A CONCENTRIC PARABOLIC SOLAR WATER HEATER WITH CONCENTRIC TUBES: EXPERIMENTAL ANALYSIS

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Abstract

The utilization of a renewable energy source not only addresses energy demands but also contributes to the attainment of long-term developmental objectives. Employing a Parabolic Trough Collector (PTC) design for evaluating heat application within a medium temperature range is of paramount importance, enhancing the accessibility of solar energy. This study involves the design of a parabolic solar water heating system featuring concentric tubes. The system is showcased at NIT Jamshedpur (latitude 22.85 N, longitude 86.25 E), with a collector structure boasting dimensions of 500 mm aperture width and 1160 mm length. The complete lifecycle of the framework, including its development, creation, implementation, and assessment, is executed within the institute. Operating with water as the working fluid, initially at 26 °C, and propelled through a closed loop via a 6 V micro DC submersible solar pump, the system achieves a high handling capacity of 120 liters per hour with a remarkably low current consumption of 220 mA. An in-depth analysis dissects both the optical and thermal performance of the collector, encompassing key metrics like peak optical efficiency, incidence angle modifier, heat loss, and thermal efficiency, especially focusing on the glass-covered receiver. Furthermore, this article presents methodologies for accurately estimating heat loss and system thermal efficiency. The pinnacle optical efficiency of a glass-covered system reaches nearly 46.26% under normal heat loss conditions, corresponding to an average incident solar radiation of 598 W/m2. Operating at a mass flow rate of 0.07 kg/sec and an incident solar radiation of 598 W/m2 sustained over 7 hours, the system attains a temperature of 51 °C. This study is fundamentally oriented towards the evaluation of the thermal efficiency of solar water heaters (SWHs) operating optimally under varying mass flow rates while accommodating fluctuations in storage capacity.

Keywords: Parabolic trough collector; Solar water heater; Solar radiation; Thermal efficiency; Heat transfer rate; concentric tubes.

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Nomenclature

A_a	*Surface area of the tube [m^2]*	Q_u	*Available Solar Radiation [W]*
A	*Aperture [m]*	Q_u	*Usable energy gain [W]*
d	*Diameter[m]*	T	*Temperature [K]*
c_p	*Specific heat capacity [$Jkg^{-1}K^{-1}$]*	η	*Efficiency of the system*
k	*Thermal conductivity [$Wm^{-1}K^{-1}$]*	$\dot{V}$	*Volume Rate of flow [m^3s^{-1}]*
ρ	*Density [kgm^{-3}]*	t	*Time*
μ	*Dynamic viscosity [Pa s]*	***Subscripts***	
G_b	*Global Solar Radiation*	o	*outer surface/outlet*
C	*Concentration ratio*	i	*inner surface/inlet*
L	*Length of the tube [m]*	1	*inner tube*
$\dot{m}$	*Mass flow rate of the flowing fluid [kgs^{-1}]*	2	*outer or annulus tube*
f	*Focal length*	w	*Water*
ϕ_r	*Rim angle*	f	*fluid*

1. Introduction

Amidst a world where energy demand stands as an essential universal requirement, the current phase of industrialization has propelled a notable upswing in energy consumption and the exploitation of natural resources. This trend is magnified by the continuous growth of the global population, which in turn intensifies the need for energy. Consequently, conventional energy sources, including coal, petroleum, and natural gas, are facing an alarming depletion rate. This pressing circumstance has sparked considerable attention towards renewable energy resources as a viable countermeasure to the waning availability of conventional energy sources. Nonetheless, the primary hurdle faced by renewable energy lies in its inherent lower efficiency compared to traditional sources. Within the realm of diverse sustainable energy sources encompassing tidal, wind, geothermal, solar, hydro, and biofuels, our project casts a spotlight on solar energy. Solar thermal systems emerge as a transformative solution, providing pristine and ecologically sound energy to fuel both industrial and residential domains. Their significance in this domain is substantial. Our project, in specific, delves into the intricacies of three concentrating solar technologies: parabolic trough collectors, compound parabolic collectors, and parabolic dishes. These ingenious technologies harness the direct radiance of the sun, channeling its energy into a focused beam that heats a conduit, serving the heating requirements of both residential and industrial sectors [1], [2]. The parabolic trough collector (PTC) emerges as a distinguished and widely adopted option within the solar energy landscape, as indicated by data from the International Energy Agency [3], [4]. Impressively, around 76.6% of all solar plants have opted to integrate this technology into their operations. The prominence of PTC technology stems from its strategic emphasis on facilitating large-scale energy generation, particularly capitalizing on its cost-effectiveness within this expansive operational scope. This deliberate focus on large-scale application aligns with its intrinsic attributes that enable efficient harnessing of solar energy resources. Moreover, the utilization of PTC technology holds substantial potential in addressing the critical challenges entrenched in conventional energy sources. The concept of dispatchable power generation, achievable through the conversion of solar thermal energy, introduces an innovative and transformative solution to the persistent issues linked with traditional energy sources [5], [6]. By offering a means to generate power at desired intervals, solar thermal energy via PTCs offers a flexible alternative to overcome limitations posed by conventional energy systems. This not only contributes to diversifying energy generation but also provides an avenue for tackling issues related to energy reliability and stability, thereby augmenting the resilience of energy grids. This profound potential underscore the critical role that PTC technology can play in reshaping the energy landscape, ushering in new paradigms of sustainable and adaptable power generation. In geographical areas characterized by limited resources and a shortage of specialized personnel, such as rural regions within developing nations, the imperative to adopt simpler and more cost-effective technologies becomes paramount [2]. While stationary collectors might compromise optical efficiency due to their inability to track the sun's movement, they offer a distinct advantage in terms of cost-effectiveness and streamlined operational procedures [7], [8]. Consequently, these collectors emerge as a practical alternative, especially for applications that do not demand exceptionally high efficiency or elevated temperature levels. Functioning within the medium temperature spectrum of 80–250℃ [5], [9], [10], these collectors hold the potential to serve an extensive array of agricultural-related purposes. This versatility is rooted in their capacity to cater to various temperature requirements, aligning with the diverse needs of agricultural processes. Historically, the research focus within the domain of parabolic trough collectors (PTCs) has leaned heavily towards enhancing their efficiency in large-scale operations [11]–[13].

However, this emphasis has resulted in relatively limited exploration of simpler and more accessible system configurations. The prime objective of our study was to meticulously assess the thermal efficiency and operational parameters of rectangular glass-covered concentric tubes integrated into solar collectors. Through a sequence of foundational tests and rigorous analysis, our endeavor was to quantitatively gauge the thermal performance of a solar water heater. By doing so, we aimed to contribute significantly to the progression of solar thermal technology. Our investigation seeks to bridge the gap between the high-efficiency aspirations of large-scale PTC systems and the practical implementation considerations of more straightforward and readily deployable configurations. Ultimately, our study endeavors to offer insights that not only enrich the understanding of solar thermal applications but also pave the way for more effective and accessible solar heating solutions.

PTC Geometry

The arrangement involves a metallic tube strategically positioned at the focal point of the parabolic collector, effectively channeling all incident sunlight onto its surface. This configuration necessitates the presence of a receiver or absorber capable of facilitating the passage of heat transfer fluid. The outcome of this investigation culminated in the development of a Parabolic Trough Collector (PTC) characterized by specific geometric attributes and technical particulars, meticulously detailed in Table 1. Illustrations in Figures 1(a) and 1(b) provide schematic representations of a parabolic section and a cross-section of the PTC, highlighting their key geometric properties [14], [15].

For the determination of the absorber tube's diameter and length, a commercially available model was employed. The radial dimension of a parabola at any point, often referred to as the "mirror radius" (r), holds significance in this context. Additionally, the outer boundary radius is variably designated as the "rim radius," "maximum mirror radius," or "parabolic radius." Describing the parabola's shape within a Cartesian coordinate system (x, y), the equation governing its curvature is derived [15]. This mathematical formulation encapsulates the geometrical essence of the parabola's curvature, underpinning its structural characteristics within the collector system.

Geometry Profile $$y^2 = 4fx \quad (1)$$

Concentration ratio $$C = Area\ of\ aperture/Area\ of\ receiver \quad (2)$$

Aperture of parabola $$a = 4f \times \tan(\phi_r/2) \quad (3)$$

Rim radius $$r = \frac{2f}{1+\cos\phi} \quad (4)$$

Parabolic receiver diameter D is obtained by

$$D = 2r_r \times \sin(0.267) \quad (5)$$

$$D = \frac{a \times \sin(0.267)}{\sin(\phi_r)} \quad (6)$$

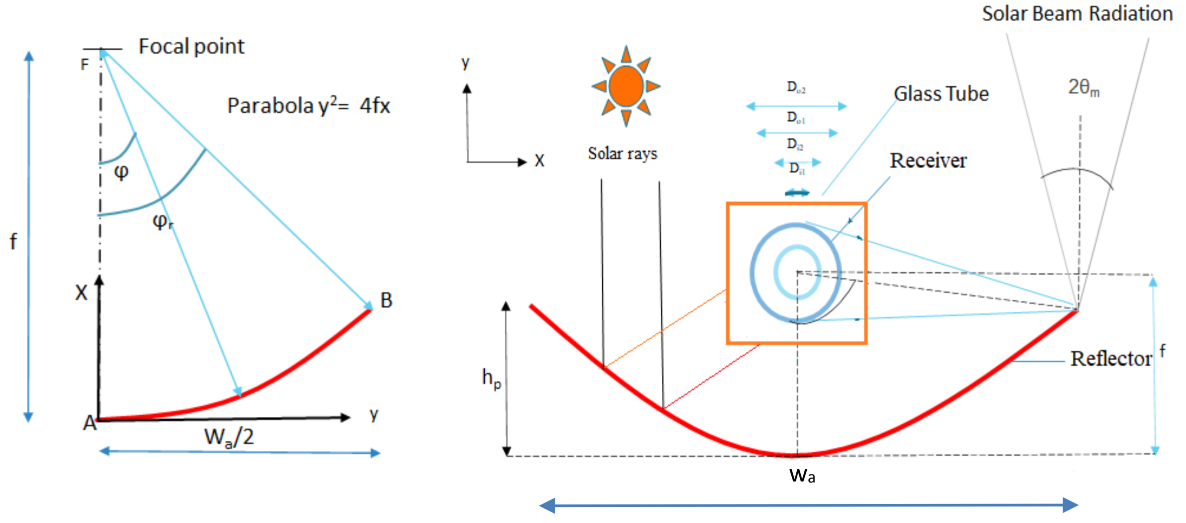

Fig. 1. (a) Section modulus of Parabolic Receiver[15]; (b) Schematic view of parabolic reflector.

Table 1. PTC Geometric and Technical Parameter

S.No.	Name of the component	Dimensions / Values (mm)	Quantity	Material
1	Parabolic reflector	Length=1000 Breadth=500	1	Aluminum
2	Reflective film Thickness	0.05	1	Aluminum
3	Focal length	125	-	-
4	Wood structure	Length =1000 Breadth=600 Depth=100	1	Wood
5	Inner pipe	Length=1000 Inner dia.=17.6 Outer dia.=20.3	1	Galvanized Iron
6	Outer pipe	Length=1004.4 Inner dia.=28 Outer dia.=33	1	Galvanized Iron
7	R-socket	Length=45.3 Small dia.= 28.4 Big dia.=40	1	Galvanized Iron
8	T-Plug	Length=62.4 Outer dia. Of small side=27.4 Outer dia. large side=40	1	Galvanized Iron
9	Socket	Outer dia.=40 Inner dia.=33 Length=45	1	Galvanized Iron
10	Connector	Length=43 Outer dia.=31 Inner dia. =27	1	Galvanized Iron
11	Column stand	Length=1400 Dia.=25	1	Iron
12	Water Jar	35 Liter	1	Fiber
13	Rim angle (deg)	90	-	-
14	Concentration Ratio	15.15	-	-
15	Receiver Type	-	-	Glass-covered
16	Absorbance	0.93-0.95	-	-
17	Transmittance	0.95	-	-

A detailed schematic modal with the data acquisition system is shown in figure 2.

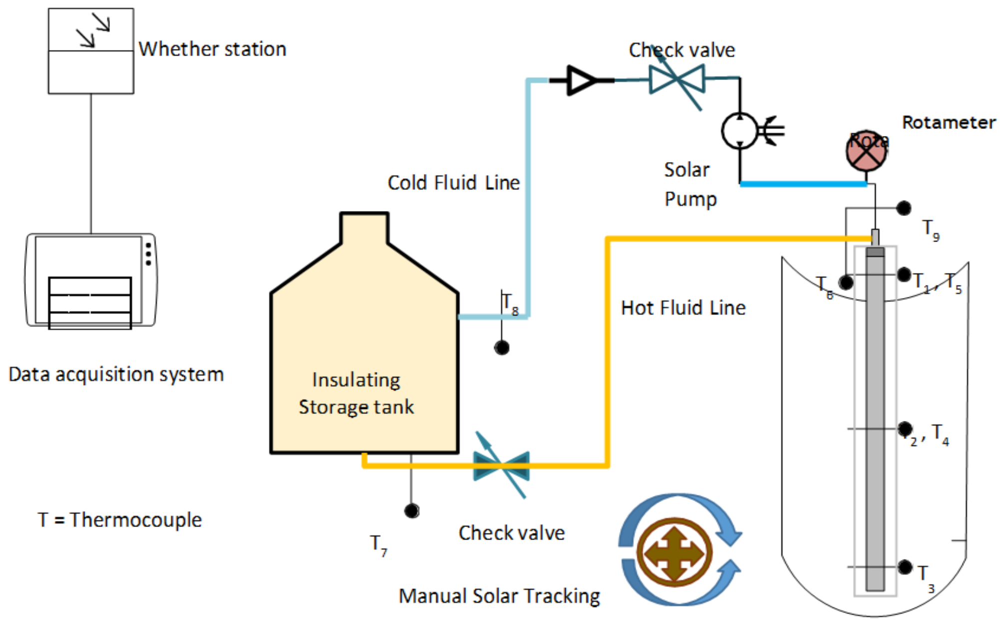

Fig. 2. Detailed schematic modal with the data acquisition system

1.1. PTC and TES Construction

In the context of this research, a novel approach was taken to design and fabricate the Parabolic Trough Collector (PTC) with the dual objectives of reducing manufacturing costs and simplifying the technical expertise required for construction and operation. Wood collector plates, featuring intricately carved grooves that mimic the shape of parabolas, were adopted in instances where easy installation and alignment were imperative. These plates serve as an alternative to traditional parabolic collector plates, offering enhanced ease of integration. Notably, a pivotal element of this design involves a clamp mechanism at the base of the collector plate, facilitating controlled tilting for optimal solar radiation tracking.

The functionality of the PTC rests on the phenomenon of solar radiation redirection. Incident sunlight is skillfully reflected onto the parabolic collector plate, which consequently converges into a focused line onto the absorber pipe. This concentration effect amplifies heat generation, and the resulting thermal energy is efficiently captured as water circulates through the annular space surrounding the absorber pipe. The PTC's physical specifications for this experiment encompass dimensions of 1 meter by 0.5 meters, translating to a projected area of 0.5 square meters. Additionally, the focal point of the parabolic collector, situated 125mm away from the absorber pipe, has been precisely determined. To further optimize its reflective properties, the collector or reflector plate is coated with a 0.05mm reflective layer. This specialized coating not only enhances the surface polish but also augments the overall reflectivity of the system. A critical consideration during the experiment is to ensure that the sun rays reaching the collector plate assembly align parallel to the tracking pin. Any necessary adjustments are made to ensure this parallel alignment, optimizing the system's solar radiation capture efficiency.

For the experimental setup, a plastic water jar with a maximum capacity of 35 liters is employed. The pipe and hose connections are insulated with nitrile foam to minimize heat dissipation. To further mitigate heat loss, the water jar can be insulated using glass wool, enhancing the system's overall thermal efficiency. This carefully designed and implemented approach combines innovative adaptations with well-established principles to create an efficient and effective solar energy capture system.

2. Experimental Procedure

The experimental investigation took place atop the mechanical engineering department's roof at NIT Jamshedpur in India. This location sits at an elevation of 159 meters and bears geographical coordinates of 22.85 degrees north latitude and 86.25 degrees east longitude. To facilitate precise solar tracking, a manual tracking mechanism was devised utilizing a tracking pin. This mechanism ensures that the orientation of the parabolic solar collector assembly aligns optimally with the sun's path.

The integration of the intake pipe plays a crucial role in this setup. It needs to establish seamless connections with both the water jar and the concentric absorber tubes, with utmost diligence employed to prevent any instances of leakage at these critical junctures. The water's path is channeled from the input pipe through the annular gap existing between the concentric pipes, ultimately reaching an outlet situated at the upper part of the absorber pipe. Here, a tap mechanism regulates the rate of flow. The quantification of water's mass flow rate involves the utilization of a stopwatch, which is paused as water exits the outlet and is collected in a measuring jar. Adjusting the water flow rate is achievable by manipulating the tap located at the exit.

Incorporating precise temperature measurement, a mercury thermometer is employed to gauge both the surface temperature of the outlet and the absorber pipe. Figure 3 depicts a visual representation of the experimental arrangement, showcasing a concentrated parabolic rectangular glass-covered solar water heater with a forced fluid circulation system. This illustrative figure serves to encapsulate the essence of the experimental setup, encapsulating its intricate design and configuration.

1-Storage Tank
2-Parabolic Reflector
3-Concentric Tube
4-Rectangular Glass Cover
5-Solar Panel
6-Wheel Base Assembly
7-Tracking Pin
8-Vertical Stand
9-Submersible Pump
10- Check Valve

Fig. 3. Glass covered Concentric tube Parabolic solar water heating system with forced circulation

2.1. Thermal Performance

According to Equation (7), instantaneous PTC efficiency (ɳ) can be defined as the ratio of usable energy gain (Q_u) to available solar radiation (Q_s). To calculate the instantaneous efficiency of the collector (ɳ) without the concentrator (parabolic trough) , the aperture area (A_a) and the direct solar radiation (G_b) of Eq. (7) were used instead of the receiver area (A_r) and global solar radiation (G_b)[2].

$$\eta = \frac{Q_u}{Q_s} = \frac{mC_p(T_f - T_i)}{A_a G_b t} \qquad (7)$$

3. Results And Discussion

Conducting measurements every 15 minutes, direct sun radiation was assessed using a manual tracking system. Throughout the experiment, the mass flow rate for the closed-loop forced circulation remained steady at 0.07 kg/sec. A solar pump was employed to drive the circulation within the system. The experiment spanned seven hours, commencing at 10 a.m. and concluding at 4 p.m., during which significant data were collected and simplified for clarity. Initial temperature measurements were taken using mercury thermometers.

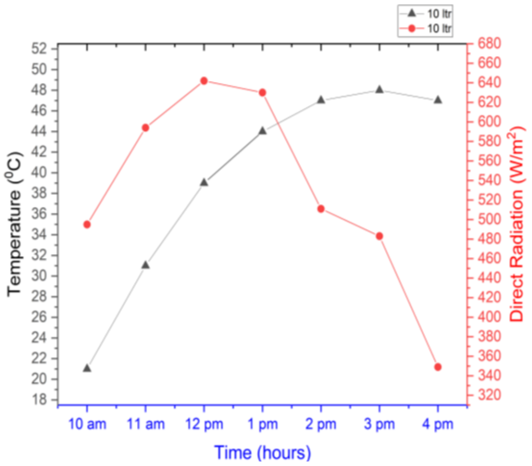

Fig. 4. Variation of solar radiation and temperature with respect to time for 10-liter storage tank

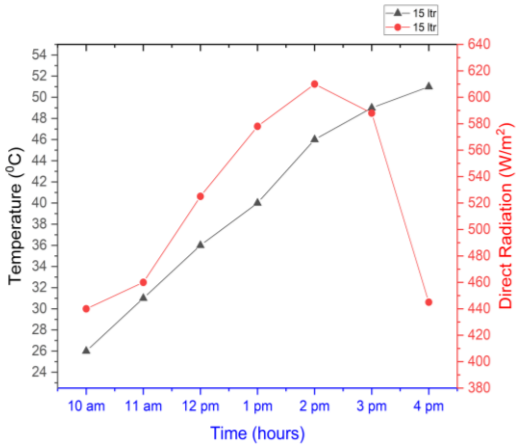

Fig. 5. Variation of solar radiation and temperature with respect to time for 15-liter storage tank

Direct sun radiation was tracked using a pyrheliometer positioned at the solar radiation hub, with radiation increments recorded hourly. The experiment employed a total water storage tank volume of 10 liters. On the specified date, as depicted in Figure 4, the highest recorded direct solar radiation reached 642 W/m², peaking between 12 and 1 p.m. Similarly, the maximum temperature achieved was 47°C, with the lowest temperature touching 21°C over the entire seven-hour duration. After 10:00 a.m., the temperature exhibited an ascending trend until reaching its pinnacle, after which it stabilized. This temperature equilibrium indicated that any received energy was dissipated through radiation and convection, resulting in a temperature balance.

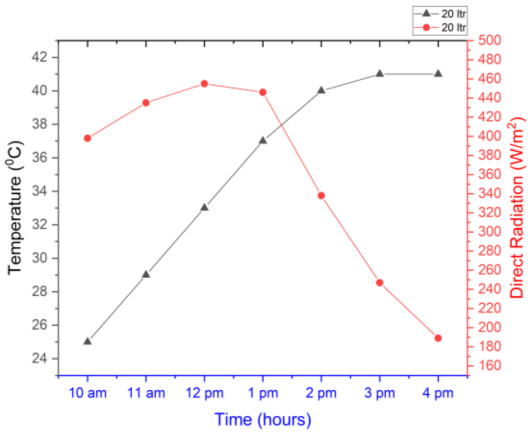

Fig. 6. Variation of solar radiation and temperature with respect to time for 20-liter storage tank

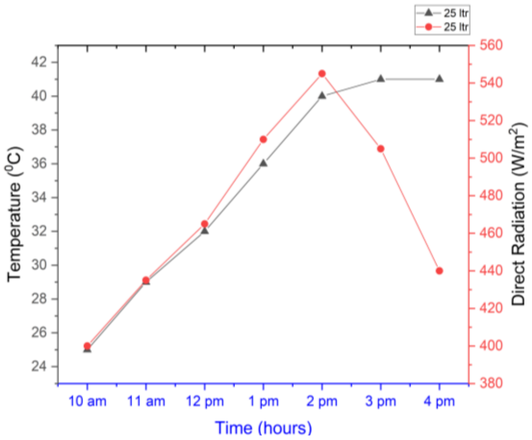

Fig. 7. Variation of solar radiation and temperature with respect to time for 25-liter storage tank

The water storage tank's total capacity should amount to 15 litters. Illustrated in Figure 5 is a time-dependent graph displaying water temperature and solar radiation data for each hour. The peak direct solar radiation recorded on this particular day occurred at 2 p.m., reaching 610 W/m², with the solar radiation zenith observed between 12 p.m. and 2 p.m. Starting at 440 W/m² at 10 a.m., the solar radiation exhibited a decline post-2 p.m., nearing 440 W/m². Concurrently, the highest temperature attained on that day was 51°C, while the initial temperature stood at 26°C.

For a water storage tank with a capacity of 20 litters, Depicted in Figure 6 is a graphical representation correlating time with water temperature and solar radiation for each hour. The peak direct solar radiation recorded during the day occurred at 12 p.m., measuring 455 W/m². At 10 a.m., the solar radiation stood at 398 W/m², but a decline began after 12 p.m., with levels nearing 189 W/m². Similarly, the highest temperature observed on this day reached 41°C, while the initial temperature was 25°C. For a water storage tank capacity of 25 litters, Figure 7 presents a time-versus-temperature-and-solar-radiation graph for each hour. The maximum direct sun radiation recorded on that particular day was 545 W/m² at 2 p.m. At 10 a.m., the solar radiation was 400 W/m², and a decrease commenced after 2 p.m., stabilizing near 440 W/m². Similarly, the highest temperature reached 41°C, while the initial temperature was 22°C.

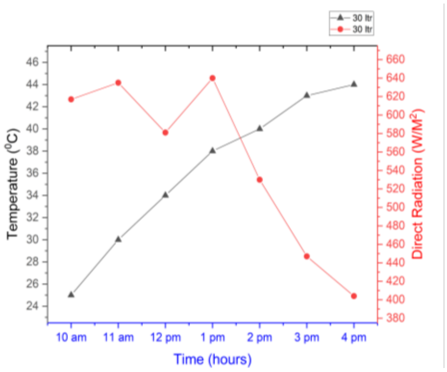

Fig. 8. Variation of solar radiation and temperature with respect to time for 30-liter storage tank

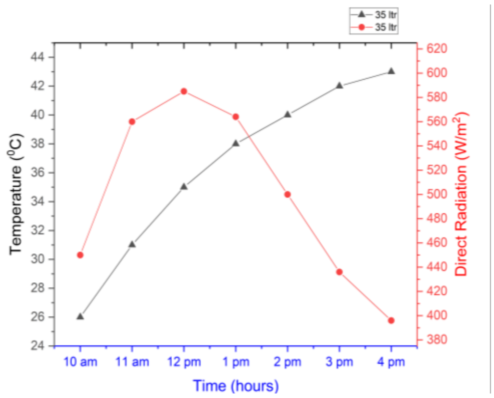

Fig. 9. Variation of solar radiation and temperature with respect to time for 35-liter storage tank

For a water storage tank with a capacity of 30 litters, Figure 8 illustrates a time-based graph depicting the relationship between time, water temperature, and solar radiation for each hour. The day's maximum direct solar radiation was recorded at 1 p.m., measuring 640 W/m². It began at 617 W/m² at 10 a.m., but underwent a decline after 1 p.m., eventually stabilizing around 404 W/m². Additionally, the highest temperature experienced on that day reached 43°C, while the initial temperature stood at 25°C.

For a water storage tank with a capacity of 35 litters, Figure 7 presents a time-versus-temperature-and-solar-radiation graph for each hour. On this particular day, the highest recorded direct sun radiation occurred at 12 p.m., registering 585 W/m². At 10 a.m., the solar radiation level was 450 W/m², but it began to decrease after 12 p.m., eventually reaching around 396 W/m². Furthermore, the highest temperature achieved was 43°C, while the initial temperature was 26°C.

As depicted in Figures 10 and 11, the highest average direct radiation is attainable with a 35-liter capacity, while the lowest average direct radiation is achievable with a 20-liter capacity. These figures highlight an average direct radiation span ranging from 350 to 600 W/m².

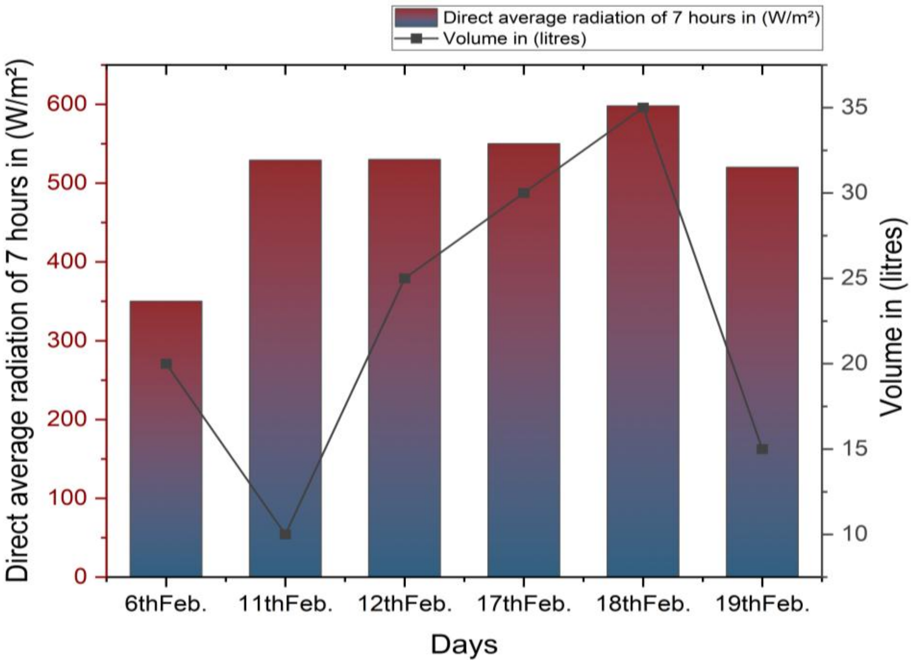

Fig. 10. Variation of Average Direct Solar Radiation and storage capacity with respect to day

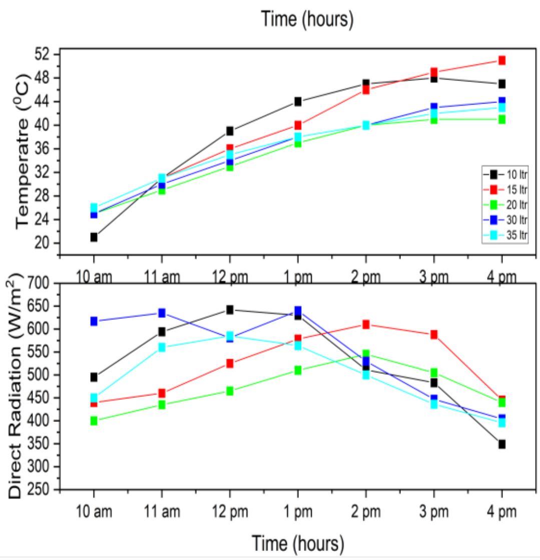

Fig. 11. Variation of Direct Solar Radiation and Temperature with respect to time

Figure 11 illustrates the fluctuations of solar direct radiation and temperature over time. The recorded extremes for temperature within the storage tank at the conclusion of each day's experimentation were 51°C as the maximum and 41°C as the minimum.

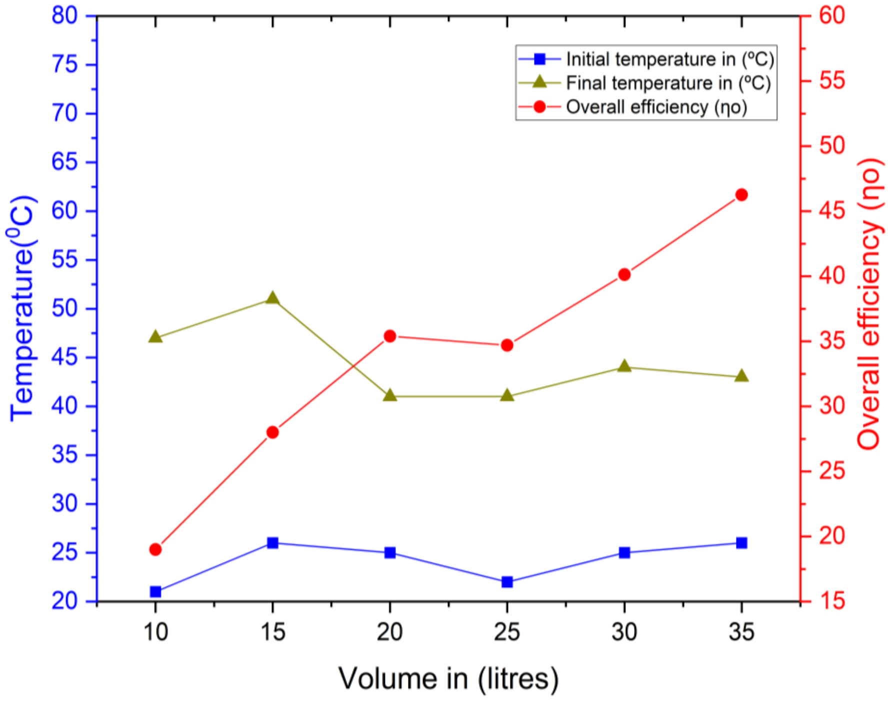

Fig. 12. Variation of Temperature and Overall Efficiency with respect to Storage capacity

As depicted in figure 12, there's a noticeable correlation between the water volume within the storage tank and the corresponding temperature. An increase in water volume results in a decrease in storage tank water temperature, but it also coincides with an improvement in overall efficiency. Among the tested volumes, the 15-liter container attains the highest temperature, while the 20-liter container demonstrates the lowest temperature. It's important to note that this relationship is contingent upon the available radiation on the given day; higher radiation levels correspond to elevated temperatures. Based on the graph presented above, a trend becomes evident: with increasing water volumes, the system's efficiency experiences enhancement. This trend reaches its pinnacle when the maximum water volume is utilized. This observation implies that employing a larger water volume minimizes losses from the absorber pipe, optimizing the storage of heat within the water.

4. Conclusion

Based on the experimental work presented, the following conclusions have been drawn:

- The study has established a direct relationship between the quantity of water in a closed-loop forced circulation system and the resulting overall efficiency.
- The efficiency of the system is determined by the chosen water volume and the average direct radiation experienced over a 7-hour runtime.
- For a 35-liter storage tank filled with water initially at 26°C, an efficiency of 46.26% was achieved, accompanied by an average direct radiation of 598 W/m².
- On the same day, a 10-liter capacity yielded an efficiency of 19%, with a maximum outlet temperature of 47°C and an initial temperature of 21°C. The average direct radiation stood at 529 W/m².
- Among the experiments conducted, the highest temperature reached was 51°C, achieved with a 15-liter tank capacity. This also resulted in a 28% efficiency and an average direct radiation of 520 W/m².

Contributions of the Authors: The manuscript was authored by NS, who also led the development of the simulation work related to the bayonet tube. RVS took on the role of a research mentor, contributing to paper review and data analysis. SK played a critical role in the thorough review of the manuscript.

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Availability of Data: The data that supports the outcomes of this research can be obtained by making a request to the corresponding author. In line with data sensitivity considerations and the commitment to preserving participant privacy and confidentiality, access to the data will be granted following formal request and approval by the relevant ethical review board. Requests for data access should be directed to [Nishant Singh, email: kaalkhanday@gmail.com].

Declaration of Conflict of Interest: The authors confirm the absence of conflicts of interest relevant to this study.

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