Performance Augmentation Analysis of Flat Plate Solar Collector Using Innovative Design

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Abstract: ***Flat plate solar collector still plays a dominant role in direct application of solar energy for water heating in household sector. Present experimental work is an innovative approach which, dealt with analysis of flat plate solar collector efficiency with innovative collector design. Design modifications of solar collector always offer an important criterion to achieve significant effect on thermal efficiency of solar collector. In present experimental work we have developed single spiral shaped collector tube, compare to numbers of riser tubes connected with headers. Keeping all other parameters similar to conventional design, we have observed very encouraging outcomes in efficiency of solar collector. Under natural mode of testing, Enhancement in thermal efficiency achieved is15.34% comparing to conventional design. Overall material shaving is 30% and cost of manufacturing is also reduced significantly due to material shaving.***

Keywords: FPSC, solar intensity, efficiency, spiral design

1. Introduction

Solar energy is lifeline of planet earth. Progress of civilization is driven by energy. Conventional energy sources available on earth itself created during millions of years with the help of solar energy. Use of this energy creates pollution due to emissions of harmful gases. Instant use of solar energy is almost pollution free. It can be used for heating of water or any working fluid. Solar energy can be directly converted into electricity by photovoltaic systems. Solar collector is device which absorbs that part of incident solar radiations, which has more heating value and convert it into heat content of working fluid flows through tubes. FPSCs are simplest kind of collectors, very convenient to design, cost effective, robust and require negligible maintenance cost. There are various parameters which affects thermal conversion efficiency of solar collector. These are as follows: collector plate position, coating of collector plate, its material, properties of glazing, spacing between riser tubes with respect to diameter, flow rate, intensity of incident radiation, bottom insulation thickness and side insulation and most recently and very prominent method of enhancement in efficiency of solar collector have been in use is application of advanced working fluid in place of water or oil. Apart from advanced working fluids i.e. nanofluids other parameters are either design variables or process and input optimization methods. Most important among all parameters which govern directly or indirectly thermal efficiency of FPSC is innovation in design. Design modification offers inbuilt and inherent capability in functioning of the system. Once we improve the design other parameters are bound to change in compatibility with systems requirement. Many academicians, researchers, engineers have contributed through their design, process and technological knowhow to facilitate efficient functioning of FPSC in domestic and industrial sector in every nook and corner of the world. Here we would like to cite their contributions briefly to get sharp peep and its significance.[1] performed experimental and Modeling of modified solar collector with corrugated channel & enhanced surface area exposed to heat transporting fluid using FEM. Authors concludes that serpentine geometry performs better than parallel geometry of fluid transporting duct. Authors performed testing of collector under transient working conditions[2]. It has been concluded by authors that wind velocity (magnitude and direction) is the most influencing factor which affect performance of collector, followed by decay of collector surface, heat loss by convection, thermal inertia and angle of incident radiation. Verma & Tiwari[3] extensively reviewed thermo physical properties of working fluids which affect thermal efficiency of FPSC. Hiroshi Tanaka[4]performed theoretical analysis for enhancement in thermal efficiency due to reflector attachment over collector plate. At inclination angle of reflector less than 30° with respect to collector plate, author observed average enhancement of absorbed solar radiation : 19%, 26% and 33% throughout the year at the ratio of l_R/l_C =0.5,1.0 and 2.0 with proper adjustment of collector and reflector angle. Cruz-Paragon et al.[5] systematically and scientifically characterized FPSC. Authors emphasized that dynamic and transient behavior of FPSC can better be validated with established results using simple design modification compatible with simple sensors rather than using complex CFD and FEA techniques of validation. Maldonado et al.[6] investigated instantaneous efficiency with respect to design and operating parameters. Authors observed average global thermal efficiency 30.2%. M. Khamis Mansour [7]has investigated thermal performance of FPSC based on square mini channel design of collector plate. Author observed that heat removal factor enhanced by 16.1% compare to conventional collector. Colangelo et al.[8] have investigated performance of FPSC for improved and innovative design of top or bottom header to make it suitable for Al_2O_3/water nanofluid. Experimental observations reveals that sedimentation rate is highly reduced thus performance of working fluid enhanced significantly. Thermal conductivity enhanced by 6.7% while heat transfer coefficient enhanced by 25% at 3% volume concentration of nanofluid. Wang et al.[9]have investigated effect of novel heat collecting flat plate collector plate surface and effect of tilt angle on performance of flat plate solar collector. Authors have incorporated corrugated surface design (upper part) and flat in (lower part) of collector plate. Validated by CFD simulation, instantaneous efficiency achieved was 85.1% at 0.15kg/s mass flow rate and tilt angle varies,(10° April to September) and 30° to 35° rest of months at Guangzhou of China. Visa et al.[10] developed isosceles trapeze shape collector which can incorporate multi-color absorber plate. Experimental results indicate 62.38% efficiency in indoor testing and 62% efficiency in outdoor testing. Nikolic and Lukic [11] performed both theoretical and experimental investigation of doubly exposed FPSC performance. Results shows that proposed design have significant enhancement in thermal power capacity compare to conventional design of solar collector. Highest difference in thermal power achieved was 48% compare to conventional one. Alvarez et al.[12] performed experimentation with numerical modeling to assess the performance of corrugated surface of collector in terms of enhanced energy absorption capacity. Results indicate that corrugated model achieved highest yield: 86% followed by 80% and 77.9% by BBC and Roth type respectively. Equivalent Collector is 88% of BBC and 44% of Roth type among best working type collectors. Hussain &Harrison [13] performed experimental evaluation of effect of back mounted air channel in FPSC to overcome excessive rise of plate temperature in stagnant state of working ~170°c, when air channel opens, temperature brought down due to passive flow of air below the surface of hot plate, temperature declined to 120°c, thus it enhancing life of the collector. Balaji et al.[14] have investigated effect of twisted tube as heat transfer enhancer joined with inner lining of tube material in contrast to earlier work where enhancers were freely inserted into the tubes. Observations confirm maximum enhancement in temperature, 1.172 and 1.112 times more for rod and tube enhancers compared to plain tube solar collector. Facao [15] optimized the flow distribution in FPSC by riser and header configurational changes.

Purpose of present paper is to introduce innovative design of FPSC plate and riser tube. Spiral single piece collector heat absorbing duct tube is innovative in design and also optimum heat absorbing area coverage of collector plate. Compare to conventional Z shape design, spiral design requires lesser material and maintenance cost. Chances of sedimentation of nanoparticles also minimized in case of advanced heat transporting fluids.

2 Experimental procedure

Keep all valves closed, fill up the cold water tank 1, open the valves 1 and 2 and fill cold water tank 2, when the cold water tank is full open the valve 3 and 4 and allows the water to flow into the hot water tank, once the hot water tank overflows and water comeback to the cold water tank 1 close the valves 1, 2 and 3.Measure the wind speed at different locations of the collector by using anemometer. Then use an average value for calculation. Similar to the wind speed measure the ambient air temperature. Connect all the meters and note all the readings. Measure the radiation level at different locations on the collector glazing by using the radiation meter; use an average value for calculation. Note the values shown by different meters after every 10 minutes. To know the mass flow rate open the three ways valve and note the time required to fill a desire amount of water in the beaker. Repeat the above step to know mass flow rate during the whole experiment. Use an average value of mass flow rate for calculation. Keep the system ON until the outlet water achieved a stable temperature.

Fig:1 (a) Conventional Experimental set –up

Fig:1 (b) set-up with modified design

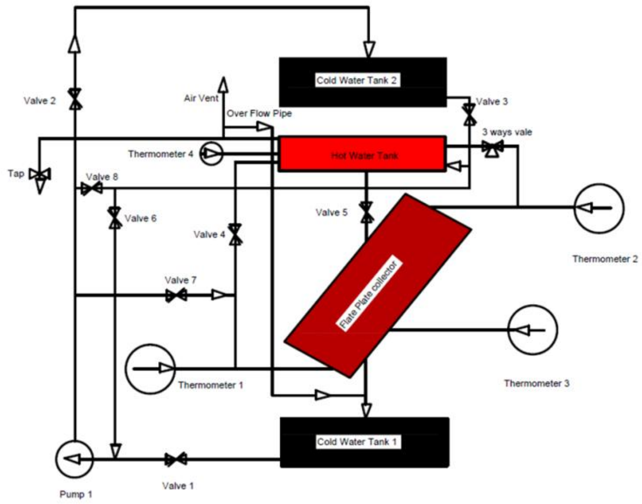

Fig: 2 schematic of experimental set-up

2.1 Conventional design

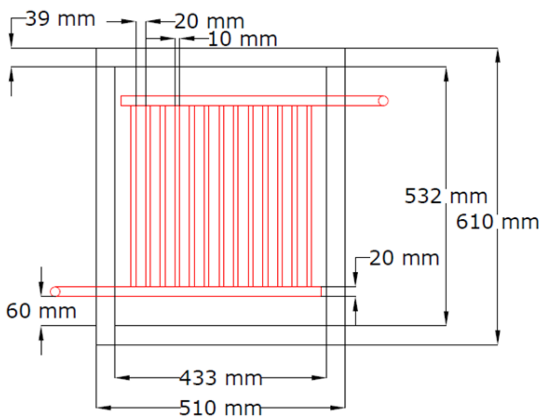

Fig: 3 design specifications of conventional collector tube

2.2 Design modification:

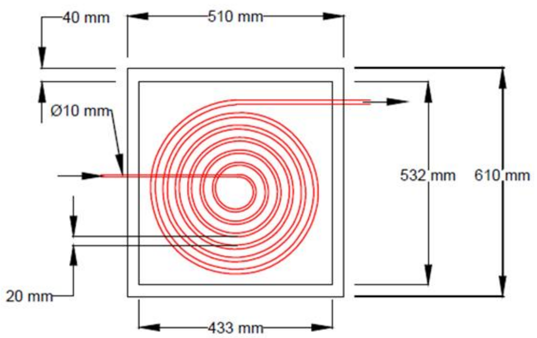

Fig: 4 Details of modified design

2.3 Specification of collector and its components

1) *Specification*	2) *Dimension*		3) *Unit*
	4) *Previous based design*	5) *Modified (circular) design*	
Collector occupied volume	53.2×43.3×8.5	53.2×43.3×8.5	cm^3
Absorption area	0.230	0.230	m^2
No of glazing plate	–	–	1
Gap between tubes	2	2	cm
Glazing thickness	2.5	2.5	mm
Collector tube outer diameter	12.5	12.5	mm
Collector tube inner diameter	10	10	mm
Centre distance between tubes	3.5	3.5	cm
Back insulation thickness	2.5	2.5	cm
Conductivity of back insulation	0.047	0.047	W/mK

3 Experimental observation and analysis

Experiments testing of conventional collector and modified collector were performed in siphon mode according to ASHRAE standard norms. Testing was performed in month of October to November 2018 between 10.00 AM to 4.00 PM. Mass flow rate was kept 0.5 lpm (optimum for designed collector spiral duct flow). Figs: 5 & 6 exhibits variation of plate, tank and mean temperature of inlet and outlet temperature. Between 1.00 pm to3.00 pm operating.

Parameters have highest gain in terms of plate temperature, fluid inlet and outlet temperature. Instantaneous efficiency graph, Fig: 7 reveals that efficiency reaches maximum at 1.pm and it remains almost constant between 1.0 pm to 3.00 pm which is maximum insolence period interval during October to November. Instantaneous efficiency reaches upto ~80% which is highest for any collector system recorded so far.

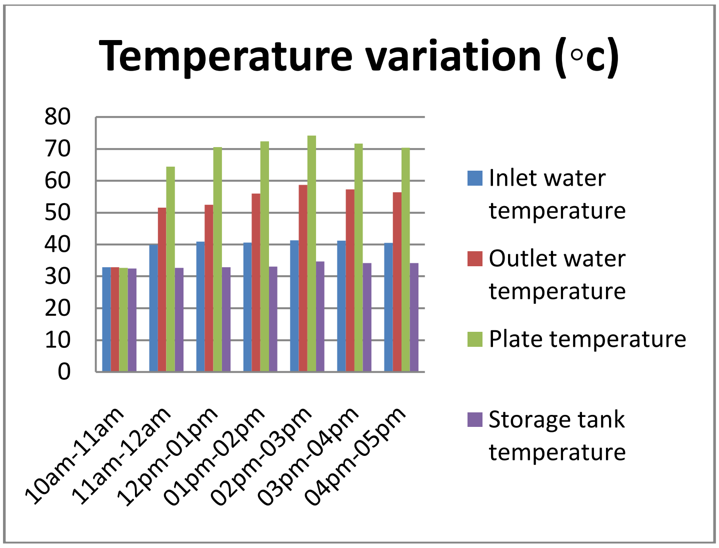

Figure: 5 temperature variation with time graph

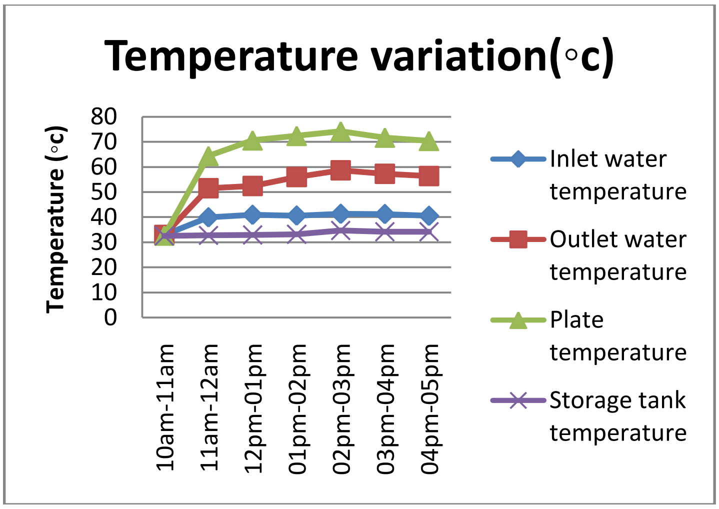

Figure: 6 continuous temperature variations with time

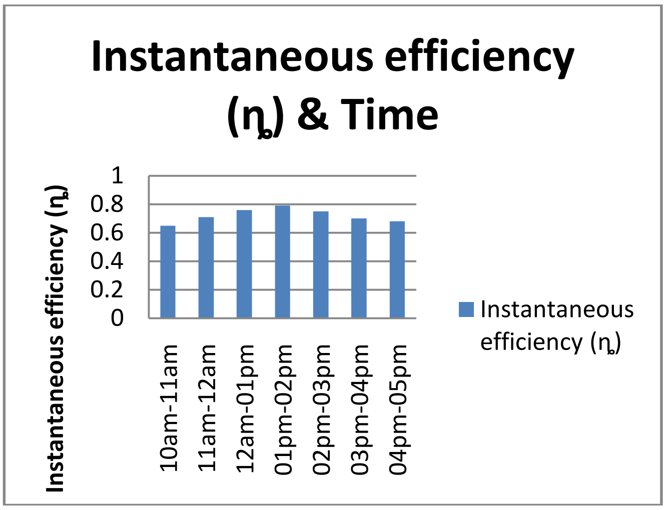

Figure: 7 instantaneous efficiency versus time graph at constant flow rate 0.5lpm

4 Conclusion and future scope

On the basis of experimental observations and analysis we can conclude that highest temperature gain in terms of temperature difference between outlet and inlet temperature of working fluid water is (~20°C) for spiral design duct and ~10°C for conventional design. Only drawback for spiral design is low flow rate (0.5lpm compare to 1.5 to 2 lpm for conventional collector. For small domestic application spiral design is highly recommended for high efficiency, low cost of material and long durability.

Further research is required to check new design with position of collector plate over spiral duct, spacing between duct and insulating material and selective coating of collector plate to further enhance efficiency of FPSC. FURTHER enhancement in efficiency can be achieved with use of new working fluid in place of water.

Mathematical Equations:

Efficiency is the most important factor for a system. This factor determines the system output. For a plate collector based solar water heater system the efficiency is defined as the ratio of useful energy delivered to the energy incident on the collector aperture. The value of efficiency is dominated by various parameters like product of glazing's transmittance, absorptance of absorbing plate, intensity of global radiation falling on the collector, nanofluid inlet temperature and ambient air temperature. Heat loss coefficient (U_L) can be determined by following equation

$$U_L = U_t + U_b + U_\theta \quad [16]\ (1)$$

The top loss coefficient can be calculated by using the following formula, Klein correlation[17]

$$U_t = \left\{ \frac{\frac{1}{N}}{\frac{C}{T_P}\left[\frac{T_P - T_a}{N+f}\right]^{0.33}} + \frac{1}{h_a} \right\} + \left\{ \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{\varepsilon_p + 0.5N(1-\varepsilon_P) + \frac{2N+f-1}{\varepsilon_g} - N} \right\}$$

(2)

Where,

$$C = 365.9 \times (1 - 0.00883\beta + 0.0001298 \times \beta^2)$$

$$f = (1 + 0.04h_a - 0.0005h_a^2) \times (1 + 0.091N)$$

$h_a = 5.7 + 3.8V$ (V is a wind velocity)

The heat loss from the bottom of the collector is first conducted through the insulation and then by a combined convection and infrared radiation transfer to the surrounding ambient air. The heat loss from the back of the plate rarely exceeds 10% of the upward loss. To calculate the bottom loss coefficients we can use the following formula:

$$U_b = \frac{k_b}{x_b} \quad (3)$$

Typical value of the heat loss coefficient ranges from 0.3 to 0.6W/m^{2}k.In a similar way, the heat transfer coefficient for the heat loss from the collector edges can be obtained by using the following formula:

$$U_e = U_b\left(\frac{A_e}{A_c}\right) \quad (4)$$

1. Fin Efficiency (F):

For straight fin with rectangular profile the fin efficiency is given as

$$F = \frac{\tanh\left[\frac{m(W-D)}{2}\right]}{\left[\frac{m(W-D)}{2}\right]} \qquad (5)$$

$$m = \sqrt{\frac{U_L}{K\delta}}$$

Collector efficiency factor can be defined as

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L\,[D + (W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right]} \quad (6)$$

Heat Removal Factor (F_R) can be defined as

$$F_R = \frac{\dot{m}C_p}{A_C U_L}\left[1 - \exp\left(-\frac{U_L F' A_C}{\dot{m}C_p}\right)\right] \quad (7)$$

Another formula for F_R,

$$F_R = \frac{\dot{m}C_p\left[T_{fo} - T_{fi}\right]}{A_C\left[I_t\,\tau_0\,\alpha_0 - U_L\left(T_{fi} - T_a\right)\right]} \quad (8)$$

Flow factor (F''): It is the ratio of the heat removal factor (F_R) and the collector efficiency factor $\left(F'\right)$ mathematically,

$$F'' = \frac{\dot{m}C_p}{A_C U_L F'}\left[1 - \exp\left(-\frac{U_L F' A_C}{\dot{m}C_p}\right)\right] \quad (9)$$

The parameter,

$\frac{\dot{m}C_P}{A_C U_L F'}$ is called the collector capacitance rate. It is a dimensionless parameter and the sole parameter upon which the collector flow factor depends.

Collector plate temperature (T_P), at any point of time the collector plate temperature is given as,

$$T_P = T_i + \frac{Q_u}{A_c F_R U_L}(1 - F_R) \quad (10)$$

Where, the useful heat gain Q_u is given as,

$$Q_u = A_C F_R \left[I_t (\tau_o \alpha_o) - U_L (T_i - T_a) \right] \quad (11)$$

Thermal efficiency of the collector (η): It is the ratio of the useful heat gain to the Total input energy. Mathematically

$$\eta = F_R \left[\tau_0 . \alpha_o - \frac{U_L (T_i - T_a)}{I_t} \right] \quad (12)$$

Thermal Efficiency of the collector when angle of incidence is not 90° (η_θ).The equation (12) for the thermal efficiency is applicable for normal incidence angle situation. In a situation where angle of incidence is not 90° we will have to add a new parameter is known as incident angle modifier (k_θ). the necessity of (k_θ) is arise due to change in $(\tau\alpha)$ product. For a flat plate collector (k_θ) is given as:

$$\kappa_\theta = 1 - b_0 \left(\frac{1}{\cos\theta} - 1 \right) - b_1 \left(\frac{1}{\cos\theta} - 1 \right)^2 \quad (13)$$

For a single glaze collector we can use a single order equation with b_0=0.1

$$\kappa_\theta = 1 - b_0 \left(\frac{1}{\cos\theta} - 1 \right)$$

Thus for a collector where angle of incidence is not 90°, the efficiency can be calculated by using the following equation,

$$\eta_\theta = \kappa_\theta F_R \left[(\tau_0 . \alpha_0) - \frac{U_L (T_i - T_a)}{I_t} \right] \quad (14)$$

First law of thermodynamics (energy analysis):

Thermal energy balance equation

$$m_P C_P \left(dT_{P,avg} / dt \right) + \dot{m} C_P (T_{out} - T_{in}) = \eta_o I A_c - U_C \left(T_{P,avg} - T_e \right) T_c$$
(15)

The thermal efficiency of the *FPSC* (η) is therefore:

$$\eta_C = \frac{\dot{m} C_P (T_{out} - T_{in})}{I A_c} \quad (16)$$

Pumping power and pressure drop:

$$\Delta p = f \frac{\rho V^2}{2} \frac{\Delta l}{d} + k \frac{\rho V^2}{2} \quad (17)$$

f = Friction factor, for laminar flow $f = \frac{64}{Re}$

$$\text{Pumping power} = \left(\frac{\dot{m}}{\rho_{nf}} \right) \times \Delta p \quad (18)$$

And

Reduction in size of collector can be calculated by the equation:

$$A_C = \dot{m} C_P (T_{out} - T_{in}) / I \eta_C \quad (19)$$

Nomenclature:

BBC: Brown Boveri Corporation
Roth: Roth werke product
FEM: finite element method
FPSC: Flat plate solar collector
$\mathbf{l_C}$ =length of collector
$\mathbf{l_R}$ =length of reflector

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