

# Experimental Study on U- pipe Evacuated Tube Solar Collector with Reflected Shield

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**ABSTRACT:**Energy is one of the most essential requirements of living hood. In present scenario conventional energy resources for producing energy to sustain our lives has become a necessity. Since these sources are depleting at faster rate and cost of energy is increasing simultaneously, so conversion of renewable form of energy is much desired and solar energy is a good resource. In solar heating system the evacuated tube solar collector (ETSC) perform better than that of flat plate collector. In this investigation having three Evacuated tube solar collectors, each consist of fifteen evacuated tubes with reflected shield at different centre distance between the tubes. A copper pipe (through-flow pipe) is bent 15 times to form 15 U-shape turns. Each U-turn is immersed in an evacuated tube.

In this study investigate and compare the thermal performance of three set of evacuated tube with U-pipe arranged at three different centre distance 65, 90 and 115mm respectively. A comparison of the thermal performance of systems of U-pipe ETSC having the temperature and efficiency curves are made at different flow rate. The average thermal efficiency of 90mm centre distance U-pipe ETC is less than that of other collector. If fluid thermal mass is neglected then the useful energy output will be over predicted in numerical simulations. Moreover, the flow rate may also affect system thermal performance. The optimal flow rate for maximum useful energy is determined by meteorological conditions such as solar radiation and outdoor temperature, and the thermal performance of the collector.

**KEYWORDS:**Evacuated-tubes solar collector, U-pipe, Reflected shield, Centre distance.

## I. INTRODUCTION

The crucial point in designing any solar collector is to allow maximum possible amount of solar radiation to reach the absorber part of the collector, and concurrently, reducing thermal losses from the absorber to the minimum. Evacuated-Tube Solar Collector (ETSC) offers feasible solution to this problem. An evacuated tube is composed of two coaxial glass tubes forming an annulus (Fig.1).The space between the two tubes is evacuated to eliminate convective losses. The outer tube is the transparent cover while the inner tube is the absorber which is coated from outside (vacuum side) with a selective paint to maximize solar absorptance. One end of the evacuated tube is closed while the other is left open. The solar collector usually incorporates several evacuated tubes forming a parallel array at three different center distance with reflected shield.

Heat can be extracted from the tubes by a variety of ways. The simplest way is achieved by the direct connection of the tubes to the storage unit. The working fluid can be either a liquid or a gas. When water is used as the working fluid, it is directly circulated between the tank and tube cavity via natural circulation. The temperature range in this type is limited by water boiling point. However, air or other gases may also be used as working fluids which necessitates the use of an appropriate fan or blower to circulate the fluid.

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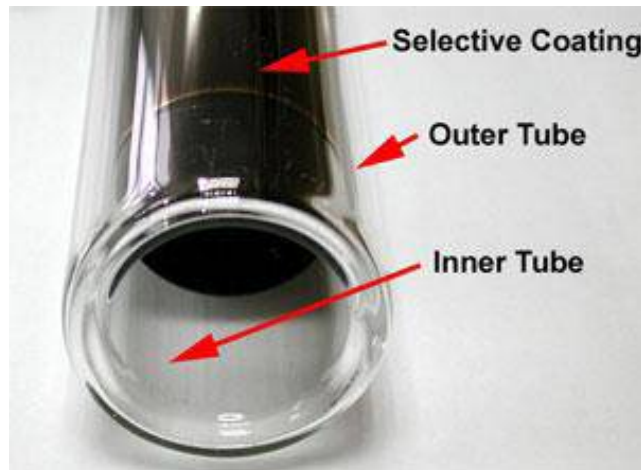


Fig. 1 An evacuated tube shown from its open end.

Table 1. Evacuated Tube Basic Specifications

Length (nominal)	1500mm
Outer tube diameter	47mm
Inner tube diameter	34mm
Glass thickness	1.6mm
Thermal expansion	$3.3 \times 10^{-6} \text{ } ^\circ\text{C}$
Material	Borosilicate Glass 3.3
Absorptive Coating	Graded Al-N/Al
Absorptance	>92% (AM1.5)
Emittance	<8% (80°C)
Vacuum	$P < 5 \times 10^{-3} \text{ Pa}$
Stagnation Temperature	>200°C
Heat Loss	<0.8W/ ( m <sup>2</sup> °C )
Maximum Strength	0.8MPa

## II. RELATED WORK

A comparative test on flat plate collector and evacuated tube collector was done by E.Zambolin and D.Del Col. [1]. They carried a test on the collectors to install in parallel and same working condition. They presented in terms of daily efficiency versus daily average reduced temperature difference this allow to represent the comparative characteristics of the two collectors when operating and variable condition, especially with wide range of incidence angles. As a result in the daily tests the evacuated collector displayed a higher efficiency for a large range of operating

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conditions as compared to that flat plate collector. An experimental study by Guiqiang Li and Gang Pei [2] on low-concentration evacuated tube (LCET) because of the development of the energy demands, solar energy medium-temperature applications (80°C) for refrigeration, building heating, seawater desalination, thermal power generation etc. In The investigation on a solar collector for medium-temperature applications. Ray trace outcome at the incident angles between 0 and 60° shows that the average optical efficiency can reach 76.9%. The results comprehensively indicate the good performance of LCET solar collector for medium-temperature applications. Budihardjo I. and Morrison G.L. [3] studied the performance of water-in-glass evacuated tube solar water heaters using experimental measurements of optical and heat loss characteristics and a simulation model of the thermosyphon circulation in single-ended tubes. The performance of water-in-glass evacuated tube solar collector systems are compared with flat plate solar collectors in a range of locations. The performance of a typical 30 tube evacuated tube array was found to be lower than a typical 2 panel flat plate array for domestic water heating in Sydney. Dilip Mishra [4] investigated experimentally using evacuated collector with U-Tube. Depending on the temperature change of atmosphere, variation in solar irradiation the thermal performance of evacuated U-tube solar collector has analysed. The analysis utilizes the set of observed data for different operating conditions. In this study it is found that the concept of inserting copper fin in to it, has increased the thermal performance of evacuated tube collector by 10% -15% from water-in-glass evacuated collector. K.S. Ong and W.L. Tong [5] discussed in this article compares the outdoor performance of two solar water heater systems incorporating the evacuated glass U-tube solar collectors operating under natural convection. Their performance would depend on collector and storage tank designs and sizes, weather conditions (solar radiation intensity and ambient temperature) and direction in which the balconies are facing. They were tested the panels in both the vertical and inclined positions using the same tank but at different times of the year. The result shows that the inclined panel system performed better than the system with the vertical panel system.

Zhang X.R. and Yamaguchi H. [6] experimentally studied a different design of the working fluid pipe used to extract energy from the evacuated tube. They used a U-shape stainless steel pipe equipped with especially designed fin. One U-shape pipe with a fin is inserted in each evacuated tube. Supercritical CO<sub>2</sub> is circulated in the U-shape pipe as the working fluid. The study shows the potential of using CO<sub>2</sub> in power generation via evacuated tube solar collector array. An Experiment and simulation were conducted by Pin-Yang Wang and Hong-Yang Guan [7] on an evacuated tubular solar air heater with simplified compound parabolic concentrator (CPC). The system connected 10 panels and includes a simplified CPC and an all-glass evacuated tube with a U-shaped copper tube. The experimental results show that the system can provide the heated air exceeding 200°C. The whole system has an outstanding high-temperature collecting performance and the present heat transfer model can meet the general requirements of engineering calculations. Xinyu Zhang and Shijun You [8] were presented an Experimental performance evaluation and comparative analyses based on heat extraction of direct-flow coaxial evacuated-tube solar collectors with and without heat shields. The test system to evaluate the thermal performance of medium-temperature solar collectors was developed. The experimental analysis shows the evacuated-tube solar collector performed better with a heat shield, especially at higher working temperatures.

To obtain medium and higher temperatures, other fluids with higher boiling temperatures may be used either as working fluids or as intermediate media between the inner surface of the tube and the main working fluid. In such a case, U- pipe must be inserted inside each glass tube to circulate the main working fluid. Despite the numerous researches found in the literature that tackled various the evacuated-through-U-pipe configurations, many points are still not fully studied and documented. One of such points of increasing interest is the use of evacuated-tube solar collectors as steam generators. To achieve this that, efficient heat transfer between the tube cavity and the U- pipe must

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be ensured. A feasible solution to that is by filling the tube with a liquid whose boiling temperature is far above that of water.

### III. EXPERIMENTAL RIG AND TEST PROCEDURE

The experimental rig consists of three panels, each have fifteen evacuated glass tubes are fitted in square manifold. In the collectors evacuated tubes are arranged at different center distance of 65, 90 and 115mm connected with storage tank and water tank at inlet and outlet. The experimental system of photograph view is shown in Fig.2.



Fig.2 The evacuated U-tube solar collector under study.

Each panel is made up evacuated tube with U-shaped copper tube connected with inlet and outlet pipe. The structure and arrangement of U tube collector is shown in Fig.3 and 4. A simplified reflected shield is attached back of glass evacuated tube. Reflected shield can absorb solar radiation without following the tracks of the sun. It also has the advantage of concentrating the diffuse radiation, which is impossible when using an imaging collector. The tubular absorber is an all-glass evacuated solar tube, which consists of two concentric glass tubes sealed at one end with an annular vacuum space and a selective absorbing coating on the outer surface (vacuum side) of the inner tube.

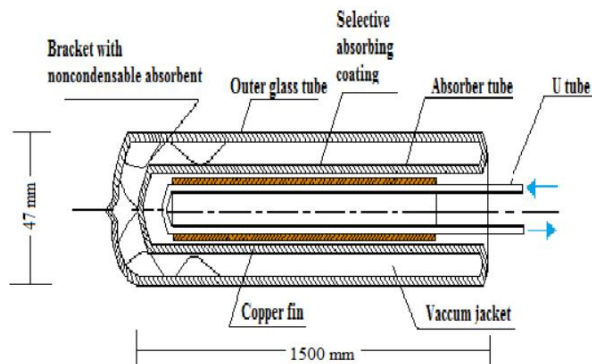


Fig.3 Axial structure of evacuated U-tube solar collector tube with copper fin

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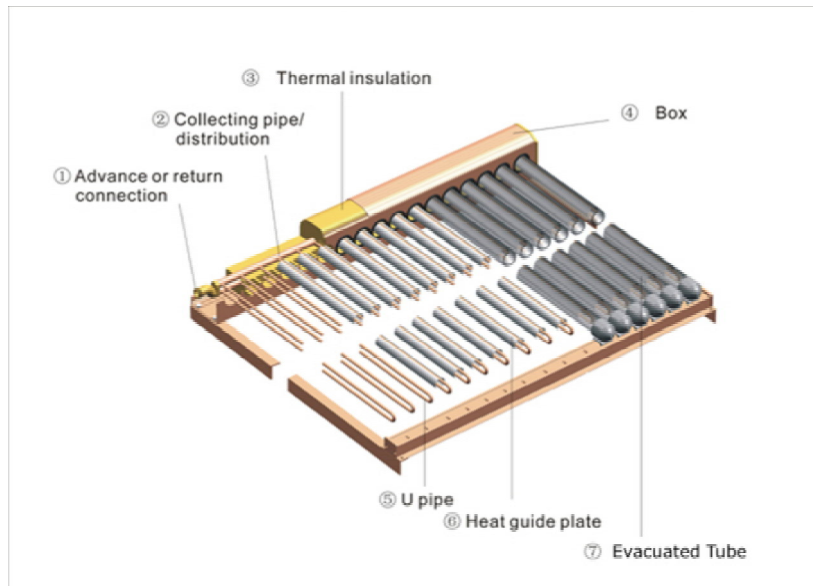


Fig. 4 Arrangement of U- tube in evacuated solar collector.

This simplified reflected shield is designed with a flat curve bottom instead of involute curve shape bottom for reducing processing difficulty and cost. In addition, the upper half part of reflected shield is also cut to decrease cost and increase actual acceptance angle. The simplified reflected shield as shown in Fig.5 is made of a stainless steel mirror (2 mm thick, 330 mm wide and 146 mm high) welded directly on the steel shelf. Its concentrating ratio is 2.18 (the ratio of lighting area of simplified reflected shield to external surface area of evacuated tube) and the reflectivity of 8.5.



Fig. 5 Simplified reflected shield



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Water acting as a working fluid is circulated inside the collector from water tank. A regulation valve to control the amount of mass flow rate out of the water. After adjusting the regulation valve the water mass flow rate is measured by rotameter. The water temperature at the inlet and at the outlet of the collectors is measured by a thermocouple (T-type). A Copper–constantan thermocouple is used to measure the ambient temperature. Eppley radiometer are used to measure the solar irradiance. A PSP model pyranometer, classified as secondary standard supplied by Eppley laboratory, USA, measures the solar irradiance on the plane of the collectors. Finally an anemometer measures the air speed, being a parameter that influences the heat loss from the collector. Test are carried out for about 6 hours from 10.00am to 4.00pm. The tests have been performed at different days on summer period from March to May 2016 for 12° tilt angle of collectors. The data are collected at an interval of 15 minutes. At each interval the water inlet and outlet temperatures are measured. Solar radiation intensity (irradiance) and the ambient temperature are also measured and registered at each time interval. The water mass flow rate is adjusted by regulation valve of 15kg/hr.m<sup>2</sup>. The value is kept constant all over the whole test period. The tests are repeated for other values of mass flow rate at 30kg/hr.m<sup>2</sup> and 45kg/hr.m<sup>2</sup> on other testing days.

## IV. THERMAL PERFORMANCE OF A SOLAR COLLECTOR

The actual useful energy of a solar collector for near normal incidence angle of the solar radiation can be expressed as [9]

$$Q_u = F_R \cdot A_a [(\tau\alpha) \cdot G - U_L (T_m - T_a)] \quad (1)$$

where  $Q_u$  is the useful output power transmitted to the liquid,  $F_R$  the collector efficiency factor,  $A_a$  the aperture area of collector,  $(\tau\alpha)$  the effective transmittance–absorptance product at normal incidence,  $G$  the global solar irradiance,  $U_L$  the overall heat loss coefficient and  $(T_m - T_a)$  the difference between the average fluid temperature in the collector  $T_m$  and the ambient air  $T_a$ .

The efficiency is equal to:

$$\eta = \frac{Q_u}{G \cdot A_a} = F_R \left[ (\tau\alpha) - U_L \frac{T_m - T_a}{G} \right] \quad (2)$$

and thus:

$$\eta = F_R [(\tau\alpha) - U_L T_m^*] \quad (3)$$

Where,  $T_m$  is the reduced temperature difference. If the heat loss coefficient is considered as the sum of two terms, a constant factor and a second term dependent on the temperature difference between fluid and ambient air ( $T_m - T_a$ ), the efficiency equation can be written as:

$$\eta = \eta_o - a_1 T_m^* - a_2 G (T_m^*)^2 \quad (4)$$

If the  $a_2$  coefficient is assumed to be without statistical significance, a first order equation is obtained, Eq. (5), which means that the overall heat loss is a linear function of the temperature difference between fluid and ambient air.

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$$\eta = \eta_o - aT_m^* \quad (5)$$

In the tests, only high irradiance levels and thus low diffuse fractions are accepted by the standard. Therefore very stable and sunny weather conditions are needed.

The following measurements have been acquired: global irradiance on the collector plane, inlet and outlet fluid temperature in the collectors, surrounding air temperature and fluid flow rate. The surrounding air speed has been measured on the side of the test rig, the values are pretty constant, between 0.7 and 1.3 m/s. The test period includes a pre-conditioning period of at least 15 min, followed by measurement periods of 6 hrs. This procedure has been repeated varying the inlet fluid temperature and finally the results are reported in diagrams plotting the efficiency against the reduced temperature difference.

## V. EXPERIMENTAL RESULTS AND DISCUSSION

Analysis of the experimental results obtained for the U-pipe ETSC's at different center distance (65, 90, and 115mm) with heat shield involved determining the increase in fluid temperature and fluid temperature differential across each solar collector, heat flow rates, and thermal performance. Determination of the solar collector efficiency, according to ISO9806 [10], requires at three independent data records of at three mass flow rate of different inlet temperatures spaced evenly over the operating temperature of the solar collector, to give a total of at least 9 data records

### 4.1. Temperature profiles of the U-pipe ETSC's with reflected shield:

The test results for the temperature difference of the U-pipe ETSC's with heat shield at various flow rate (15, 30 and 45kg/hr.m<sup>2</sup>) are illustrated in Fig. 6, 7 & 8. The main parameters recorded during the test. Flow rate is kept constant for the whole day. The inlet temperature of water in to the collector is nearly same for these collectors.

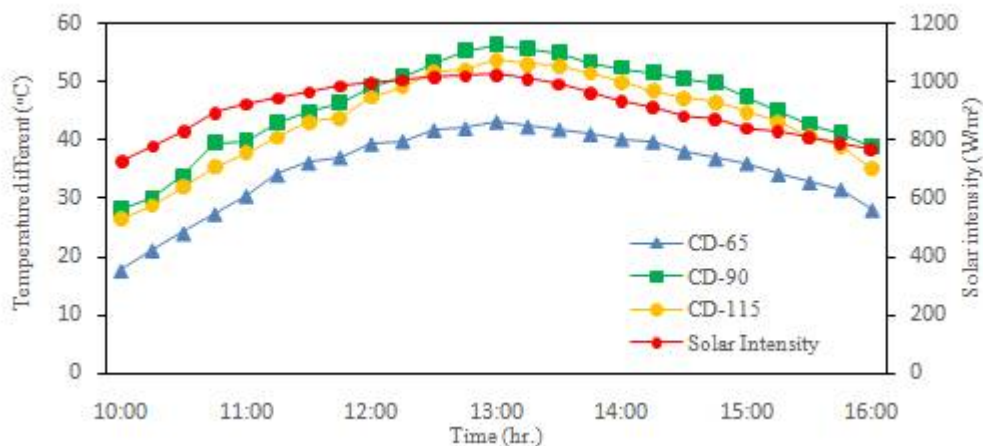


Fig.6.Solar Intensity and Temperature difference with time for each panel at 15kg/hr.m<sup>2</sup>.

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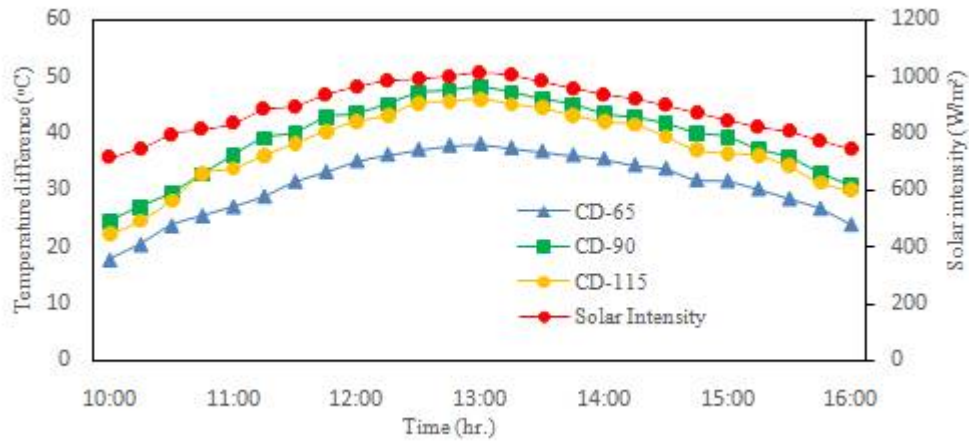


Fig.7. Solar Intensity and Temperature difference with time for each panel at 45kg/hr.m<sup>2</sup>

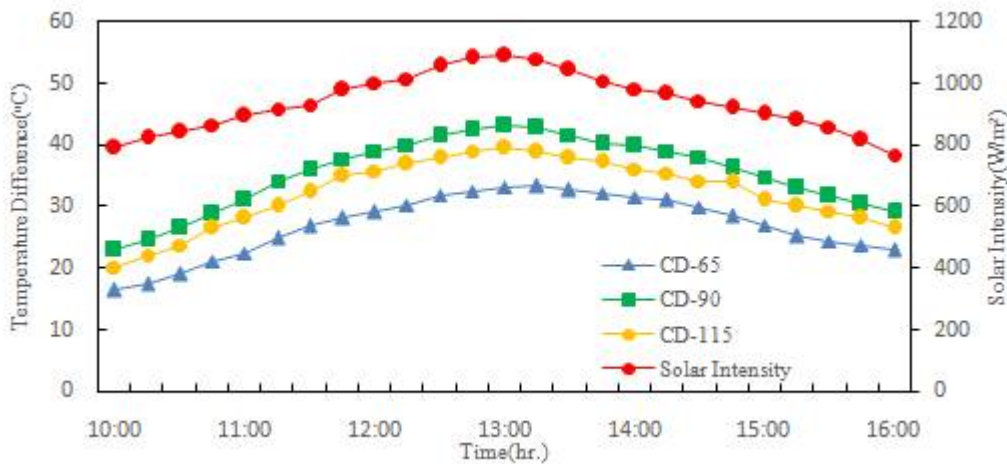


Fig.8.Solar Intensity and Temperature difference with time for each panel at 45kg/hr.m<sup>2</sup>

The temperature difference between the three collectors, the 90mm center distance ETC is increased with inlet temperature. The outlet temperature and the temperature difference abruptly increased. The maximum temperature difference between the outlet and inlet was 43.2°C for the 65mm CD ETC, 56.4°C for the 90mm CD ETC and 53.8°C for the 115mm CD ETC for the flow rate of 15kg/hr.m<sup>2</sup> and intensity of radiation 1025W/m<sup>2</sup> at 13:00hr..The 90mm CD ETC revealing an improvement of 26.4% over 65mm CD ETC and 4.6% over 115mm CD ETC when using a heat shield. The maximum temperature difference between the outlet and inlet was 38.1°C at 13:00hr. for the 65mm CD ETC, 48.2°C for the 90mm CD ETC and 46.1°C for the 115mm CD ETC for the flow rate of 30kg/hr.m<sup>2</sup> and intensity of radiation 1018W/m<sup>2</sup>. The 90mm CD ETC revealing an improvement of 21% over 65mm CD ETC and 4.4% over 115mm CD ETC when using a heat shield. The maximum temperature difference between the outlet and inlet was



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33.2°C at 13:00hr. for the 65mm CD ETC, 43.1°C for the 90mm CD ETC and 39.5°C for the 115mm CD ETC for the flow rate of 45kg/hr.m<sup>2</sup> and intensity of radiation 1120W/m<sup>2</sup>. The 90mm CD ETC revealing an improvement of 22.96% over 65mm CD ETC and 8.3% over 115mm CD ETC when using a heat shield. These test results show that the 90mm CD ETC with a reflected shield had better thermal performance at higher temperature difference than to other collector.

## 4.2. Collector efficiency

Thermal Performance Tests for ETC Solar Collectors are carried for analyse the efficiency based on the absorber area  $A_a$ . To get information about the quality of the components used in the collector (such as absorber, cover etc.) the efficiency based on the absorber area is more powerful. This vacuum tube module is equipped with a heat shield. Due to the concentration of the solar radiation, the collector efficiency could become greater than 1 if its physical absorber area is taken as a reference. But it is more realistic to use the area of the concentrator as reference. In this case, the maximum possible efficiency will become 1 if all components of the collector are ideal (i.e. with no losses).

The graph shows the collector efficiency functions for the three collectors based on the absorber area  $A_a$  in Fig.9, 10, 11. The efficiency of the 90mm CD collector was reached higher value compared to other collectors for all flow rate. The maximum efficiency was 34.43% for 65mm CD ETC, 44.10% for 90mm CD ETC and 42.59% for 115mm CD ETC the flow rate of 15kg/hr.m<sup>2</sup> at 13:15hr. The 90mm CD ETC revealing an improvement of 21.92% over 65mm CD ETC and 3.4% over 115mm CD ETC when using a heat shield. The maximum efficiency was 56.03% for 65mm CD ETC, 70.86% for 90mm CD ETC and 67.72% for 115mm CD ETC the flow rate of 30kg/hr.m<sup>2</sup> at 13:15hr. The 90mm CD ETC revealing an improvement of 20.92% over 65mm CD ETC and 4.4% over 115mm CD ETC when using a heat shield. The maximum efficiency was 66.51% for 65mm CD ETC, 88.69% for 90mm CD ETC and 81.82% for 115mm CD ETC the flow rate of 45kg/hr.m<sup>2</sup> at 13:00hr. The 90mm CD ETC revealing an improvement of 25% over 65mm CD ETC and 7.7% over 115mm CD ETC when using a reflected shield.

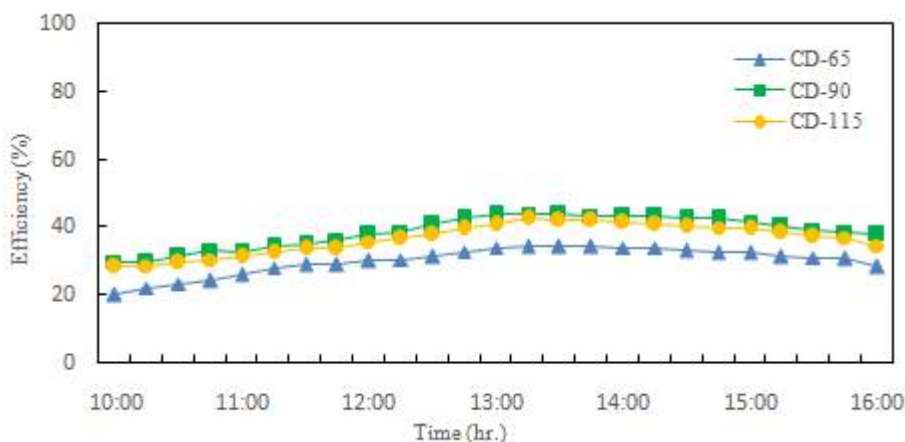


Fig.9. Efficiency Profile Comparison with Time for each panel at 15kg/hr.m<sup>2</sup>

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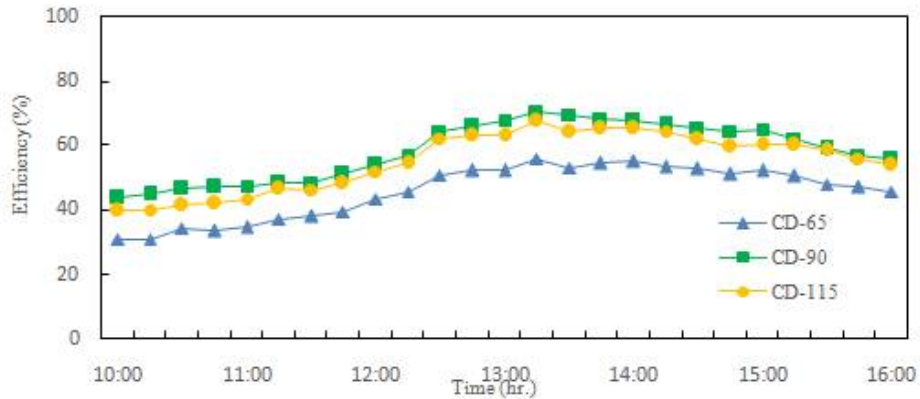


Fig.10. Efficiency Profile Comparison with Time for each panel at 30kg/hr.m<sup>2</sup>

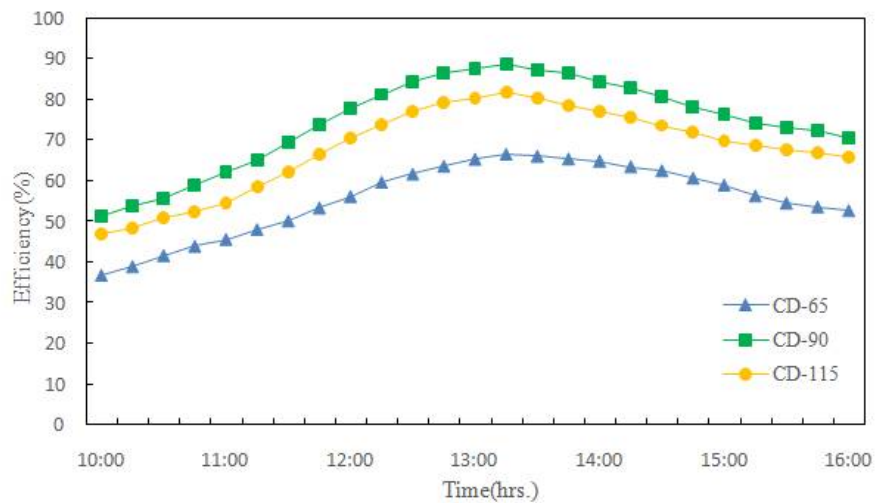


Fig.11. Efficiency Profile Comparison with Time for each panel at 45kg/hr.m<sup>2</sup>

Fig.11 shows the comparison between the instantaneous collector efficiency for three different CD ETC at the flow rate of 30kg/hrm<sup>2</sup>. The Eqs.2 plot as a straight line on a graph of efficiency versus the heat loss parameter  $(T_m - T_a)/G$  for collectors. The intercept (intersection of the line with the vertical efficiency axis) equals to  $F_R(\tau\alpha)$  for the collectors at 0.85. The slope of the line, i.e. the efficiency difference divided by the corresponding horizontal scale difference, equals to  $-F_R \cdot U_L$  at 17.84. If experimental data on collector heat delivery at various temperatures and solar conditions are plotted, with efficiency as the vertical axis and  $\Delta T/G$  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

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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.

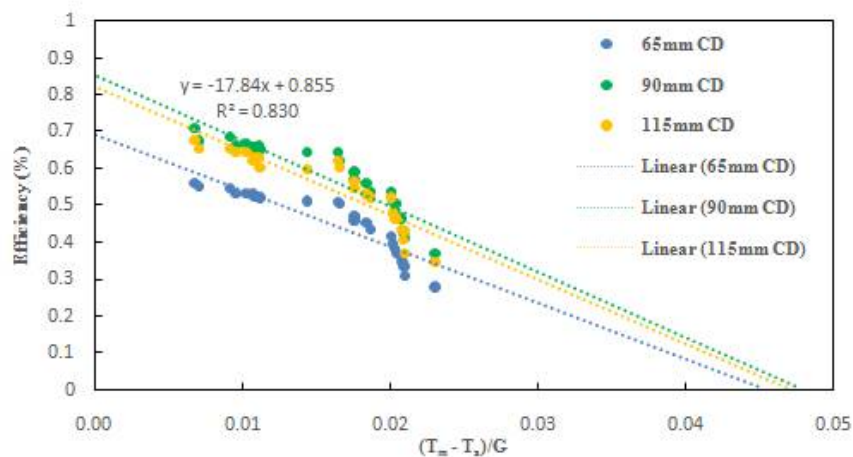


Fig.11. Effect of center distance of U-pipe ETSC

The comparison of the collectors efficiencies based on the center distance between the glass tube the 90mm CD ETSC perform better at 30kg/hr.m<sup>2</sup> flow rate.

## VI. CONCLUSION

In the present work, the thermal performance of the U-pipe ETSC collector is investigated with various CD with reflected shield. Further from study it is found that the reflected shield increase the heat from collector and traps heat for useful heating purpose of water. Thus helps in increasing collector thermal performance. The influences of atmospheric temperature and the intensity of solar radiation on the collector efficiency are studied. Effect of center distance and reflected shield and U-tube with copper fin in terms of its heat retaining capacity has been observed, it is found that the thermal efficiency of 90mm CD ETSC has been increased by 10-50% then other CD solar collectors.

In this work, the thermal performance for ETSC with heat shield has been investigated experimentally and the results from this work can be summarized as follows:

- 1) The outlet temperature and temperature difference of the collectors, 90mm CD collector abruptly increased 26% then other collectors at the flow rate of 15kg/hr.m<sup>2</sup>
- 2) The thermal efficiency of 90mm CD collector is highest value of 25% then other collector at the flow rate of 45 kg/hr.m<sup>2</sup> in the range of experimental operation.
- 3) The efficiency is intercept at about 0.85 and the slope 17.84 for 30kg/hr.m<sup>2</sup>

## REFERENCES

- [1]. E.Zambolin, D.Del Col. Experimental analysis of thermal performance of flat plate collector and evacuated tube collectors in stationary standard and daily conditions. Solar Energy 84, 1382 – 1396, 2010.
- [2]. Guiqiang Li, Gang Pei, Yuehong Su and Jie Ji. Performance study of a static low concentration evacuated tube solar collector for medium-temperature applications. I. J. of Low-Carbon Technologies, 1–7, 2014.
- [3]. Budihardjo I. and Morrison G.L., Performance of water-in-glass evacuated tube solar water heaters, Solar Energy, Vol. 83, No. 1, 49-56, 2009.

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: [www.ijirset.com](http://www.ijirset.com)

Vol. 6, Issue 11, November 2017

- [4]. Dilip Mishra. Experimental Analysis of Thermal Performance of Evacuated U-Tube Solar Collector. Advance Physics Letter. Vol-2, Issue-3, 2349-1108, 2015.
- [5]. K.S. Ong, W.L.Tong and J.K.Choong. Performance of U-tube solar water heater with vertical and inclined panels. I. J. of Low-Carbon Technologies, 1–6, 2013.
- [6]. Zhang X.R. and Yamaguchi H., An experimental study on evacuated tube solar collector using supercritical CO<sub>2</sub>, Applied Thermal Engineering, Vol. 28, 1225–1233, 2008.
- [7]. Pin-Yang Wang, Hong-Yang Guan and Zhen-Hua Liu. High temperature collecting performance of a new all-glass evacuated tubular solar air heater with U-shaped tube heat exchanger. Energy Conversion and Management 77, 315–323, 2014.
- [8]. Xinyu Zhang, Shijun You, and Hongchuan Ge. Thermal performance of direct-flow coaxial evacuated-tube solar collectors with and without a heat shield. Energy Conversion and Management 84, 80–87, 2014.
- [9]. Duffie, A., Beckman, W.A., 2006. Solar engineering of thermal processes 3rd ed., J. Wiley & Sons, 2006.
- [10]. 'Thermal Performance Tests For Solar Collectors', International Standard Organisation ISO, TC 180 SC5, ISO Standard 9806-1.2
- [11]. Dilip Mishra, Dr. N. K. Saikhedkar, Evacuated U-Tube Solar Water Heating System- A Descriptive Study. IJIRSET Vol. 3, Issue 5, May 2014, 12627 – 12635.
- [12]. Ghoneim AA, Fisch N, Ammar ASA, Hahne E. Investigation of evacuated tube collectors. Int. J. Solar Energy 1994, 16:15–25.
- [13]. Window B, Zybert J. Optical collection efficiencies of array of tubular collectors with diffuse reflectors. Solar Energy 1981, 26:325–331.

## Nomenclature and abbreviations:

$A_a$	absorber area of the collector, m <sup>2</sup>
$a$	heat loss coefficient for linear regression, (W/(m <sup>2</sup> K))
$c$	specific heat of fluid, kJ/(kg °C)
$F_R U_L$	heat Loss Coefficient (W/m <sup>2</sup> -K)
$F_R(\tau\alpha)$	solar collector absorber coefficient
$G$	solar irradiance, W/m <sup>2</sup>
$m$	flow rate, kg/hr.m <sup>2</sup>
$N$	total number of observations
$T_a$	ambient temperature, °C
$T_i$	inlet temperature of solar collector, °C
$T_o$	outlet temperature of solar collector, °C
$Q_c$	heat flow collected, W
$Q_u$	useful energy gained by solar collector, kJ
$T_m^*$	reduced temperature difference, m <sup>2</sup> K/W
$T_m$	arithmetic mean temperature, m <sup>2</sup> K/W
$U_L$	measured overall heat loss of solar collector, W/(m <sup>2</sup> K)

## Greek symbols:

$\rho$	density of water, kg/m <sup>3</sup>
$\eta$	solar collector efficiency
$\eta_o$	zero-loss collector efficiency ( $\eta$ at $T_m^* = 0$ )
$\tau\alpha$	transmittance–absorptance product

## Abbreviations:

ETSC	evacuated tube solar collector
CPC	compound parabolic concentrator
CD	center distance
ETC	evacuated-tube collector
ETC-HS	evacuated-tube solar collector with heat shield
ISO	International Organization for Standardization