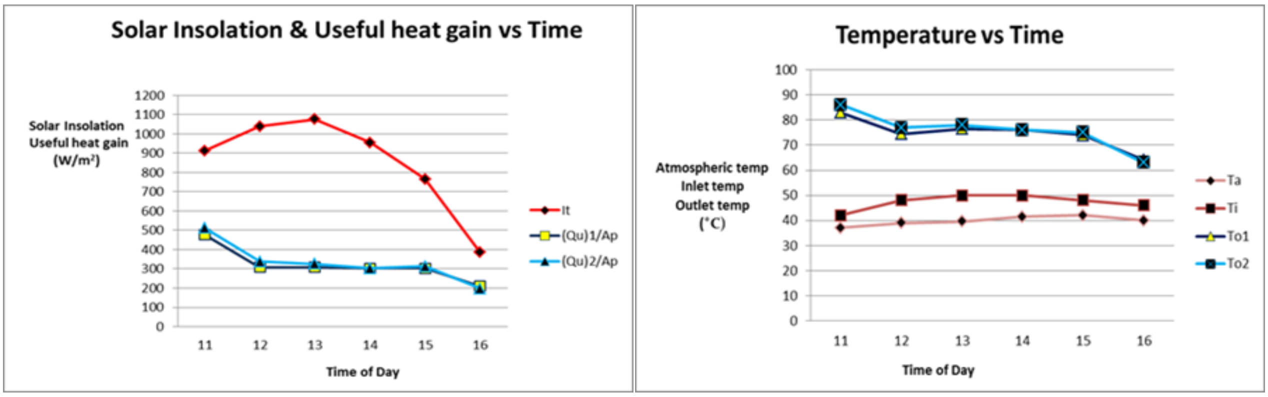

Figure 1a and 1b. Comparison of smooth tube and dimpled tube CPC for ṁ=20 lph

Table 2. Readings for water flow rate 25 liters per hour

Time of day	T_a (˚C)	T_i (˚C)	$(T_o)_1$ (w/o dimple) (˚C)	$(T_o)_2$ (with dimples) (˚C)	I_t (W/m^2)	$(Q_u)_1$ (w/o dimple) (W)	$(Q_u)_2$ (with dimples) (W)	η_1 (w/o dimple) (%)	η_2 (with dimples) (%)
11.00	34.5	41	79	84	1050.1	1104.9	1250.3	52.6	59.5
12.00	38	46	67	68.5	1096.1	610.6	654.2	27.8	29.8
13.00	38	47	68	69	1120.1	610.6	639.7	27.2	28.5
14.00	39	46	66	66.5	1037.8	581.5	596.1	28.0	28.7
15.00	39	46	68	66	919.8	639.7	581.5	34.8	31.6
16.00	37	45	58	59	641.6	377.9	407.1	29.4	31.7
Total quantity of water collected = 125 liters									
Average outlet water temperature = 67.7 ˚C (w/o dimple) & 68.8 ˚C (with dimples)									
Average efficiency = 33.3 % (w/o dimple) & 35.0 % (with dimples)									

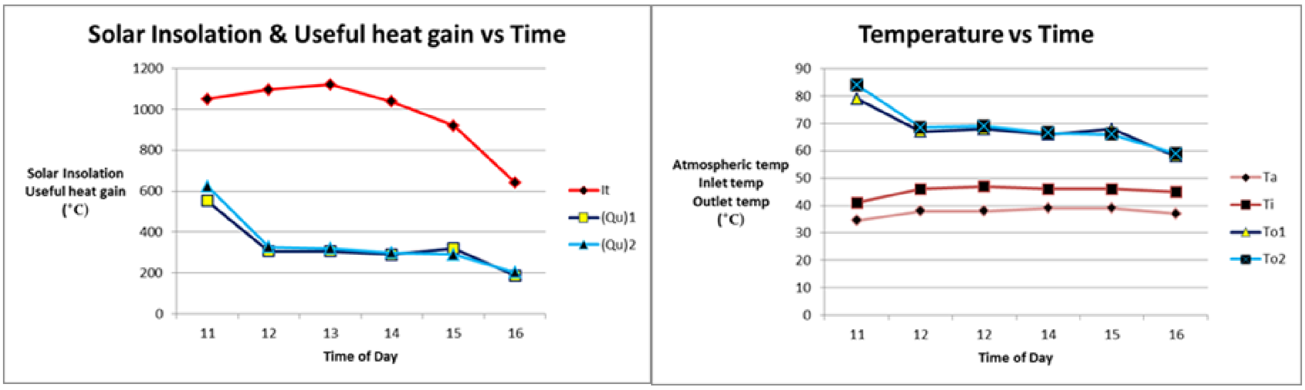

Figure 2a and 2b. Comparison of smooth tube and dimpled tube CPC for ṁ=25 lph

Table 2 depicts that total 125 liters of water above 68˚C is collected at 4.00pm for 25 lph flow rate. Dimple effect on outlet water temperature is seen in the range of -2 to 5 C˚ with an average increase of 1.1˚C and average efficiency increase of 1.7%.

Table 3. Readings for water flow rate 30 liters per hour

Time of day	T_a (˚C)	T_i (˚C)	$(T_o)_1$ (w/o dimple) (˚C)	$(T_o)_2$ (with dimples) (˚C)	I_t (W/m^2)	$(Q_u)_1$ (w/o dimple) (W)	$(Q_u)_2$ (with dimples) (W)	η_1 (w/o dimple) (%)	η_2 (with dimples) (%)
11.00	35	45	80	85	986.4	1221.2	1395.7	61.9	70.7
12.00	36.5	45	67	69	1077.1	767.6	837.4	35.6	38.9
13.00	38.5	48	69	69.5	1067.8	732.7	750.2	34.3	35.1
14.00	40.5	48	67	67.5	1008.3	662.9	680.4	32.9	33.7
15.00	41	48	65.5	66	845.9	610.6	628.0	36.1	37.1
16.00	39	46	59	57.5	634.1	453.6	401.2	35.8	31.6
Total quantity of water collected = 150 liters									
Average outlet water temperature = 67.9 ˚C (w/o dimple) & 69.1 ˚C (with dimples)									
Average efficiency = 39.4 % (w/o dimple) & 41.2 % (with dimples)									

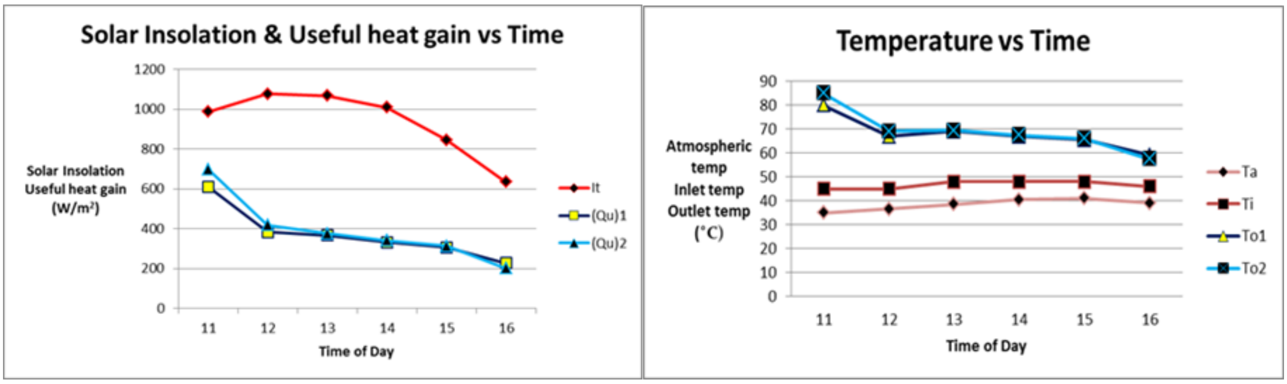

Figure 3a and 3b. Comparison of smooth tube and dimpled tube CPC for ṁ=30 lph

Table 3 depicts that total 150 liters of water above 69˚C is collected at 4.00pm for 30 lph flow rate. Dimple effect on outlet water temperature is seen in the range of -1.5 to 5 C˚ with an average increase of 1.2˚C and average efficiency increase of 1.8%.

Table 4. Readings for water flow rate 35 liters per hour

Time of day	T_a (˚C)	T_i (˚C)	$(T_o)_1$ (w/o dimple) (˚C)	$(T_o)_2$ (with dimples) (˚C)	I_t (W/m^2)	$(Q_u)_1$ (w/o dimple) (W)	$(Q_u)_2$ (with dimples) (W)	η_1 (w/o dimple) (%)	η_2 (with dimples) (%)
11.00	38	44	70.5	69	998.3	1078.7	1017.7	54.0	50.9
12.00	39.5	46	63.5	64.5	1059.6	712.4	753.1	33.6	35.5
13.00	39	47	68	69.5	1068.9	854.8	915.9	39.9	42.8
14.00	41.5	47	66	67	1007.1	773.4	814.1	38.4	40.4
15.00	42	49	65	66	889.9	651.3	692.0	36.6	38.9
16.00	41	46	59	61	649.2	529.2	610.6	40.7	47.0
Total quantity of water collected = 175 liters									
Average outlet water temperature = 65.3 ˚C (w/o dimple) & 66.2 ˚C (with dimples)									
Average efficiency = 40.5 % (w/o dimple) & 42.6 % (with dimples)									

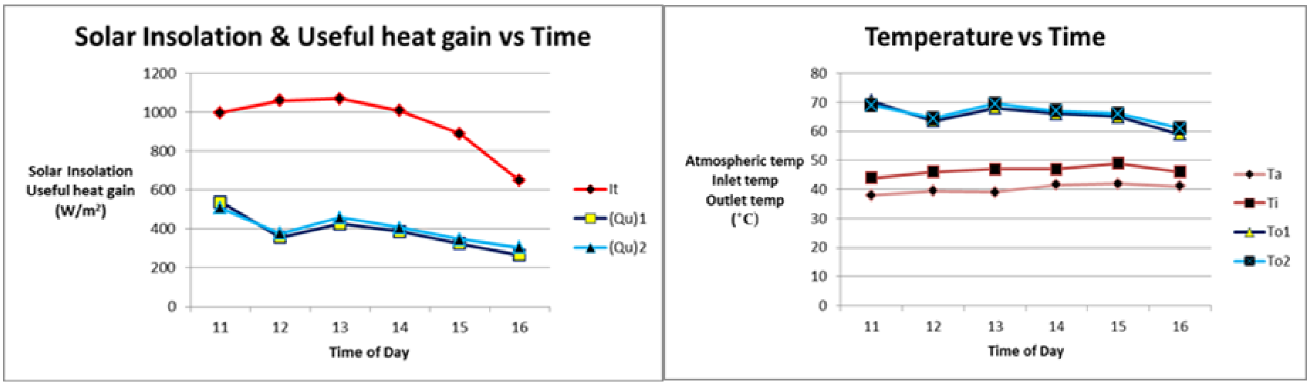

Figure 4a and 4b. Comparison of smooth tube and dimpled tube CPC for ṁ=35 lph

Table 4 depicts that total 175 liters of water above 66˚C is collected at 4.00pm for 35 lph flow rate. Dimple effect on outlet water temperature is seen in the range of -1.5 to 2 C˚ with an average increase of 0.9˚C and average efficiency increase of 2.1%.

The variation observed in the dimple effect appears due to the fact that strict quantity measurement procedures have not been followed during the fabrication of concrete plate collector and so there is a slight possibility that there is some variation in the amount of the aggregates and sand used, which resulted in the negative effect of dimples.

4. Comparison With Other Water Heating Methods

1. Electric geysers

The majority of the population in India use electricity as the energy source to heat water for bathing purpose, hence the comparison with electric geysers is done, to find energy savings, cost savings and payback period, as shown in table no. 5. Payback period (n) of CPC (concrete plate collector) SWH if replaced by electric geyser is found by the following expression:

$$C = B \times \frac{[(1+r)^n - 1]}{[r \times (1+r)^n]} \tag{3}$$

Where, C is the total cost of CPC SWH = Rs. 24,000, B is cost saved per year and r is the rate of interest = 10%. To find B, E (electrical energy saved per year) is needed which is obtained from the following equation:

$$E = \frac{\mathrm{m \times Cp \times (Th - Tc) \times (no.of\ days\ SWH\ used)}}{Efficiency\ of\ geyser \times 3600} \tag{4}$$

Where, m is quantity of water heated per day = 150 liters, C_p is the specific heat of water = 4.187 KJ/kgK, T_h is required hot water temperature for bathing = 55˚C and T_c is cold water supplied to electric geyser = 20˚C. The efficiency of the geyser is considered 90%, number of days CPC provides 55˚C water is taken 275 (30 days of summer are not considered) whereas for remaining 60 days CPC provides water at around 40˚C.

2. Solar water heaters

In order to analyze the performance of CPC, it needs to be compared with existing solar water heaters- Evacuated tube collector (ETC) and Flat plate collector (FPC) as shown in table no. 6.

Table no. 5. Economic analysis of CPC SWH if replaced by electric geyser

Hot water quantity per day	Electrical energy saved per year (E) (KWh)	Cost of electricity per unit			Cost saved per year (B) (Rs.)	Payback period (n) (years)
150 liters of water at 55˚C	2040.16	Domestic	100 units	Rs. 3.76	7,671	3.9
			200 units	Rs. 5.48	11,180	2.5
			400 units	Rs. 7.03	14,342	1.9
		Commercial	200 units	Rs. 6.60	13,465	2.1
			400 units	Rs. 8.11	16,546	1.6

Table no. 6. Comparison of CPC with ETC and FPC solar water heaters of 150 liters storage capacity

Parameter	CPC	ETC	FPC
Cost of collector	Low	Intermediate	High
Life	More than 20 years	Up to 15 years	Up to 20 years
Water temperature (normal day)	55˚C	65˚C	60˚C
Back-up water heating required	Up to 60 days	Up to 30 days	Up to 45 days
Efficiency	Low	High	In-between
Working principle	Meander	Thermo siphon effect	Thermo siphon effect
Working time	5 hours	3 hours	3 hours
Water flow through collector	Manual	Automatic	Automatic
Variance in T_o and water collected	Possible	Not possible	Not possible
Tube repairs	Very hard	Easy	Hard
Insulation	Not needed	Needed	Needed
Tank overhead collector	Not needed	Needed	Needed
Weight	Very heavy	Light	Heavy
Rigidness/ toughness	Rigid	Fragile	Less fragile
Manufacture	Easy	Hardest	Hard
Specialized workshops	Not needed	Needed	Needed
Skilled manpower	Not needed	Needed	Needed
Imports	Not needed	Done	Done

5. Conclusion

Following conclusions are made after conducting an investigation on two solar concrete plate collectors (CPC) - smooth tube CPC and dimpled tube CPC:

- Outlet water temperature obtained from CPC was in the range of 66˚C to 76˚C for water flow rates 20 liters per hour (lph), 25lph, 30lph and 35lph during the summer season with a collection of water from 100 liters to 175 liters. Thus this system will satisfy the domestic hot water for bathing purpose.

- The overall dimple effect on outlet water temperature was seen in the range of -2˚C to 5˚C, with the majority of reading showing an increase in water temperature. For dimpled tube collector, there was an increase in average outlet water temperature and average efficiency for all water flow rates. Average efficiency increase was in the range of 1.2% to 2.1% and the average increase in outlet water temperature was by 0.9˚C to 1.2˚C due to dimples. Thus dimples lead to an increased efficiency of CPC without any addition in material or cost, thus making it an effective technique.

- The payback period for replacement of electric geyser was low and varied between 1.6 years to 3.9 years as per electricity unit rates. Higher is the cost of electricity unit lesser is the payback period. Hence payback period was found lower for domestic consumers using higher electrical units and for commercial users like hostels, hotels, hospitals, etc. as they are charged higher per unit cost.

- The comparison of CPC with Evacuated tube collectors and Flat plate collectors show that CPC has lower cost, longer life, simple fabrication, rigid plate and do not need any specialized workshops, skilled manpower, insulation for collector or any imports. But CPC also has lower water temperature, longer working hours and arduous repairing of tubes compared to existing water heating systems.

- Thus CPC may or may not replace the existing solar water heaters, but this technology has tremendous scope if integrated into building roofs, during construction of buildings. This will further reduce the cost of CPC as wooden box and iron stand will be eliminated, and much cost of the collector will be merged into building construction slab; also mass procurement of materials will decrease more cost. Hence, this technology can help buildings to meet its hot water requirements at cheaper rates without any adverse effects on the environment.

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