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Thermal Performance Characterization of Evacuated Tube Collector Solar Water Heater with Constant Inlet Water Temperature

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Abstract: With large evolution in the solar technology, research is turned out to be more sophisticated. Evacuated tube collectors (ET Collectors) are the most eco-friendly and efficient solar water heaters used worldwide. A series of experiments have been performed on ETC Characterization System. The research presents the evaluation of the performance of an ET Collector and characterize the solar water heater at different wind velocity of (2, 3, 4 m/s) and solar radiation between 250 to 750 W/m^2 by keeping temperature of inlet water as constant. Examining the system performance at different temperature of inlet water of (29 °C, 40 °C, 50 °C). Net heat loss through evacuated tubes (ETs), heat loss coefficient through ETs, & the efficiency of an ET Collector has been recorded. The results show that the maximum and minimum values of heat transfer efficiency are found to be 69.16 % at 29 °C constant inlet water temperature, 750 W/m^2 solar radiation and 2 m/s wind speed and 33.37 % at 50 °C constant inlet water temperature, 250 W/m^2 solar radiation and 4 m/s wind speed, respectively. The overall heat loss coefficient and net heat loss from ETs are increased with increasing wind speed, constant temperature of inlet water & solar radiation. The maximum value of net heat loss from ETs is 68.724 Watts at 50 °C constant inlet water temperature, 750 W/m^2 solar radiation and 4 m/s wind speed. The minimum value of net heat loss from ETs are evaluated as 20.873 Watts at 29 °C constant inlet water temperature, 250 W/m^2 solar radiation and 2 m/s wind speed. Results also show that, heat transfer efficiency increases with a decrease in wind speed, decrease in inlet water temperature and an increase in solar radiation.
Keywords: Thermal Efficiency, Heat Loss Coefficient, Net Heat Loss, Inlet Water Temperature, Wind Speed, Water Chiller.

I. INTRODUCTION

With the evolution of energy demand, recent technologies move towards solar energy due to its unique abundance, eco-friendly and renewable nature. The most desirable need of the society is to get most of the energy with least investment. Since last few years, water heating for industrial and commercial purposes gets in touch with the solar energy which is tremendously available for all. Meanwhile, researchers are more interested in the radiation heating which has been used all over the world for few decades. By the time different kinds of solar water heaters are utilization.

Evacuated tube collector technology has been used commercially for over 20 years, however, all-glass evacuated tubes for solar water heating is established to be more than 1,00,00,000 tubes/year [1].

With attention to, the very first solar energy collector was invented in 1977 through William H. Goettl and named as "Solar heat collector and radiator for building roof", a designed roof structure used for collecting solar energy and radiates unwanted thermal energy into the sky, the disclosure was related to the roof construction having rafter between which a U-shaped duct made up of sheet metal and air could circulate through delivery and return passages to gain thermal energy from the sun [2].

ET collectors are the most used systems because of their unique technology of evacuated space between the environment and the absorber plate which helps in increased efficiency and better performance.

Many researchers investigated the thermal characteristics of ET collector by modifying the systems, changing the dimension of the tubes and many more. Researchers frequently examined and compared the economic feasibility and performance characteristics of Evacuated tube vs flat plate on various aspects.

Nomenclature

Q_L	Net Heat Loss from ET Collector, Watt
A_c	Total upper Area of the absorber coating, m^2
A_s	Total outer surface area of Evacuated Tubes, m^2
U_e	Heat Loss Coefficient of Evacuated Tubes, $W/(m^2. K)$
T_p	Plate Temperature, K
T_g	Uppermost Glass Temperature, K
T_a	Temperature of Ambience, K
D_1	Innermost Tube Diameter, m
D_2	Outermost Tube Diameter, m
L_c	Absorber plate Length, m
h_{ga}	Heat loss Coefficient between Outer Glass Tube & the Surrounding, $W/(m^2. K)$
$h_{pg,e}$	Heat Loss Coefficient between Absorber Plate & Outer Glass Tube, $W/(m^2. K)$
σ	Stefan Boltzmann Constant, $W/(m^2. K^4)$
ε_p	Emissivity of Absorber Plate
ε_g	Emissivity of uppermost glass Tube
η	Efficiency of ET Collector
V_a	Wind speed, m/sec
$\dot{m}$	Rate of flow of fluid, Kg/sec
Re_a	Reynolds Number
K_a	Thermal Conductivity of Air at Ambient Temperature, W/(m.K)
ϑ_a	Kinematic Viscosity of Air at Ambient Temperature, m^2/sec
Nu_a	Nusselt Number
C_p	Specific Heat of Water, J/(Kg. K)
T_{out}	Temperature of Outlet Water, °C
T_{in}	Temperature of Inlet Water, °C
I	Solar Radiation, W/m^2
N	Number of evacuated tubes

Abbreviation

ETC	Evacuated Tube Collector
ET	Evacuated Tube

Lai Yanhua [3] presented the performance of an ET Collector with subsidiary electric heater that was tested in rural areas. His research also presented the economic feasibility of the collector when the auxiliary electric heater was used with the ET Collectors & analysed the feasibility of building heating. Temperature of air in the heated space meets the demand of heating and furthermore, the system used in rural areas are economically applicative and advantageous as compared with the coal fired boilers and air conditioning devices. Methida Siritan [4] designed a pulsating heat-pipe which was closed-loop and applied on the commercial water heaters. He evaluated the performance & maximum savings by various methods. The system was designed using inside diameter of 1.78 and 1.5 mm; 1000 mm, 1250 mm and 1500 mm long evaporator and different sets of pulsating heat-pipe of closed-loop type. Result shown as, the optimum design was an evaporator length of 1250 mm, diameter of 1.5 mm, with 4 set. The economic evaluation results that the total heat gain of water was 518 Watts and the overall saving of 901.4 US Dollars over a decade with 482.4 USD investment. Mario Nájera-Trejo [5] also aimed to examined the economic workability of FPC vs ETC in a combi-system used for radiation floor heating & domestic hot water. He designed the system and analysed through TRNSYS. The results shown as, the optimum system is configured by 8 collectors with the storage relation of 40 L/m^2 for Evacuated tube collector and 12 collectors with 50 L/m^2 storage relation for Flat plate collector.

The investment return was 11 yrs. and 9 yrs. respectively for the ETC & FPC solar water heaters. Abdi Chimdo Anchala [6] compared and compared the performance of FPC with the ETCs on various parameters. In his research, performance analysis was depended on the climate conditions of Adama and the rate of flow of water through the system using T*SOL Simulation software. With this, he presented the operating conditions that impacted on solar fraction, efficiency, the temperature of exit water from the tank, the temperature of exit of the heater, absorbed useful stored energy. The system's simulation was done for 3 different flow (160, 120 & 80 L/hr.). At the mass rate of flow of 160 l/h, solar heating system efficiency was 50 % and 59 % for and FPC & ETC, respectively. Finally, evacuated tube collectors are proved to have a better efficiency, that satisfy the hot water needs.

Amanuel Andemeskel [7] experimentally evaluated the effect of width of aluminium fin coated with a solar paint on evacuated tubes. They studied the thermal performance, affected by this fin thickness. The experiment was performed with three different Al fins of variable thickness of 11, 13 and 24 micro meters. As a result, with the decrement in the thickness of Al fin, the efficiency, coefficient of heat loss and heat removal factor were found to be increased and concluded that it is suggested to use thinner Al fin of 11 micro meters with a solar coating of a single layer in Evacuated tubes.

Gholamabbas Sadeghi [8] optimized the thermal storage tank capacity and analysed the performance of the ET collectors. He simulated the ET solar energy model & utilizing Gene- Expression Programming (GEP) for varied capacities of the hot water tanks of 10 – 50 Litres and variable intensities of solar radiation through CFD. As a result, the optimum capacity of the tank was 26 L for 3 collector tubes. The performance of that heater was reported maximum of around 72 % on CFD-based approach seems to be reliable and trustworthy.

C. Wannagosit [9] theoretically and experimentally investigated the thermosyphon evacuated tube heaters and compared the mathematical models by evaluated results by an Explicit FD method. They used 8 tubes with thermosyphon dia. for condenser and evaporator of 22.22 mm and 15.88 mm, respectively. Experimental efficiency mate with the theoretical efficiency. Moreover, as a result, the efficiency of heater was 58.28 % during experiment, 57.60 % in EFD method and 55.97 % in thermal resistance method. It showed that the EFD method gives better accuracy as compared with the thermal resistance method.

C. Ramesh [10] presented a case study for the enhancement of performance of the coating of selective layer on the absorber paneland for this a response surface method was used. They used a coating of Nickel-cobalt and Black-chrome on an absorber panel of copper. To collect the experimental results the response surface method and Analysis of Variance Table was used. As a result, up to 89.3 % efficiency was improved by Black-chrome as compared to the coating of Nickel- Cobalt.

Davide De Maio [11] also presented the optimisation and efficiency analysis by selective coating for Evacuated flat plate solar collector. They designed 3 multilayer coatings of Cr_2O_3/Cr, and used genetic optimisation algorithm and film matrix method to optimise & simulate the selective layer. As a result, ensuring the robustness of the loss in efficiency varied up to ±20 % from the optimum value and was 2 % less than for the thickness of selective layer. Solar absorptance was more than 97 % and thermal emittance lower than 5 %. H. L. Yang [12] presented the antireflective and self-cleaning nano-porous film prepared by sol-gel process for evacuated tube collectors of water in glass type. As a result, in 250 nano-meters to 2500 nano-meters of broader spectrum range of, the maximum solar transmittance was 96 %.

Recently studies are going towards the performance evaluation of different fluids and using different types of fluids to investigate which fluid can give the best heat transfer characteristics of the ET collectors.

B. Kiran Naik [13] modelled and analysed the performance of U tube ET Collectors including the application of aqueous Lithium chloride solution as working fluid. He examined the flow rates of circulating fluid, temperature of inlet fluid, irradiation, size of the tube & ambience on performance of an ET Collector. As a result, the lower flow rate and optimised length of collector increased the exit water temperature. Water has more capacity to absorb heat energy as compared with the air and LiCl-H_2O solution. Raja Elarem [14] Presented a newly Evacuated solar collector with fins & incorporated the Paraffin wax with the addition of nanoparticles of copper and examined the ETC system's performance. A comparison on the Evacuated tube collector's performance with solar parabolic trough reflector & without by simulation using Ansys-Fluent. As a result, paraffin melted faster with the decrease in the thickness of the fins, moreover, by adding Cu to paraffin wax, the optimized concentration of mass at which exit water temperature was increased by 2 °C. Yong Li [15] by using PCM, the performance of ET Collector of U-tube type was presented. PCM inside the water heater reduces the fluctuation of energy as they store excess energy and releases this thermal energy to compensate the radiation in its absence. As a result, the PCM heat stored efficiency in ETC was 19.20 %. PCM has been used frequently by lots of researchers, although, Quanquan Luo [16] examined and discussed the double-pass of air type collector with embedded rod in the tubes & PCM. Piotr Olczak [17] presented heat loss analysis on the influence of ETC tracker with mirror parabolic reflector. Aluminium fins were assembled, the amplified solar radiation caused by mirror parabolic reflector were analysed and evaluated that maximum difference in the preferential and least profitable variation wasn't exceeded 2.5 % of the radiant energy absorbed.

Khawar Saeed Khan [18] presented the comparative study of solar milk pasteurization and did thermal analysis. The two most innovative collectors were compared, that were ET collectors & solar concentrators for solar milk pasteurizers based on the experimental and theoretical analysis and found that solar concentrator and ETC required 4.68 & 4.22 kWh. of energy, respectively, to get the temperature difference during the pasteurization process of 35 °C to 40 °C. As a result, the predicted values of efficiency for solar concentrator and ETC were found to be 54 % & 71.41 %, respectively. From this research the ET collectors are more efficient than all other type of solar collectors. E. Zambolin [19] experimentally, thermal performance investigation of FPC and ET Collector and evaluated the efficiency in stationary and quasi-dynamic conditions and measured for whole day the input and output curves. The results were observed as 0.027 m^2K/W with daily tests & 0.037 m^2K/W in standard conditions. Michel Hayek [20] Experimentally investigated and presented the comparison between the ET collector of water in glass type & heat pipe type, having 20 evacuated tubes. Experiment was performed under eastern Mediterranean climate. As a result, ETCs of heat pipe type were better performed and has around 20 % higher efficiency than ET Collectors without heat pipe. T-T Chow [21] also studied and analysed experimentally the comparison of heat pipe & water in glass type of ET Collectors in Hong Kong. The research present heat loss at night, daily thermal efficiency, transient efficiency, and comparison of these collectors. As a result, efficiency of ETCs of water in glass type show higher than ETCs of heat pipe type. The daily efficiency was slightly higher for heat pipe type and at night time heat loss is higher in heat pipe type collector as compared with water in glass ETCs. Aed Ibrahim Owaid [22] Experimentally presented the ETCs & heat losses in these heaters assembled with 32 collector tubes and has a hot water storage tank of 263 litres. They evaluated temperature drop at night & in the evening. Moreover, they presented the energy absorbed from irradiation during the noon time. As a result, for three days the heat losses were 27062.7 KJ for 1st day, 24743 KJ for the 2nd day and 20656 KJ for the 3rd day. Mohmoud B. Elsheniti [23] presented the performance of the ETCs with higher temperature of inlet water of 70 to 90 °C to calculate the efficiency & examined the impact of temperature of the inlet water, irradiation, number of evacuated tubes & rate of flow over the temperature of exit water & the efficiency. As a result, thermal efficiency always profitable at a smaller tubes count, although, at some certain rate of flow, increase of the temperature of exit with the tubes count but can be eliminated above a certain number. Also, the difference in the temperature of exit & inlet water decreases as time passes. Jian Wang [24] Designed and experimentally enhanced thermal emittance and solar absorptance of selective coating and transmittance of envelop tubes of ET Collectors without heat pipe. In that case, by using porous SiO_2 antireflective coating, the transmittance increased to 0.94. Results also showed that, the selective coating emittance at 180 °C was optimised to 0.95 and absorptance to 0.05.

ETCs are used worldwide on a daily basis, for domestic purposes, however, the water heater must withstand large variations of ambient conditions like intensity variation of irradiation, that greatly impact on the performance of the collectors and different wind speeds that may not affect the performance on a large scale but can affect a little bit on the heat transfer efficiency and heat loss from the water heaters. Mustafa Ali Ersoz [25] presented the performance of heat pipe type of an ET Collector by several fluids, that were, petroleum ether, methanol, hexane, acetone, chloroform & ethanol under different wind speed from 2 to 4 m/s. As a result, max. energy and exergy efficiencies were found for Acetone for air speed of 3 & 2 m/s, whereas, minimum for Hexane under all air velocities. Alicja Siuta-Olcha [26] studied experimentally the efficiency of ET Collectors with heat pipe, consist of twenty-four evacuated tubes & having solar collector area of 3.9 m^2 in polish climate. For a period of July and august, solar irradiation was 80 and 112.8 kWh/m^2, respectively. As a result, the avg. thermal efficiencies for August & July were 32.9 % & 45.3%. Results also shows that, with the increase of wind speeds from 0.09 - 0.86 ms^{-1}, & decreased efficiency was by 67 %. Shaowei Chai [27] Experimentally enhanced the thermal efficiency by using reflective coating in evacuated tubes. As a result, the heat transfer efficiency was reached 65 % to 72 % at radiation intensity of 950 Wm^{-2} and temperature of inlet from 45-70 °C & by using reflective coating the efficiency was enhanced by 10 %. This research is focussed on the thermal performance evaluation and heat losses form the ET Collector solar heater & characterise by varying ambient conditions and input parameters with constant inlet water temperature. Almost all researches are based on the dimension of the tubes, number of glass tubes, type of absorber coating, width of absorber coating, type of fluid used, inlet water temperature, solar radiation levels & different additional equipment that could improve the efficiency of an ET Collector. Although, it is known that the difference of temperatures is dominant in the transfer of heat between two entities, the performance of the ET Collector more or less, affected by the working fluid temperature. Therefore, the research has been focussed on the water temperature that is flowing in the system by keeping the temperature constant by using water chiller and evaluate the efficiency of collector & heat loss through the evacuated tubes during working conditions. Number of experiments were performed on different inlet water temperature and investigated. An increase in the radiation intensity increases the efficiency as well as increase the net heat loss from the evacuated tubes during working condition. This research involves in solar radiation changes & determined maximum and minimum efficiency in specific radiation levels including the variations of constant inlet water temperature.

II. MATERIAL & METHODS

In this research, Fig. 1. shows an ETC Characterization System which has been used and located in Renewable Energy Lab in Mechanical Engineering Department of JEC, Jabalpur, MP, India. The system is proposed by Ecosense Sustainable Solutions Pvt. Ltd [28].

Fig. 1. Evacuated Tube Collector Characterization System

The setup was basically an ET Collector, used to heat water, assembled with few sub-units having their individual task which were combined so as to conduct number of experiments with large number of variations in input parameters and ambient conditions. The system can also be used for different nanofluid characterization.

The ETC Characterization system is a unique setup which can be used for training purpose, thermal characterization of different types of fluids and research purposes in different universities and research organizations. It can run by water as well as different nanofluids as a working fluid.

Table 1. Specification of setup.

S.N.	Main Components	Sub-units	Specifications	Description
1	Radiation Generating Unit	Artificial Sunlight Source	Type	Halogen
			Number of Halogens	36
			Total Power	5400 W
		Dimmer	Capacity	1-Phase, 25 A
2	Solar Evacuated Tube Collector	Evacuated Glass Tubes	Total Number of Tubes	10
			Total Capacity	100 LPD
			Storage Capacity of a Tube	2.6 Litres
			Material of Glass	Borosilicate Glass
			Total Length of Tube	1800 mm
			Tube Outer Diameter	58 mm
			Tube Inner Diameter	47 mm
			Thickness of outer Tube	1.8 mm
			Inner Tube Thickness	1.6 mm
			Emissivity of Glass	0.88
			Outer Surface Area of Tube	3.132464 m^2
			Inclination Angle	30°
		Selective Coating (Absorber Plate)	Material of Selective Coating	(Aluminium Nitride Coating) AlN/AlN-SS/CU - Sputtering
			Absorber Plate Length	1720 mm

			Absorptance	>90%
			Emissivity of Coating	0.08
			Absorber/Collector Area	1.2698 m^2
3	Manifold	Single sided 100 LPD manifold for 10 Tubes	Insulation	50mm Poly-Urethane Foam Insulation
4	Hot Water Storage Tank	Inbuilt Heater	Power	3kW
		Storage Tank	Material	SS 316 grade 28 finish non-Magnetic
			Insulation	55 mm PUF cladding by SS mirror
			Capacity	50 Litres
5	Heat Exchanger Unit	Heat Exchanger Tank	Capacity	50 Litres
			Heat Exchanger Material	Copper
			Insulation	External Glass Wool Jackets
6	Chiller Unit	Chiller Tank	Cooling Capacity	0.3 TR
7	Water Pump	Pump 1 and Pump 2	Power	0.3 HP
8	Fan	Artificial Wind Source	Type	Tower Fan
9	Measurement Accessories	Radiation Meter	-	-
		IR Temperature Gun	-	-
		Anemometer	-	-
10	Measurement Units	Temperature Meter	Range	0-200 °C
		Flow Meter	Range	0-15 LPM
		Pressure Meter	-	-

A. Experimental Setup and Procedure

1) Evacuated tube collector

Fig. 1. shows ETC Characterization system that consists of a series of ten glass tubes supporting on a fixed structure that are connected to a header manifold. Unlike FP Collectors, these tubes are two hollow cylinders sealed at both ends between which air gets removed and made a vacuum between the two tubes, therefore, it is named as Evacuated Tube. The vacuum helps in the insulation and reduce thermal losses in significant amount to the surroundings via convection and radiation, it helps in the better performance of the ET Collectors and enhanced heat transfer efficiency as compared with other type of solar collectors.

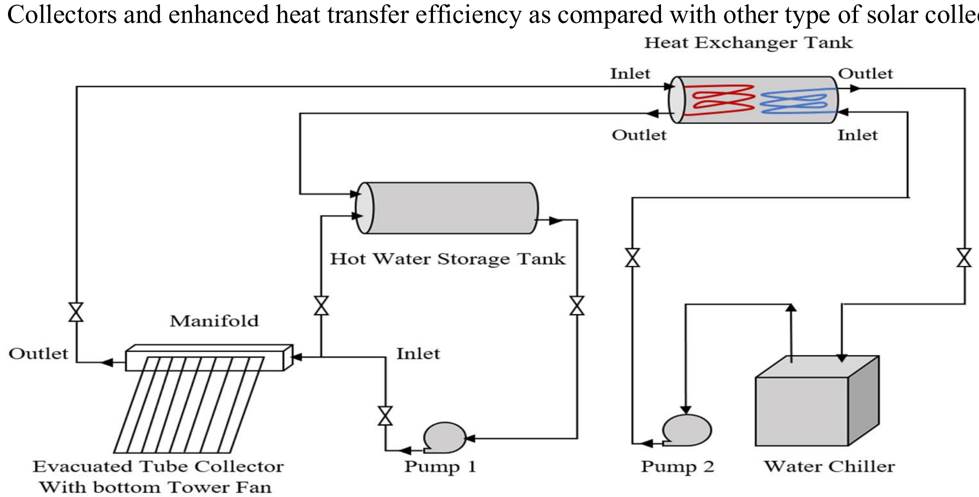


Fig. 2. A simple layout of an ETC Characterization System.

Halogen Fixture has a big assembly of a halogen unit with 32 halogen lamps fitted in three rows so that the radiation can evenly be distributed all over the evacuated tube collector. This made an artificial sunlight source. This halogen fixture attached with a regulator or dimmer which has been used to regulate manually the radiation level and power supplied to the halogens so that the experiment could perform at different radiation intensity over the Evacuated tube collector.
A tank of 50 L capacity, has been used, which stores heated water and kept it hot for a long time, without letting it cool. This tank is made with galvanised steel with a thick layer of poly urethane foam which works as a thermal insulator, whose thermal conductivity is very less so that heat losses from hot fluid into the environment can be reduced. Hence, fluid can be kept warmer for a day or two.
A small tower fan has been attached to the bottom side of the structure through which air could blow to make artificial environment. Wind speed can be adjustable at a certain range (low, medium, and high). Measurement unit consist of a display panel on which temperatures at various locations, flow-rate of fluid and pressure at few locations, displayed. In Table 1. a complete specification details of the setup is reported.

2) Cooling system with heat-exchanger and chiller

Fig. 2. clearly shows that this system has two cycles. First one is for fluid flowing through the tubes to the heat exchanger and then into the storage tank by using a forced circulation. A second cycle is used for cooling purpose. The cooling of hot fluid made it a unique experimental setup for research. This colling system has been installed with a small refrigeration unit called as a Chiller and a heat exchanger tank. The chiller system helps to stabilize the temperature of fluid in the tank. Cooling is done through heat-exchanger tank in which hot fluid coming from the exit of manifold passed through this heat exchanger and loses its thermal energy to the chilled water. Cold fluid is circulated using pump. The flow rate can be manually adjusted so that the cooling rate can be regulated.
The measurement accessories which were used during the experiments are Inclinometer, used for measurement of the inclination of the evacuated tube. IR Temperature Gun, used to calculate the plate temperature of the absorber coating. Radiation Meter, which records irradiation. An Anemometer is used to determine the velocity of the wind flowing on the collector tubes.

B. Principle

Evacuated Tube Collector solar water heater works on two basic principles. The 1^{st} one is that, any hot object always loses its energy as heat to the colder object and the outside environment. This transfer of energy i.e., heat gain and heat loss mainly by convection and radiation, which neatly impacted the efficiency of the ET Collector. The thermal insulation & design conditions help in preventing and slow down heat losses by a considerable amount between the hot object and its environment. In this research we have examined the heat transfer efficiency of the ET Collector in different cases, when solar radiation vary, wind velocity over the tubes increases and with different inlet water temperature keeping constant. The 2^{nd} one is that, the heat energy, transmitted to the object or losses from the object, directly concerned to the difference of temperature of an object & the environment and heat transfer is more rapid when this difference in temperature is very large. In this research heat loss from the evacuated tubes has been evaluated in different cases when the solar radiation vary, wind velocity over the tubes increases and with different inlet water temperature keeping constant.

C. Method

In this research number of experiments had been performed by keeping some parameters fixed for a set and number of experiments were performed for different combinations and input parameters. From Fig. 2., to make inlet water temperature constant, chiller unit was used. Both the tanks were filled with water and start the system by switch on the halogen, fan, pump 1, pump 2, chiller and measurement unit. Flow rate of water be fixed at 1 Litres/min. Inlet temperature of water at manifold be fixed and storage tank temperature kept constant by using chiller unit that continuously cool down the fluid through heat-exchanger by regulating rate of flow of fluid across the heat-exchanger. To rise the inlet temperature from lower to higher for the experiment, an inbuilt heater had been used.

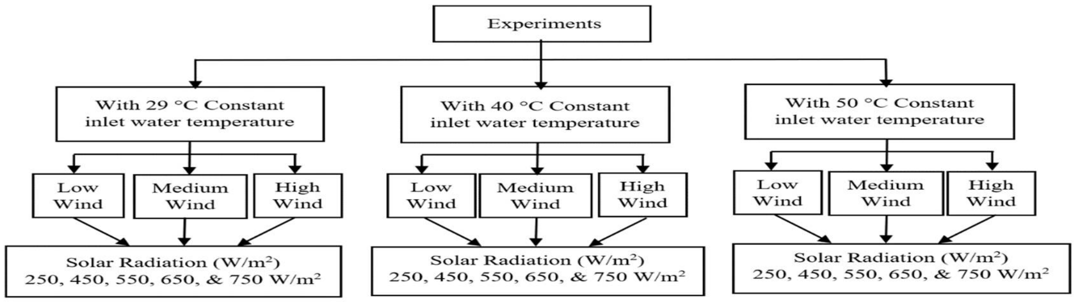


Fig. 3. A simplified layout diagram for the plan of experiments performed in this research.

Fig. 3. shows a complete experimental procedure which has been performed for constant inlet temperatures of 29 °C, 40 °C and 50 °C with wind speed from Low to high range. Wind velocity kept fixed at 2 m/sec for each set of constant inlet temperatures and same sets were made for the wind velocity of 3 m/sec and 4 m/sec respectively. The solar radiation has taken as 250 Watt/m^2, 450 Watt/m^2, 550 Watt/m, 650 Watt/m^2 and 750 Watt/m^2. These radiations were taken by keeping each radiation level fixed for 50 minutes and took the temperature readings at various locations for every 10 minutes.

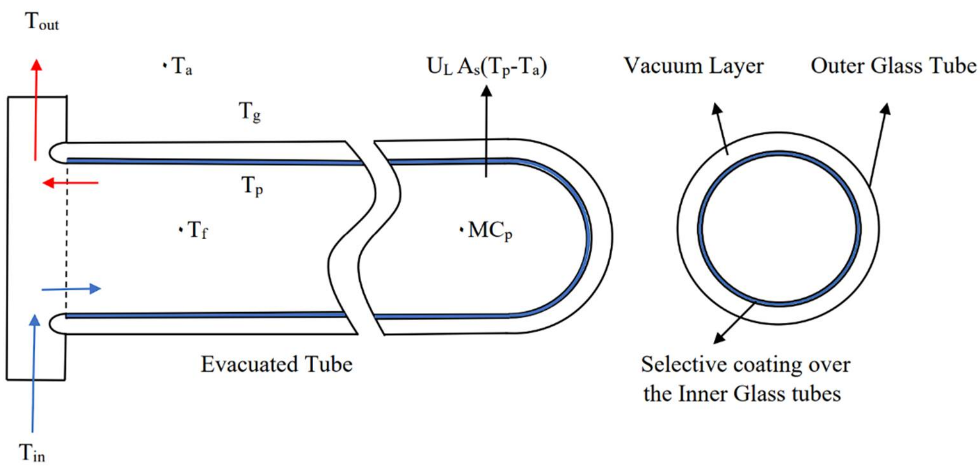


Fig. 4. A simple cross section view of ET Collector

Fig. 4. shows the solar collector's schematic diagram of a simple cross section view of ET Collector attached with a manifold through which cold fluid flow from below and heated fluid flow upward. This process of flow of hot fluid and cold fluid is basically known as thermosyphon process. The temperature distribution affect heat loss coefficient and overall heat losses from the tubes to the atmosphere, due to which hot water loses heat to the atmosphere. There were 8 temperature sensors, 4 at upper glass tubes and 4 at lower glass tubes, average values of these temperature sensors were used to calculate outer glass tube temperature.

Fig. 5. (a) shows the simplified electrical analogy of evacuated tube's heat loss coefficient. Heat loss could be convective and radiative from the tubes due to temperature difference. Diagram shows the heat loss from the absorber coating to the uppermost glass tube and due to vacuum between the plate and outer glass tube there were only radiative heat loss. Second was the radiative & the convective thermal losses from upper tube to the atmosphere. Hence, U_e could be simplified in Fig. 5. (b).

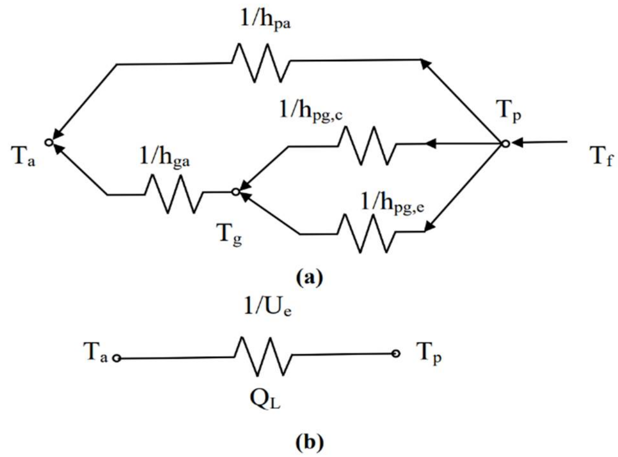


Fig. 5. (a) Electrical Analogy of Thermal Resistance in different modes from Evacuated Tube.
(b) Equivalent Electrical Analogy

Heat loss coefficient from the evacuated tubes has been divided into three parts and eliminating the other losses that was convective loss through vacuum layer ($h_{pg,c}$) because of negligible amount of heat losses compared to other, therefore, ($h_{pg,e}$) between absorber plate and uppermost tube by radiation, (h_{ga}) between uppermost glass tube and atmosphere, (h_{pa}) between absorber plate and atmosphere, are considered.

Net heat loss through the evacuated tubes is mathematically expressed as

$$Q_L = A_s U_e(T_p - T_a) \quad (1)$$

Collector or absorber area is the half-curved surface of absorber coating which is shown by

$$A_c = (\pi/2)D_1L_cN = 1.2698 \text{ m}^2 \quad (2)$$

Uppermost area of the tubes through which heat loss by radiation & convection expressed as

$$A_s = \pi D_2L_cN = 3.13246 \text{ m}^2 \quad (3)$$

The Heat Loss Coefficient between the absorber & the atmosphere is expressed as

$$U_e = \frac{1}{\frac{1}{hga}+\frac{1}{hpg,e}} \quad (4)$$

Heat loss coefficient between uppermost tube & the surrounding is expressed by

$$h_{ga} = Nu_a(K_a/D^2) + (\sigma\varepsilon_g(T_g^2+T_a^2)(T_g+T_a)) \quad (5)$$

where $\sigma = 5.67*10^{-8}$ W/m^{2}K^4

Radiative heat loss coefficient across the absorber coating and outermost glass tube is expressed as

$$h_{pg,e} = \sigma\varepsilon_p(T_p^2+T_g^2)(T_p+T_g) \quad (6)$$

Nu_a can be calculated by following formula

For $0.1 < Re_a < 1000$; $Nu_a = 0.4 + 0.54(Re_a)^{0.6}$

For $1000 < Re_a < 50000$; $Nu_a = 0.3(Re_a)^{0.6}$ (7)

Reynolds Number of wind flow over the tubes is expressed as

$$Re_a = (V_aD^2)/\vartheta_a \quad (8)$$

Efficiency of the ET Collector is expressed by

$$\text{ET Collector efficiency } (\eta) = \frac{\text{Heat gain}}{\text{Total incident radiation}}$$

$$\eta = \frac{\dot{m}Cp(To - Ti)}{IAc} \quad (9)$$

III. RESULTS

A. *Effect of Wind Speed, solar radiation, and inlet Water Temperature on thermal Efficiency.*

Table 2. Efficiency (η) Vs Solar Radiation (I) at 2 m/s wind speed at different constant inlet water temperatures.

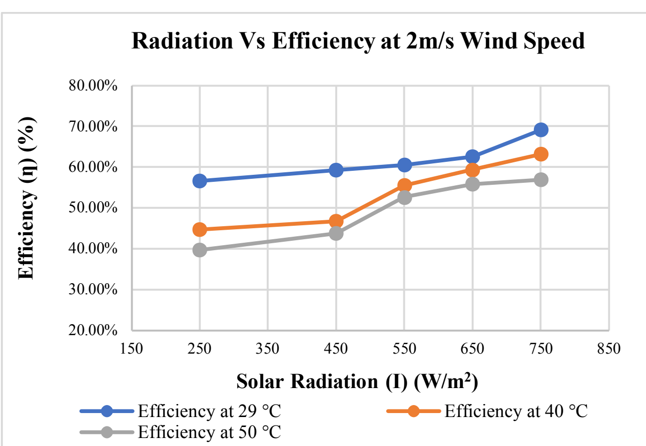
S. N.	Radiation, I (W/m^2)	Efficiency, η (%) at 29 °C	Efficiency, η (%) at 40 °C	Efficiency, η (%) at 50 °C
1	250	56.5865963	44.7054765	39.6875193
2	450	59.2510632	46.7702552	43.743495
3	550	60.5327611	55.5051762	52.5823057
4	650	62.5491113	59.3643596	55.8020282
5	750	69.1607119	63.149329	56.9249646

Table 3. Efficiency (η) Vs Solar Radiation (I) at 3 m/s wind speed at different constant inlet water temperatures.

S. N.	Radiation, I (W/m^2)	Efficiency, η (%) at 29 °C	Efficiency, η (%) at 40 °C	Efficiency, η (%) at 50 °C
1	250	50.0741062	41.158762	39.0292393
2	450	57.6734761	46.2199795	41.2684754
3	550	59.9243374	54.6003308	50.5383138
4	650	62.3031943	55.4274907	54.0728346
5	750	65.1303213	60.9597496	54.4102

Table 4. Efficiency (η) Vs Solar Radiation (I) at 4 m/s wind speed at different constant inlet water temperatures.

S. N.	Radiation, I (W/m^2)	Efficiency, η (%) at 29 °C	Efficiency, η (%) at 40 °C	Efficiency, η (%) at 50 °C
1	250	49.7432084	40.7293431	33.3710191
2	450	53.8305796	43.3714364	38.4502048
3	550	59.0846089	53.4999349	45.9194075
4	650	60.409042	54.0447781	47.3813575
5	750	63.9102914	58.4465963	48.6721484



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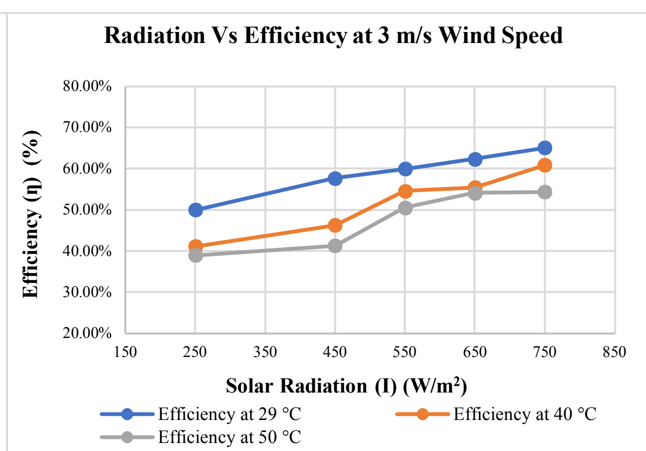

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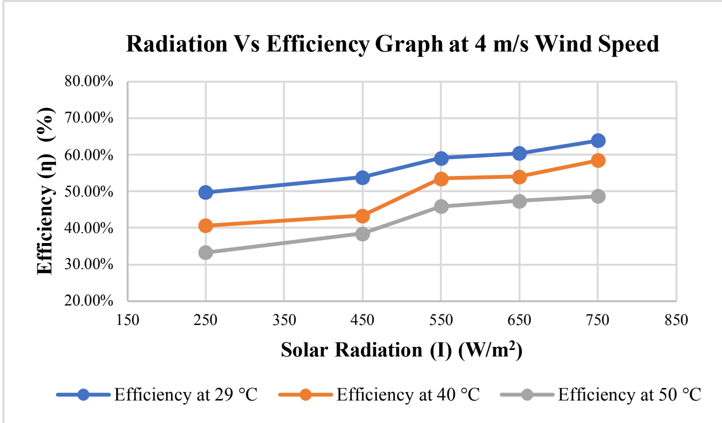

(c)

Fig. 6. Radiation Vs Efficiency graph at (a) 2 m/s wind speed, (b) 3 m/s wind speed and (c) 4 m/s wind speed at different constant inlet water temperature

In Fig. 6. graphs clearly show that, the efficiency enhances with increase in incident radiation.

- In Fig. 6. (a). at 2 m/s wind speed, graph shows the efficiency at 29 °C increased from 56.58 % to 69.16 % with the increase in radiation from 250 W/m^2 to 750 W/m^2. Similarly for 40 °C and 50 °C, efficiency increased from 44.7 % to 63.15 % and 39.69 % to 56.92 %, respectively.
- In Fig. 6. (b). at 3 m/s wind speed, graph shows the efficiency at 29 °C increased from 50.07 % to 65.13 % with the increase in radiation from 250 W/m^2 to 750 W/m^2. Similarly for 40 °C and 50 °C, efficiency increased from 41.16 % to 60.96 % and 39.03 % to 54.41 %, respectively.
- In Fig. 6. (c). at 4 m/s wind speed, graph shows the efficiency at 29 °C increased from 49.74 % to 63.91 % with the increase in radiation from 250 W/m^2 to 750 W/m^2. Similarly for 40 °C and 50 °C, efficiency increased from 40.73 % to 58.45 % and 33.37 % to 48.67 %, respectively.

For a glance, at 2 m/s wind speed & 750 W/m^2, with the increase of inlet temperature from 29 °C to 50 °C, efficiency has decreased by 17.7 %. But, at 750 W/m^2 & 29 °C, with the increase of wind speed from 2 m/s to 4 m/s, efficiency just decreased by 7.51 %. As a result, the efficiency is significantly decrease with higher constant inlet water temperature and slightly decrease with increase in wind speed.

"A summarised result comes out as, with higher radiation level, lower inlet water temperature and least wind speed leads to the best heat transfer efficiency."

Therefore, based on the research, the maximum and minimum values of heat transfer efficiency are found to be 69.16 % at 29 °C constant inlet water temperature, 750 W/m^2 solar radiation and 2 m/s wind speed, and 33.37 % at 50 °C constant inlet water temperature, 250 W/m^2 solar radiation & 4 m/s wind speed, respectively.

B. Effect of wind speed, solar radiation, and inlet water temperature on heat loss coefficient.

Table 7. Heat Loss Coefficient (U_e) Vs Solar radiation (I) at 2 m/s wind speed and different constant inlet water temperature.

S. N.	Solar Radiation, I (W/m^2)	Heat Loss Coefficient, U_e (W/m^{2}K) at 29 °C	Heat Loss Coefficient, U_e (W/m^{2}K) at 40 °C	Heat Loss Coefficient, U_e (W/m^{2}K) at 50 °C
1	250	0.501274488	0.529450787	0.583680434
2	450	0.522611443	0.545233197	0.592434776
3	550	0.533507395	0.554773449	0.603463968
4	650	0.541408118	0.565005328	0.610272392
5	750	0.549418565	0.575665371	0.621958091

Table 8 Heat Loss Coefficient (U_e) Vs Solar radiation (I) at 3 m/s wind speed and different constant inlet water temperature.

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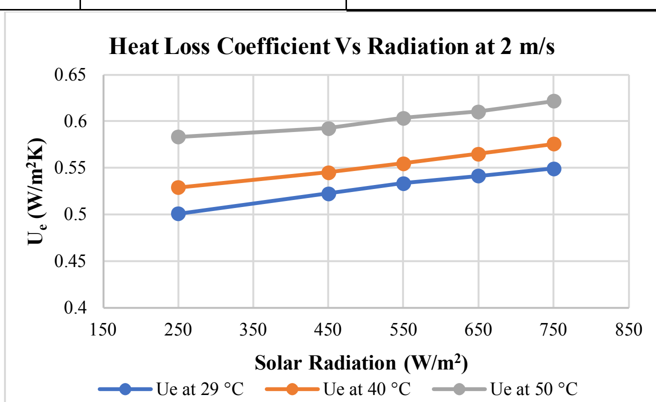
S. N.	Solar Radiation, I (W/m^2)	Heat Loss Coefficient, U_e (W/m^2K) at 29 °C	Heat Loss Coefficient, U_e (W/m^2K) at 40 °C	Heat Loss Coefficient, U_e (W/m^2K) at 50 °C
1	250	0.504630713	0.53126	0.58372
2	450	0.520280165	0.54782	0.593123
3	550	0.529726519	0.55794	0.604214
4	650	0.538997179	0.56614	0.612498
5	750	0.550198936	0.577942	0.623298

Table 9. Heat Loss Coefficient (U_e) Vs Solar radiation (I) at 4 m/s wind speed and different constant inlet water temperature.

S. N.	Solar Radiation, I (W/m^2)	Heat Loss Coefficient U_e (W/m^2K) at 29 °C	Heat Loss Coefficient, U_e (W/m^2K) at 40 °C	Heat Loss Coefficient U_e (W/m^2K) at 50 °C
1	250	0.505368903	0.534360203	0.584680693
2	450	0.52063819	0.553273006	0.594402376
3	550	0.536423641	0.563778646	0.605078873
4	650	0.548078414	0.574720186	0.614770027
5	750	0.555304529	0.584228513	0.626724476



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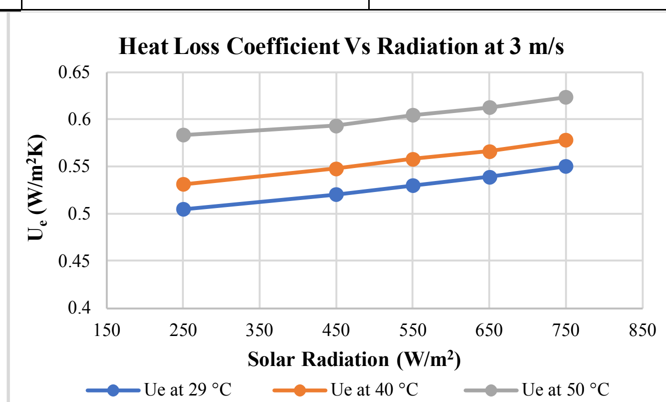

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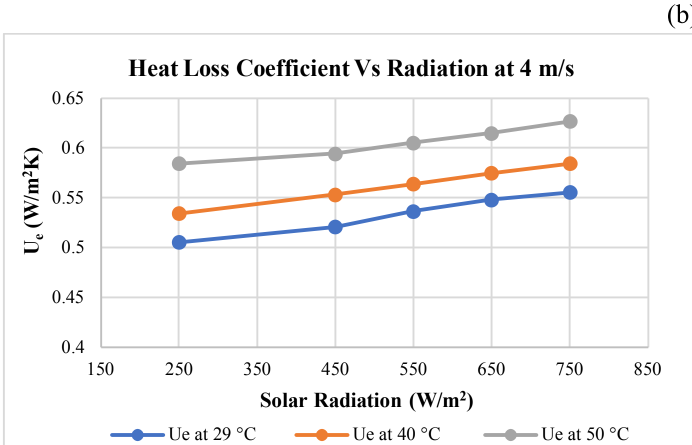


(c)

Fig. 7. Heat loss coefficient Vs irradiation graph at (a) 2 m/s wind speed, (b) 3 m/s wind speed and (c) 4 m/s wind speed at different constant inlet water temperature.

In Fig. 7. Graphs clearly shows that the heat loss coefficient U_e increases with increase in radiation and constant inlet water temperature.

- In Fig. 7. (a). at 2 m/s wind speed, graph shows the heat loss coefficient at 29 °C increased from 0.509274488 W/m^{2}K to 0.549418565 W/m^{2}K with the increase in radiation from 250 W/m^2 to 750 W/m^2. Similarly, for 40 °C and 50 °C, heat loss coefficient increased from 0.529450787 W/m^{2}K to 0.575665371 W/m^{2}K and 0.583680434 W/m^{2}K to 0.621958091 W/m^{2}K, respectively.
- In Fig. 7. (b). at 3 m/s wind speed, graph shows the heat loss coefficient at 29 °C increased from 0.504630713 W/m^{2}K to 0.550198936 W/m^{2}K with the increase in radiation from 250 W/m^2 to 750 W/m^2. Similarly for 40 °C and 50 °C, heat loss coefficient increased from 0.53126 W/m^{2}K to 0.577942 W/m^{2}K and 0.58372 W/m^{2}K to 0.623298 W/m^{2}K, respectively.
- In Fig. 7. (c). at 4 m/s wind speed, graph shows the heat loss coefficient at 29 °C increased from 0.505368903 W/m^{2}K to 0.555304529 W/m^{2}K with the increase in radiation from 250 W/m^2 to 750 W/m^2. Similarly for 40 °C and 50 °C, heat loss coefficient increased from 0.534360203 W/m^{2}K to 0.584228513 W/m^{2}K and 0.584680693 W/m^{2}K to 0.626724476 W/m^{2}K, respectively.

As a result, with higher constant inlet water temperature, the heat loss coefficient has increased significantly and slightly increase with increase of wind speed.

"Therefore, a summarised results comes out as, with higher radiation , higher inlet water temperature and higher wind speed, the system suffer more heat loss and hence reduced efficiency."

Therefore, based on the research, the maximum and minimum heat loss coefficient U_e are found to be 0.626724476 W/m^{2}K at 50 °C constant inlet water temperature, 750 W/m^2 radiation and 4 m/s wind speed, and 0.501274488 W/m^{2}K at 29 °C constant inlet water temperature, 250 W/m^2 solar radiation and 2 m/s wind speed, respectively.

C. Effect of wind speed, solar radiation, and inlet water temperature on net heat loss.

Table 10. Net heat loss (Q_L) at 2 m/s wind speed and different constant inlet water temperature at different radiation levels.

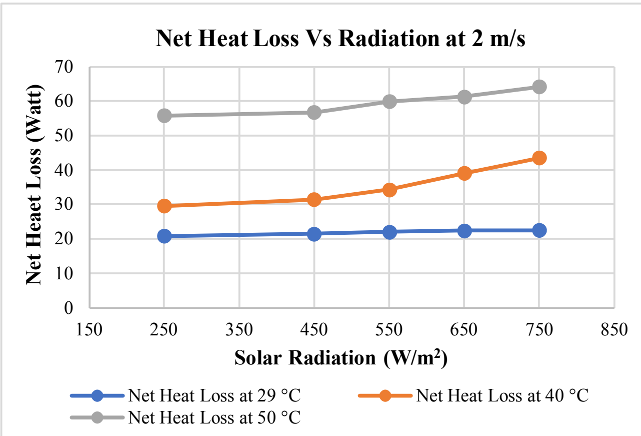
S. N.	Radiation, I (W/m^2)	Net Heat Loss, Q_L (Watt) at 29 °C	Net Heat Loss, Q_L (Watt) at 40 °C	Net Heat Loss, Q_L (Watt) at 50 °C
1	250	20.87270607	29.63740369	55.80423299
2	450	21.4540398	31.45443882	56.75158237
3	550	22.05813932	34.27661517	59.85058756
4	650	22.37056207	39.01630107	61.25341089
5	750	22.55155283	43.60897149	64.14209263

Table 11. Net heat loss (Q_L) at 3 m/s wind speed and different constant inlet water temperature at different radiation levels.

S. N.	Radiation, I (W/m^2)	Net Heat Loss, Q_L (Watt) at 29 °C	Net Heat Loss, Q_L (Watt) at 40 °C	Net Heat Loss, Q_L (Watt) at 50 °C
1	250	21.89944941	30.192	55.53428
2	450	22.47560026	35.167	57.45671
3	550	23.80234281	37.282	59.98298
4	650	26.35815478	41.597	62.14873
5	750	27.12897254	45.982	65.98421

Table 12. Net heat loss (Q_L) at 4 m/s wind speed and different constant inlet water temperature at different radiation levels.

S. N.	Radiation, I (W/m²)	Net Heat Loss, Q_L (Watt) at 29 °C	Net Heat Loss, Q_L (Watt) at 40 °C	Net Heat Loss, Q_L (Watt) at 50 °C
1	250	22.16649265	36.80091488	55.13054538
2	450	23.63994684	37.37192818	57.35342808
3	550	27.41637174	41.66455235	60.50388856
4	650	30.5531073	46.19873625	63.55603317
5	750	31.72917687	48.36229655	68.72449791



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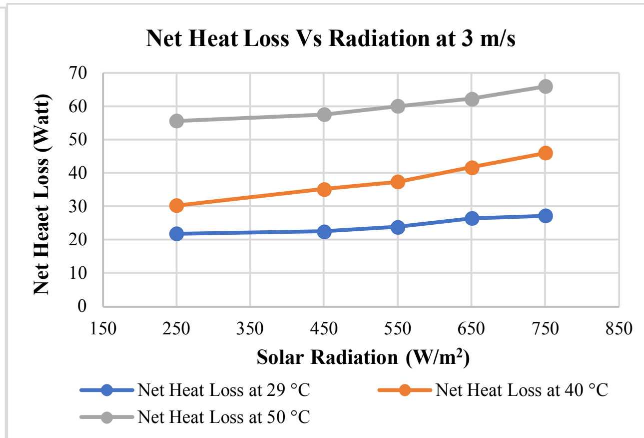

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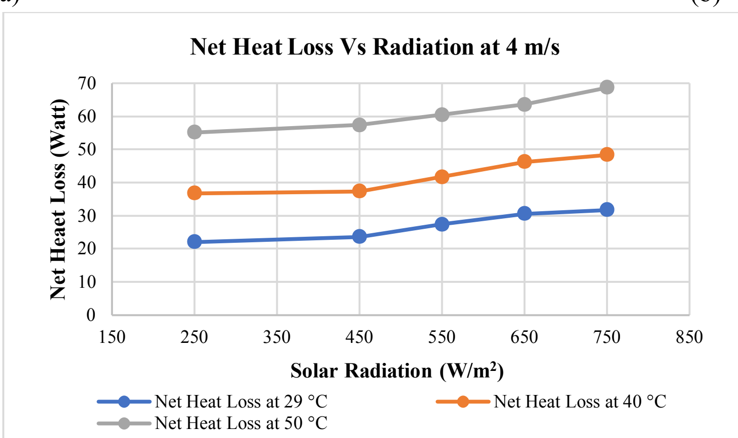

(c)

Fig. 8. Net heat loss vs radiation graph at (a) 2 m/s wind speed, (b) 3 m/s wind speed and (c) 4 m/s wind speed at different constant inlet water temperature.

In Fig. 8. graphs clearly show a large increase in the net heat loss with increase in solar radiation, wind speed and inlet water temperature.

- In Fig. 8. (a). at 2 m/s wind speed, graph shows the net heat loss at 29 °C increased from 20.87270607 Watt to 22.55155283 Watt with the increase in radiation from 250 W/m² to 750 W/m². Similarly, for 40 °C and 50 °C, net heat loss increased from 29.63740369 Watt to 43.60897149 Watt and 55.80423299 Watt to 64.14209263 Watt, respectively.
- In Fig. 8. (b). at 3 m/s wind speed, graph shows the net heat loss at 29 °C increased from 21.89944941 Watt to 27.12897254 Watt with the increase in radiation from 250 W/m² to 750 W/m². Similarly for 40 °C and 50 °C, net heat loss increased from 30.192 Watt to 45.982 Watt and 55.53428 Watt to 65.98421 Watt, respectively.

- In Fig. 8. (c). at 4 m/s wind speed, graph shows the net heat loss at 29 °C increased from 22.16649265 Watt to 31.72917687 Watt with the increase in radiation from 250 W/m^2 to 750 W/m^2. Similarly for 40 °C and 50 °C, net heat loss increased from 36.80091488 Watt to 48.36229655 Watt and 55.13054538 Watt to 68.72449791 Watt, respectively.

As a result, with higher constant inlet water temperature, the net heat loss increased significantly & slightly increase with increase in wind speed.

"Therefore, a summarised result comes out as, with higher radiation , higher inlet water temperature and higher wind speed, the system suffer more heat loss and hence reduced thermal efficiency. "Therefore, based on the research, the maximum and minimum values of net heat loss of evacuated tubes are found to be 68.72449791 Watt at 50 °C constant inlet water temperature, 750 W/m^2 solar radiation and 4 m/s wind speed, and 20.87270607 Watt at 29 °C constant inlet water temperature, 250 W/m^2 solar radiation and 2 m/s wind speed, respectively.

IV. CONCLUSION

This work shows that the temperature of inlet water greatly affects the heat transfer performance in evacuated tube solar collector. Lower inlet temperature and higher radiation level are key factors dominant on the performance of ET collectors. Finally, it is concluded that

1) With higher constant inlet water temperature, higher wind speed, & decrease of intensity of radiation, the efficiency decreases. The maximum and minimum heat transfer efficiency is found to be 69.16 % at 29 °C constant inlet water temperature, 750 W/m^2 solar radiation and 2 m/s wind speed, and 33.37 % at 50 °C constant inlet water temperature, 250 W/m^2 solar radiation and 4 m/s wind speed, respectively.

2) With higher constant inlet water temperature, higher wind speed & radiation, the heat loss coefficient increases. The maximum and minimum overall heat loss coefficient is found to be 0.626724476 W/m^{2}K at 50 °C constant inlet water temperature, 750 W/m^2 solar radiation and 4 m/s wind speed, and 0.501274488 W/m^{2}K at 29 °C constant inlet water temperature, 250 W/m^2 solar radiation and 2 m/s wind speed, respectively.

3) Similarly, heat loss increases with increase in all these parameters value. The maximum and minimum net heat loss is found to be 68.72 Watt at 50 °C constant inlet water temperature, 750 W/m^2 solar radiation and 4 m/s wind speed, and 20.87 Watt at 29 °C constant inlet water temperature, 250 W/m^2 solar radiation and 2 m/s wind speed, respectively.

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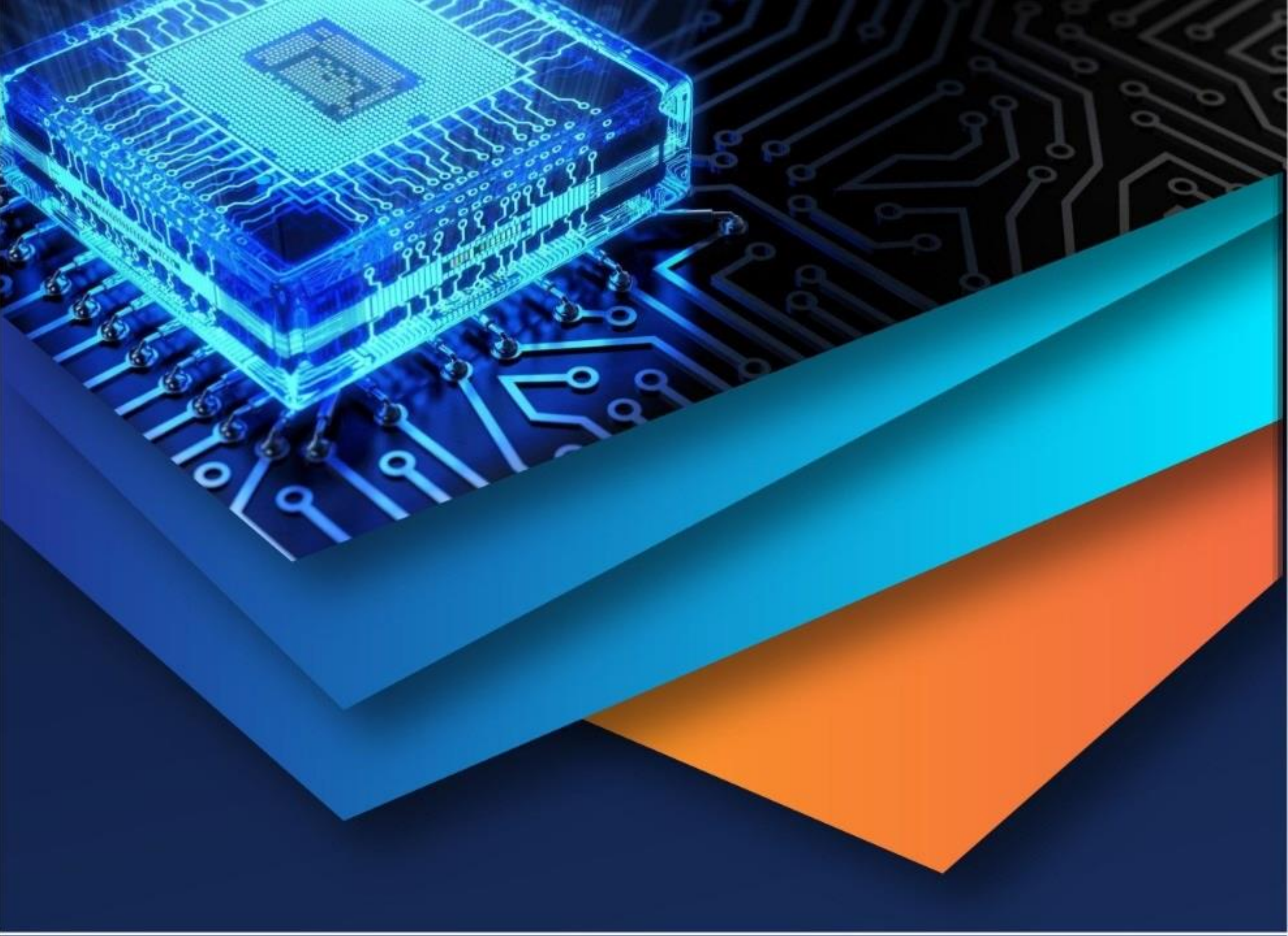

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