Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 09, September-2016

Experimental Investigation of Solar Flat Plate Collector with Inner Grooved Copper Tube

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***Abstract*—Flat plate collector is a low temperature solar thermal collector which is used for domestic water heating, air heating/drying and applications requiring fluid temperature of 40ºC to 100ºC.The major parts responsible for working of FPC are absorber tube, absorber plate and transparent cover. Various enhancement techniques have been used to increase the heat transfer characteristics of flat plate collector with insertions (twisted tapes, wire coil) into the copper tube and by modifying the surface area of copper tube with respect to design. This paper is used to enhance the heat transfer characteristics of solar flat plate collector with the help of an inner grooved copper tube instead of existing copper tube.**

Keywords—Inner grooved copper tube, heat transfer enhancement, Solar Flat Plate Collector

I. INTRODUCTION

Solar flat plate collectors are in wide use primarily for domestic hot water applications. Since, the conversion efficiency of the collector system is less, design modifications have been suggested in the literature such as substituting the transparent cover, absorber material, selective coating, implementing solar tracking, optimization of a number of covers, distance between covers and absorber plate, etc, to increase performance.

Kumar and Prasad [1] investigated flat plate collector with twisted tapes as turbulence promoters and their result showed that there was a reduction in heat loss thereby increases in thermal performance when compared to normal one at different mass flow rates. Adullah et al [2] experimentally investigated the performance of newly designed flat plate collector having single and double outfitted honeycomb arrangement and the result showed that there was reduction in top and bottom heat loss; thereby reducing overall heat removal factor. It also showed the combined honeycomb arrangement was quite efficient, but the overall setup has limitations like reduction in optical efficiency and difficulty in affording gap between them. Viorel badescu [3] studied the performance of solar flat plate collector with uniform and variable fin thickness and developed optimum fin geometry for better performance of solar flat plate collector. The studied showed that we can reduce the cost of collector and can increase the surface area in case of FPC having fins with optimum variable thickness. Hobbi and Siddiqui [4] experimentally studied the impact of heat transfer enhancement devices like twisted strip, conical ridges and coil-spring wire on flat plate collector, but these passive devices created turbulence resulting in inefficient heat transfer rates at their studied geometry. Jaisankar et al [5] compared the heat transfer, thermal performance and friction factor characteristics of helical twisted tube inserted flat plate collector with the plain tube solar collector. The result showed that there was in increase in thermal performance with a corresponding increase in solar intensity. Amori and Jabouri [6] designed two new flat plate collector; one with accelerated absorber and riser with converging duct whose outlet area is small whereas other one is similar to conventional FPC. The setup was tested with different water withdrawal profiles as well as with horizontal and vertical storage tank having helical coiled tubes and their result showed there was a considerable increase in thermal performance and stratification in the storage tank with respect to design and helical tube insertion. Herrero martin et al [7] simulated and designed a flat plate collector with wire coil insertion enhancement technique after serious study and the analyzed the setup with varying mass flow rate, inlet temperature and weather conditions with respect laminar, transitional and low turbulence flow. They attained a considerable enhancement whose useful power ratio is quite higher than standard FPC. Amrutkar et al [8] designed a flat plate collector with different geometric absorber configuration at laboratory IS condition, and their study explained that for the same outlet temperature as that of conventional one we can reduce the area and number of tubes with change in absorber geometry. Iordanou [9] experimentally enhanced the heat transfer rate of flat plate collector with Aluminium/stainless steel porous medium insertion to the copper tubes. This results in increase in contact area of fluid to the absorber and also even distribution of heat to the fluid so that outlet temperature was increased. Raj Thundil karupparaj et al [10] designed a low cost flat plate collector with GI sheet absorber plate whose efficiency was found to be nearly closer to the normal collector at different operating conditions. Raja Sekhar et al [11] conducted experiments on the horizontal circular pipe subject to heat flux and low Reynolds number with water, Al203 nano fluid and twisted tapes. The result shows that there was a considerable enhancement of heat transfer coefficient and friction factor with nano fluid compared to water and usage of twisted tapes was advantageous. Alberto Garcia [12] designed a flat plate collector with wire coil insertion with respect to European standards and the result showed an increase in thermal efficiency and useful power collected with no additional pressure loss but it showed lower potential heat transfer enhancement with subject to increasing mass flow rate. Gurveer Sandhu [13] experimentally investigated the combined effect of insert devices and inclination angle on the performance of solar flat plate collector with different flow and insert devices with Reynolds number between 200-8000. The result showed that concentric coils achieved greater enhancement of the Nusselt number compared to the other inserts and inclination angle does not have a significant impact. The above study shows that no importance is given to enhance the heat transfer rate of flat plate collector with change in geometry of copper tube. Our study is to improve the surface area of copper pipe with the help of inner grooved structure. This may result in reduced heat loss, increase in contact area of fluid to the absorber plate, considerable changes in mass flow rate and increased outlet temperature of fluid at different operating conditions. The objectives of this study are to fabricate a prototype of Flat plate collector with inner grooved copper tube, to test the entire setup under standard test conditions at VIT University and to compare the result with the values of conventional Solar Flat Plate Collector experimentally.

II. EXPERIMENTAL SETUP

The experiments were conducted in Laboratory conditions at VIT University with different inlet temperature and mass flow rates with tilt angle $\beta = 22^0$. The major components of the setup are Flat plate collector with inner grooved copper tube; test setup tank with forced circulation, digital temperature indicator and solar radiation measuring instruments (Pyranometer, pyrheliometer) and the working fluid is water.

A. Flat Plate Collector (FPC)

The flat plate collector was manufactured with two copper tubes; one a newly designed inner grooved tube having thickness 0.5mm and another plain copper tube with thickness 0.7mm. The specifications are shown in Table. I. The FPC consists of two riser tubes – one is newly manufactured with straight grooving inside the copper tube so that its surface area is quite higher than the conventional copper tube which is attached to the setup as the other tube; both connect to the common header through which water is forced at equal mass flow rates. It has top transparent cover which is a 4mm float with emissivity 0.92 whose purpose to capture incident solar radiation and not to reflect the heat energy from the setup, below that absorber plate with aluminium absorber placed in surface contact with the two riser tube whose purpose is to transfer the captured heat energy to the working fluid; the third layer is an aluminium back sheet with purpose to prevent convection loss of heat energy from the absorber plate and the last layer is that glass wool insulation which is used to reduce the bottom convection heat loss. The test setup is run with working fluid as water from the forced circulation tank having the facility of mass flow rate adjustment.

TABLE I. Specifications of FPC

Collector size	1530 x 500 x 80 mm
Absorber plate	Aluminium (k= 205 w/m.k) 1450*460 mm Thickness = 6mm
Riser	Inner grooved copper tube 12.7 mm OD, 0.5 mm thick Plain copper tube 12.7 mm OD, 0.7mm thick
Header	Copper tube 15.7 mm, 0.9mm thick
Plate emissivity/absorptivity	0.90/0.10 ± 0.02
Glazing Emissivity/absorptivity	Float glass 4mm thick (0.92/0.08 ± 0.02)
Plate to cover spacing	35 mm
Back sheet	Aluminium 1400 x 425mm Thickness = 6mm
Back insulation	Glass wool 25.4 mm k = 0.04 w/m.k
Location	VIT university, Vellore (12.9202° N, 79.1333° E)
Tilt angle	$\beta = 22^0$
Painting	Selective coated black paint
Tube center to center distance	22 mm

Fig. 1.Experimental setup of FPC with inner grooved and plain tube

B. PYRANOMETER AND PYRHELIOMETER

Pyranometer is an instrument used to measure global or diffused radiation over a hemispherical field of view. It consists of sensing element with black surface exposed to solar radiation. The hot junction of a thermocouple is attached to the black surface while the cold junction is placed in a way that it does not receive radiation. This measures the radiation in millivolts ranging from 0-20 mV when e.m.f is generated between the junctions due to the principle of Seebeck effect.

Fig.2. Pyranometer and pyrheliometer

Pyrheliometer is used to measure suns direct/ beam radiation. It works on the same principle of pyranometer but the tube with alignment indicator and two axis tracking mechanism will make the device to be focused on the direction so that only direct radiation reaches the black surface.

C. Supporting Instruments

Fig.3. Measuring jar, Storage tank and Thermocouple

The test setup tank with forced circulation is made up of stainless steel material having a rectangular cross section. The tank is used to store the water or working fluid for the experiment and to deliver the fluid with the mass flow rate as decided. The tank is getting two inlet ports with storage capacity of 15 liters and to sustain the flow of water to the absorber tube of flat plate collector a 0.5 HP - AC motor is being connected with the storage tank. Measuring jar is used to check the mass flow rate of water at the outlet of the absorber tube. The digital temperature indicator with k-type thermocouple is used to measure the temperature in Celsius by the principle of Seebeck effect.

D. Fabrication of Inner Grooved Copper tube

The grooved surface will make the working fluid to have higher contact with the copper tube so that maximum heat captured from the solar radiation is transferred in addition to that cost and weight of the material can be reduced. This will result in efficient operation of FPC with reduction in cost with a simple change of inner grooved copper tube material which makes the solar water heater as an essential home appliance. The process of grooving is done in a straight manner by hydraulic machinery with to and fro motion driving of gear on the inner surface of tube with 34 fins with a decrease in thickness of 0.2 mm when compared to the existing 0.7 mm copper tube. The grooving was done only with 30 cm length tube so five separate tubes were taken and grooved separately.Finally, all the tubes were brassed together to make a complete 1.5 m length inner grooved tube.

Fig.4. Inner view of grooved pipe

III. METHODOLOGY

The test was carried on 16^{th} and 17^{th} of April at a different mass flow rate 27 LPH, 36 LPH and 45 LPH with varying inlet water temperature by recirculating the water from the outlet of FPC. The experimentation was done to find out the optimum mass flow rate for operating FPC since it has got only two riser tubes and if we use the same mass flow rate that operates 9 riser tubes of commercial FPC on this setup it will not give the result because of decrease in No.of tubes, the width of the collector. Then the performance of FPC was analyzed with the optimum mass flow rate on 23^{rd} of April from morning 10.00 AM to afternoon 02.00 pm. The data values are recorded and the calculations are made with the following formulae. The instantaneous efficiency of the FPC results where compared with the theoretical values obtained through calculations.

- The angle of declination of the sun is given by

$$\delta = 23.45 \, sin \, [360 \, (284 + n)/365] \qquad (1)$$

where δ is the declination angle and n is the day number.

- The watch time is converted into solar time by

$$Solar\ time = \text{Watch time} - 4(L_{st} - L_{lo}) + \text{EOT} \qquad (2)$$

WhereL_{st} is the Indian standard latitude = 82.5^0E,$L_{lo}$is the local latitude and EOT is the Equation of Time can be found by

$$\text{EOT} = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \qquad (3)$$

(in minutes)

B can be found by

$$.B = \frac{360\,(n-81)}{364} \qquad (4)$$

(in degrees)

where n is the day number

- Hour angle(ω) is given by

$$\omega = 15(\text{Solar time} - 12) \qquad (5)$$

(in degrees)

- Angle of incidence is given by

$$\cos\theta = \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \cos\delta\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \qquad (6)$$

(in degrees)

where φ is the Latitude, φ is the slope (or) tilt angle and γ is the surface azimuth angle.

- Solar flux incident on the collector is given by

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r \text{ (in Ws/m}^2\text{)} \quad (7)$$

Where I_b is the beam radiation; I_d is the direct radiation

$$r_b = \frac{\cos\theta}{\cos\theta_z};\; r_d = \frac{1+\cos\beta}{2};\; r_r = \rho\left(\frac{1-\cos\beta}{2}\right)$$

- The Transmissivity and absorptivity of the glass cover system for beam and direct radiation is given by

$$(\tau\alpha)_b = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \quad (8)$$

$$(\tau\alpha)_d = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \quad (9)$$

where $\tau = \tau_r . \tau_\alpha$

$$\tau_\alpha = e^{-\frac{k\delta_c}{\cos\theta_2}}$$

τ_α is the transmissivity based on absorption, k is the property of the glass cover known as its extinction coefficient. Its value for a plane glass varies from about 5 to 25m^{-1} depending on the glass quality. Assuming the glass cover is of average quality, k=15m^{-1}. The glass cover used for this work is plane of thickness δ_c =3mm.

$$\tau_r = \frac{1}{2}(\tau_{r1} + \tau_{r2})$$

τ_r is the transmissivity based on reflection.

$$\tau_{r1} = \frac{1-\rho_1}{1+(2M-1)\rho_1}$$

$$\tau_{r2} = \frac{1-\rho_2}{1+(2M-1)\rho_2}$$

$$\rho_1 = \frac{\sin^2(\theta_2-\theta_1)}{\sin^2(\theta_2+\theta_1)}$$

$$\rho_2 = \frac{\tan^2(\theta_2-\theta_1)}{\tan^2(\theta_2+\theta_1)}$$

where M is the refractive index of the glass, θ_2 is the refractive angle and θ_1 is the incidence angle.

- Incident flux absorbed by absorber plate is given by

$$S = I_b r_b (\tau\alpha)_b + \{I_d r_d + (I_b + I_d) r_r\}(\tau\alpha)_d \quad (10)$$

(in W/m^2)

- The overall loss co-efficient is given by

$$U_l = U_t + U_b + U_s \quad (11)$$

Where U_t is the top loss co-efficient, U_b is the bottom loss co-efficient and U_s is the side loss co-efficient

$$U_t = \left\{\frac{N}{\frac{C}{T_{pm}}\left[\frac{(T_{pm}-T_a)}{(N+f)}\right]^e} + \frac{1}{h_w}\right\}^{-1} + \frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{(\varepsilon_p + 0.00591Nh_w)^{-1} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - 1}$$

(W/m^2.c)

$$U_b = \frac{k_i}{\delta_i}$$

U_s = Negligible

$$f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N)$$

$$C = 520(1 - 0.000051\beta^2)$$

$$e = 0.430\left(1 - \frac{100}{T_{pm}}\right)$$

- Heat removal factor is given by

$$F_R = \frac{\dot{m}C_p}{U_l A_p}\left[1 - e^{\left(\frac{-F' U_l A_p}{\dot{m}C_p}\right)}\right] \quad (12)$$

where

$$F' = \frac{1}{WU_l\left(\frac{1}{U_l[(W-D_o)\emptyset + D_o]} + \frac{\delta}{k_a D_o} + \frac{1}{\pi D_i h_f}\right)}$$

- The heat gained by the collector is given by

$$q_u = F_R A_P[S - U_l(T_{fi} - T_a)] \quad (13)$$

(in watts)

where A_P is the collector surface area in m^2, T_{fi} is the inlet fluid temperature and T_a is the ambient temperature in ^{o}c.

- The instantaneous efficiency is given by

$$\eta = \frac{q_u}{I_T A_P} \quad (14)$$

- The practical efficiency is given by

$$\eta = \frac{\dot{m}C_P\Delta t(T_o - T_i)}{I_g A_P} \quad (15)$$

where m is the flow rate of the water in litres per hour, C_P is the heat transfer co-efficient of water in J/kg^{0}c, Δt is the sunshine hour in seconds T_o,T_i is the outlet temperature and inlet temperature of water and I_g is the global solar radiation in (W/m^2).

IV. RESULTS AND DISCUSSIONS

To validate the experimental setup, the performance of FPC is to be investigated for that the measurements were taken on 23rd April from 10.00AM to 02.00 PM with mass flow rate 45LPH and different inlet temperature. Here the mass flow rate was decided with previous experiments on 16th and 17th April on different working condition having different mass flow rates and inlet temperature.

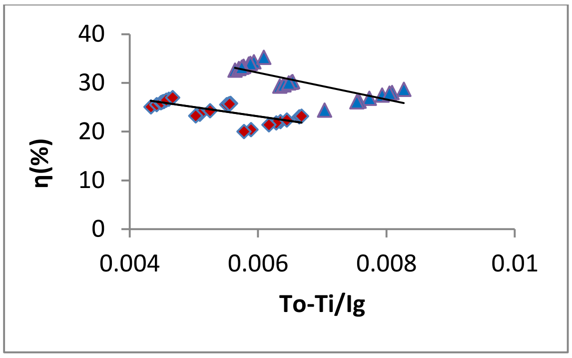

Fig.5. Performance curve of FPC on 16.04.2014

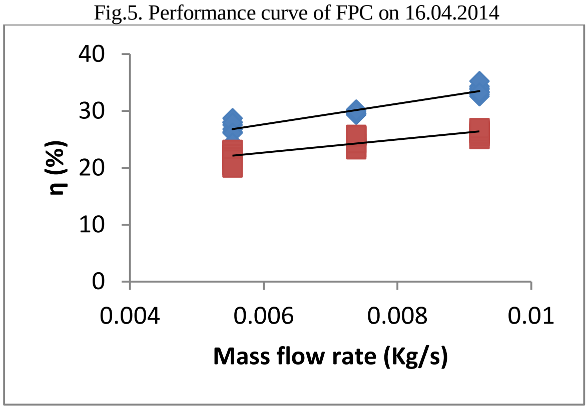

Fig.6. Comparison of different flow rate with efficiency on 16.04.2014

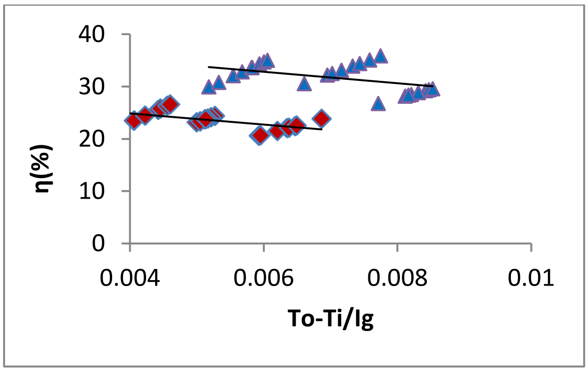

Fig.7. Performance curve of FPC on 17.04.2014

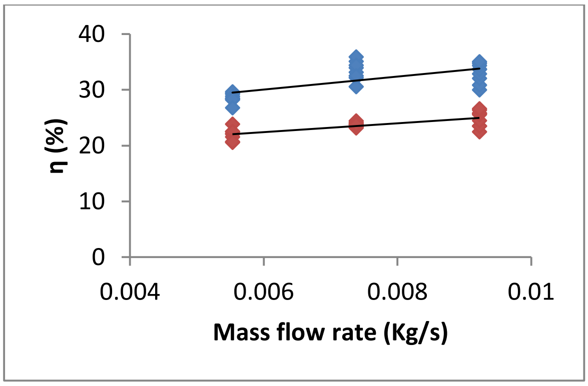

Fig.8. Comparison of different flow rate with efficiency on 17.04.2014

Fig.6 and Fig.8 shows the variation of FPC efficiency with respect to mass flow rates 27LPH, 36LPH and 45 LPH. The result shows that there was an increase in efficiency if flow rate is increased. The reason is that if the flow rate is high the amount of heat exchanged between the fluid and the tube will be higher so that there was an increase in efficiency. If flow rate is less the temperature of outlet water will be quite high, but the product flow rate and temperature difference can't compensate with the result of high flow rate results. These two curves also indicate the optimum mass flow rate, i.e. 45LPH at which the FPC works so efficiently. The graph also shows that the inner grooved tube has transferred maximum heat from the incident solar radiation to the working fluid while compared to the normal plain tube. Fig.5 and Fig.7 shows the performance curve of FPC. The curve has a maximum No. of point at three different places since the experimentation was done with different mass flow rate with time interval of 2 hours and the results shows that inner grooved tube has got a maximum result while compared to plain tube. From these results we have done the experimental investigation of newly manufactured FPC on 23.04.2014 with an optimal mass flow rate 45 LPH.

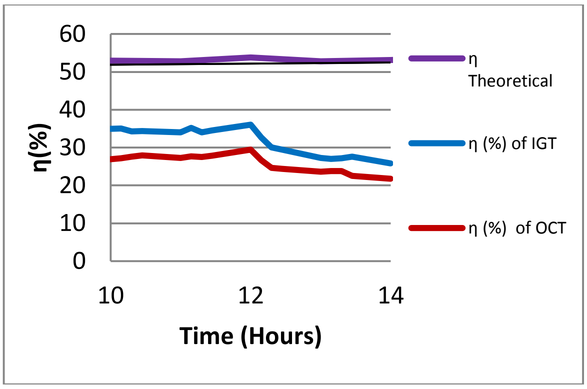

Fig.9.Instantenous Efficiency of FPC with respect to time on 23.04.2014

The Fig.9 shows the theoretical and practical efficiency of FPC having one inner grooved and other plain receiver tube with respect to time. The performance of inner grooved has increased maximum of 5 % in terms of instantaneous efficiency when compared to plain tube whose values varies from 20% to 30%, whereas the inner grooved tube value varies from 25% to 35%. The reason for this increase is that the inner grooved structure has reduced the thickness of copper tube so that the amount of useful heat gained by the collector tube has been increased for the same input that has been an incident on the plain tube. The result also shows the comparison of theoretical efficiency with the experimental efficiency and it clearly states that the design of new FPC was quite perfect to make it as a commercial product with inner grooved copper tube.

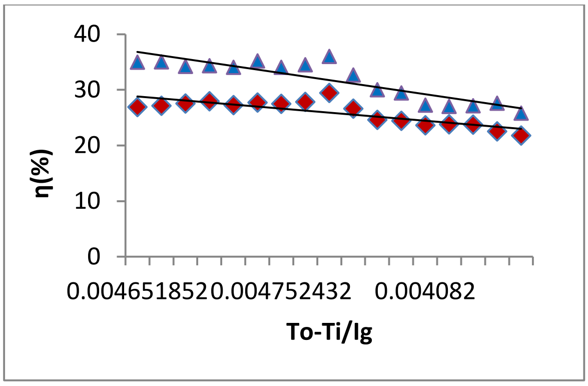

Fig.10. Comparison flow rate (45LPH) with efficiency on 23.04.2014

Fig.10. Shows the performance of FPC with the mass flow rate 45 LPH. This clearly specifies that 45 LPH was quite worked efficiently.

V. CONCLUSION

An experimental investigation of FPC with different mass flow rate and inlet temperature has been conducted at VIT University. The result concludes that there was an increase in efficiency of FPC with the inner grooved tube while compared to FPC with plain copper tube. The overall increase in instantaneous efficiency of this design is 5% when compared to plain tube efficiency. This implies that if we use inner grooved tube there was an increase in outlet temperature due to increase in surface area with reduction in material cost and also this design can replace the conventional FPC.

Future Scope

The performance of solar flat plate collector will be further enhanced by implementing readily available different specification of the inner grooved tube along with Computation Fluid Dynamics (CFD).

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