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Thermal Analysis of Novel Pebble Absorber Based Solar Thermal Collector

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Abstract: The fluid flow rate of the heat absorbing medium plays a crucial role in the performance of the collector. Studies were carried out with varying fluid flow rates of 0.01 kg/s, 0.013 kg/sec and 0.016 kg/sec respectively for different days from 8:00 hour to 18:00 hour. The input parameters considered for the computational modeling are i) Solar radiation (I) ii) Ambient temperature (Ta) iii) Inlet water temperature (T_i) and iv) Mass flow rate (m_f). Experiments carried out using coated and uncoated pebbles as absorber along with a conventional flat plate collector. The efficiency of the solar thermal collector increases with flow rate and incident radiation. The coated pebble absorber collector is more efficient than the uncoated pebble absorber collector and less efficient than the conventional metal absorber collector at above mentioned flow rates. The total average efficiency of coated absorber collectorwas 67.036%, 51.35% for the uncoated absorber collector and 72.857% for the conventional copper absorber collector.

Keywords: *Pebbles, Flat plate collector, Flow rate, Tilt angle, Heat gain.*

1. Introduction

Utilizing alternative and renewable energy sources is one of the most sustainable solutions to address the current issues facing our society, such as climate change, the depletion of fossil fuels, rising energy consumption, and the high cost of electricity. Heat exchanger that transforms solar energy into the internal energy of the transport medium is a solar energy collector. The solar thermal collector is the most important part of any solar system. The flat plate collector (FPC) is the most important part of photo thermal conversion technology. For low to medium temperature heating applications, such as heating water for households and low temperature industrial uses, this type of stationary collector is widely utilized. The components of an FPC includes absorber plates, absorber tubes, glazing covers, intake and outlet valves, insulating layers, and other accessories. Low-iron glass is recognized as a good glazing material because of its relatively high transmittance for solar radiation (about 0.86-0.89) and almost insignificant transmittance for long-wave thermal radiation (5.0 m - 50 m) [1]. Metals like copper or aluminum are frequently employed in conventional solar collectors to absorb heat, and the chemical processes needed to stop these metals from corroding have unfavorable environmental effects. Mining is very dangerous because of its toxicity and harmful impacts on the environment and human health. Mining for copper generates large amounts of mine wastes, tailings, particulate pollution, and sulfur oxides (SOx). Aluminum manufacturing accounts for roughly 3% of the world's CO_2 emissions, which is more than that of steel and copper (about 40 MT annually) [2]. It is advised that a metal-free solar collector be used, with the suggested Pebble Absorber Collector being built-in on top of the building as integrated with its design, in order to combat the aforementioned negative impacts of metals. The use of a metal-free solar collector is suggested as a way to combat the aforementioned negative effects of metals. This solar collector, called a pebble absorber, can be included into the structure of the building as part of the construction process. As a result, using metals will be entirely eliminated, and the collector will need to run without maintenance for the duration of the structure. The suggested collector is therefore significantly more affordable, hygienic, and maintenance-free. Due to conventional metals toxicity and harmful impacts on the environment and human health, they are extremely dangerous. The promotion of solar systems for typical domestic uses including space heating, water heating, and cooling is now supported by a number of governmental regulations. Solar- powered goods must be produced at a rate that is corresponding to these needs. Achieving 20–30% of the possible applications in the future is the aim of the adopted policies. Solar energy collectors are a particular kind of heat exchanger that convert solar radiation energy to the internal energy of the transport medium. The solar collector is the main part of any solar system. This is a device that takes up solar radiation, transforms it into heat, and transmits that heat to a fluid running through the collector (often air, water, or oil). Concentrating and stationary non- concentrating solar collectors are the two main categories of solar collectors. Low-iron glass [1- 2] is regarded as a suitable glazing material because of its nearly negligible transmittance for long-wave thermal radiation and reasonably good transmittance for solar radiation (about 0.85- 0.87) [3,4]. In order to absorb more heat, the absorber plate is typically covered with a blackenedsurface; however, alternative colour coatings have also been suggested in the literature [5]. In light of this, a modification that substitute easily accessible, inexpensive, and non-polluting pebble absorbers for the metal absorbers of a standard solar thermal collector which is proposed in the current work. This is a safe and cost-effective replacement for the metal absorbers of a collector since pebbles are naturally accessible and don't require expensive or environmentally hazardous mining operations. Since pebbles have a high specific heat and a poor thermal conductivity, they are frequently employed as a heat storage medium. However, no attempt has been made to use them as thermal absorbers in FPCs till now. For the first time, such an attempt was made, and some early investigations indicated that replacing the metal absorbers for pebbles slightly improved the performance of the collector. There will be a lot of demand for theproposed collector because it will be less expensive than the conventional collector and becauseit has been found to improve performance. Its investment cost will also be minimal because it is planned to be developed alongside the building. According to a thorough review of the literature,no work has been done in the area of pebble absorber collectors. The direct conversion of sunlight into low-temperature heat is the simplest and direct use of solar energy. Due to its design and production, flat plate collectors are a common device for low-temperature applications (heating water, space heating, etc.) [6–10]. The solar energy that enters the flat plate collector is absorbed, transformed into heat at the absorbing plate, and then transferred to a fluid that circulates through the flat plate collector (often air, water, or water with an antifreeze ingredient). There are now several different solar collector designs in the market, including stationary, tracked, and concentrating and non-concentrating collectors. A flat plate collector's essential components are: a transparent toughened glass cover, an absorber plate (with high absorptivity), fluid tubes welded to or integrated into the absorber plate, insulation, and a container or casing that encloses the aforementioned parts. In thermal applications, insulation is crucial. In order to reduce conduction and convection losses via the sides and rear of thecollector case, flat plate collectors must, in fact, be insulated. There has been enough research done on pebbles as a heat storage medium, but not as a replacement for an absorber. Even so, thefollowing literature review was conducted to highlight the various innovative and forward- thinking efforts made to the design, adaptations, components, and theoretical analysis of Flat plate collectors. According to **Liqun Zhou et al**. [11], the collector with TIM (transparent insulating materials) is appropriate for usage in cold environment. For instance, the efficiency of the collector with TIM is 6.2% better than the standard collector with a decreased temperature differential of 0.12 m^2°C/W (Ti= 100°C). Influence of flat plate collector tilt on heat loss was studied by **P.I.** Cooper et al. [12]. They calculated the top heat loss coefficient at 0-90° tilt angles for various plates, ambient temperatures, and wind speeds, and they noted that the top heat loss coefficient value decreased from 45° to 90° tilt. In order to develop absorber materials for solar collectors, M.D.T. Afandie et al. [13] developed synthetic rubber EPDM (ethylene propylene diene monomer), dynamically vulcanized natural rubber (DVNR 7011), and DVNR 7011/stainless steel composite. They came to the conclusion that the EPDM collector has slightlybetter thermal performance than TPNR (thermoplastic natural rubber) collectors. In order to create solar collectors with high temperature but cheap cost absorbers, Wilhelm et al. [14] examined a variety of materials. Chlorinated polyvinyl chloride, polysulfone, fluoroplastics, and silicons were among the materials examined. According to a detailed study by Shukla et al (SWHs) [15], it was determined that the only PCM-based SWH designs available were preliminary ones. According to Hasnain et al. [16], heat may be absorbed at both low and high temperatures by solid objects such rocks, pebbles, concrete, sand, and bricks. The author cited a few benefits of pebbles, such as nontoxic, non-flammable, affordable, and functions as both a heat transmission surface and storage medium, as well as the fact that they have a better capacity for storing heat than other materials. Arjunan et al. [17] evaluated the performance of the still using paraffin wax, blue metal stone, black granite gravels, and pebbles as different energy storage materials and Concluded as i) the energy storage materials in the still store a significant quantity of heat at midday and release it to the basin water at night; (ii) black granite gravels are more effective than pebbles and blue metal stone when utilised as energy storage materials. The efficiency of a flat plate solar collector employing a water-based CuO nano fluid as the working fluid was theoretically examined by Nang Khin ChawSint et al. [18]. According to the findings,raising volume concentration up to 2% increased collector efficiency while having a negligible impact on nanoparticle size. Using the programme ANSYS FLUENT 14.5 and the control volume numerical approach, Sultana et al. [19] utilized computational fluid dynamics (CFD) to solve the governing equations of flow and heat transport for diffrent types of solar collectors. The ANSYS Fluent programme produced the best model with a greater thermal efficiency of 66.4%.

2. Materials and Methods

2.1. Test set-up of pebble solar thermal collector (pstc)

Three separate collector units are developed to compare the proposed pebble absorber collector with the conventional flat plate collector and to investigate thermal performance. As illustrated in Fig. 1, the three collectors were installed on the same framework and connected to a single water storage tank. The Pebble Solar Thermal Collector (PSTC) collector has a total area of 2.16 m^2, and the top of the collector is covered with a toughened glass plate of 0.005 m thick. Underneath of the absorber 0.05 m thick rockwool insulator is placed. The diameter of the circular cross-sectioned inlet and outflow ducts is 0.0508 metres. Fig. 1 depicts three distinct configurations of the collector used in the experiments: one with coated pebbles as the absorber, one with uncoated pebbles as the absorber, and one with conventional copper tubes. The 0.0508 m diameter inlet and outlet ducts have a circular cross section. To adjust the tilt angle of the collector, the header side is provided with a nut and bolt arrangement, while the bottom side is connected to the frame permanently. The working fluid made to flow over the pebble surface following a zig-zag pattern produced by inserting baffles in its path in the PebbleCollector. In order to maximise the incidence solar radiation, the experimental setup was oriented in the south with an inclination equal to the location's latitude (14°).

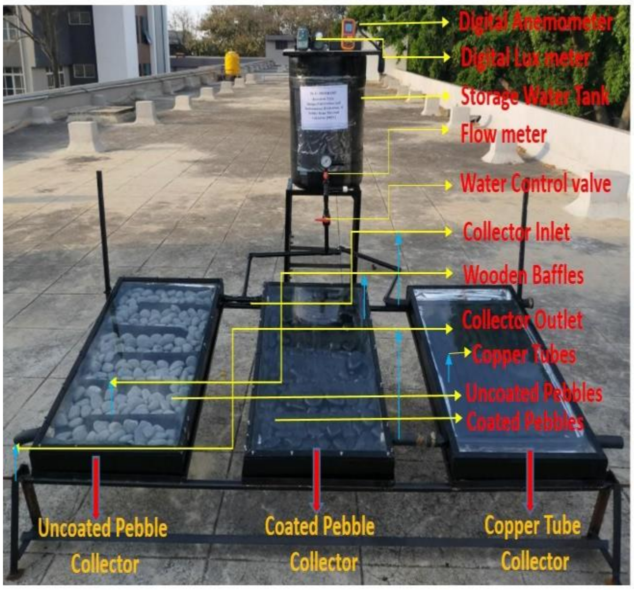

Figure 1: Experimental Setup

A 50-liter water storage tank was positioned six feet above the collectors to provide water to the collectors. The experimental work carried out at Siddaganga Institute of Technology in Tumkur, Karnataka. The wind speed and direction are measured using a GM 8901 digital anemometer. The amount of water flowing through a pipe is measured with a Konark flowmeter. The temperature of the solar flat plate collector's inlet and outlet as well as the intake tank was measured using T type thermocouples. Instead of using a metal absorber, pebbles were placed on the base surface, and baffles were placed in its path to cause water to flow over the pebble surface in a zigzag pattern. One of the most often utilised types of glass for solar applications are toughened glass, also known as tempered glass. It is made from regular glass that has been thermally tempered during production. The underside of the collector was insulated with rock wool that was 5 cm thick in order to reduce heat loss by conduction from the absorber.

3. Simulation Analysis

3.1 Modeling of the Proposed Collector

modeling is the process of creating an object's geometry, which is a mathematical description compatible with computers. The setup was modelled using the CATIA V5 modelling software, which is illustrated in Figure 2, and then imported into the ANSYS simulation software. Figure 2and figure 3 illustrates the front view and side view of the 3D isometric model

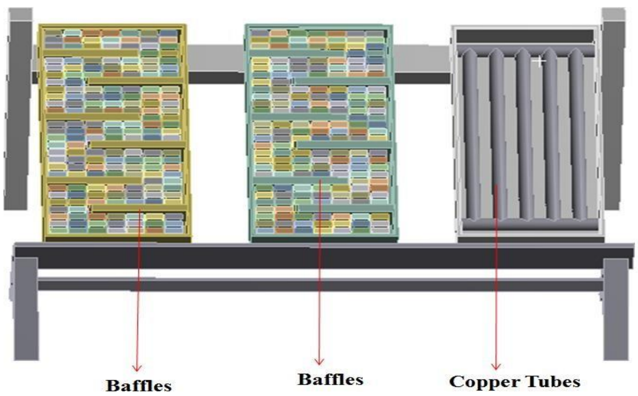

Figure 2: Front view of 3D isometric Model.

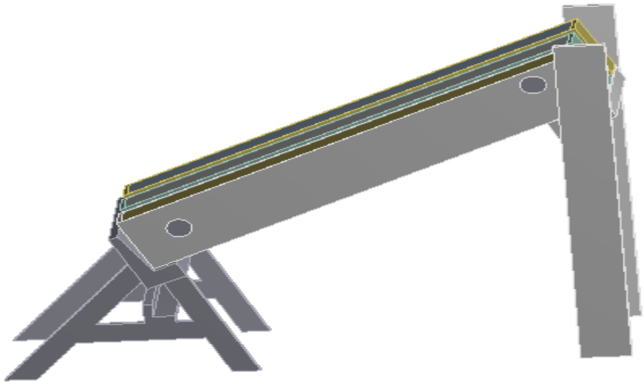

Figure 3: Side view of the 3D isometric Model.

3.2 Grid generation

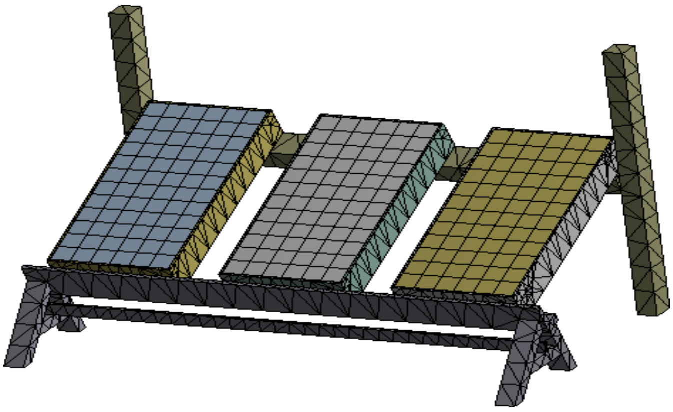

Figure 4: Meshing of proposed collector

ANSYS software was used to mesh the domain; the mesh has an impact on the simulated model accuracy, convergence, and speed. Here, hexa-hedral meshing elements were combined with tetra dominating meshing elements (Figure 4), as their accuracy level is quite high and they automatically mesh any unmeshed regions. 4,32,891 elements and 11,93,432 nodes with a non- uniform quad grid and 0.6 mm cell size were produced by meshing (minimum value). Total mesh generation included 0.17 million surface meshes and 0.68 million Tetrahedral meshes.

3.3 Temperature Distribution

The average outlet temperature of simulation results and the average outlet temperature ofexperimental data were compared in order to validate the suggested (PASTC) model. Theillustration shows that the top part of the collector has warmer than the lower part of the collector. This is predicted because the water from the inlet absorbs heat as it flows in a zigzag pattern through the baffles and over the upper surface of the pebbles, as illustrated in Figure 5 (Path line plot based on Temperature). This study makes it abundantly evident that modelling and simulation are effective tools for advancing FPC technology.

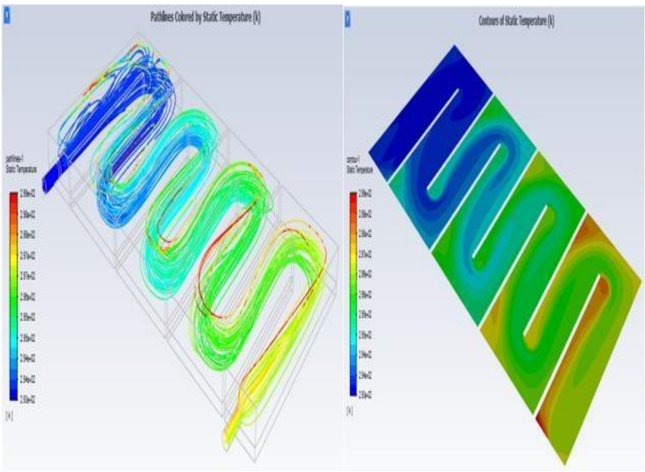

Figure 5: Path line plot based on Temperature

4. Performance Analysis of Pebble Absorber Solar Thermal Collector (Pastc)

Tests were run by adjusting the following operational settings, and the findings were also theoretically confirmed, in order to assess the performance of the modified collector and to compare it with the traditional collector.

a. Flow rate of the heat absorbing medium [water]
b. Tilt of the collector [12° and 18°]

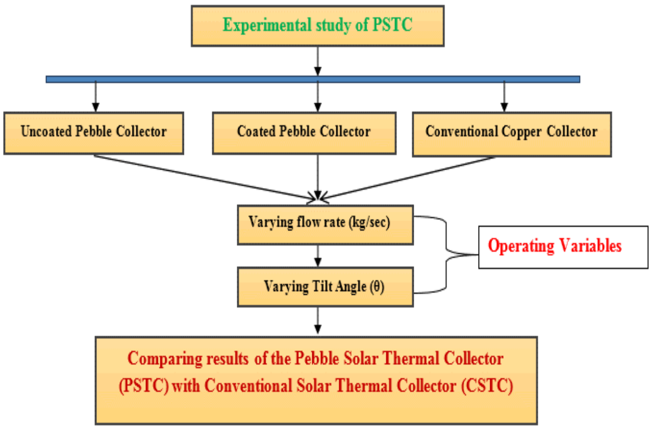

Figure 6: Following diagram shows the experimental methodology

4.1 Varying Flow rate of the heat absorbing medium (water-Kg/sec)

Trials were undertaken over a number of days with variable flow rates in order to betterunderstand how the heat absorption medium affects the performance of the collector. These findings show that the simulated and observed values are not significantly different, indicating good agreement between the two. Overall, tests were run for each set of six days at six different flow rates. The tests were carried out at various flow rates of 0.01 kg/sec, 0.013 kg/sec, 0.015 kg/sec, 0.016 kg/sec, 0.02 kg/sec and 0.025 kg/sec to know the influence of flow rate on the performance. The main goal of this work is to evaluate, both simulation and experimental, the effects of various flow rates on conventional, coated, and uncoated pebble collectors in order to achieve improved thermal performance.

4.2 Varying Tilt of the Collector (ɵ)

Although it is theoretically known that an FPC performs best when tilted at an angle corresponding to the location's latitude, experiments were conducted to see how well the FPC performed when tilted at two additional tilt angles, 12° and 18°, in accordance with the literature.Because a 14° tilt angle was used in the prior study to evaluate performance at different flow rates. The sun radiation was measured using a solarimeter installed on the plane of a proposed flat-plate solar collector, and the maximum incoming radiation angle was identified.

5. Results and Discussions

5.1.1 For a flow rate of 0.01 kg/s

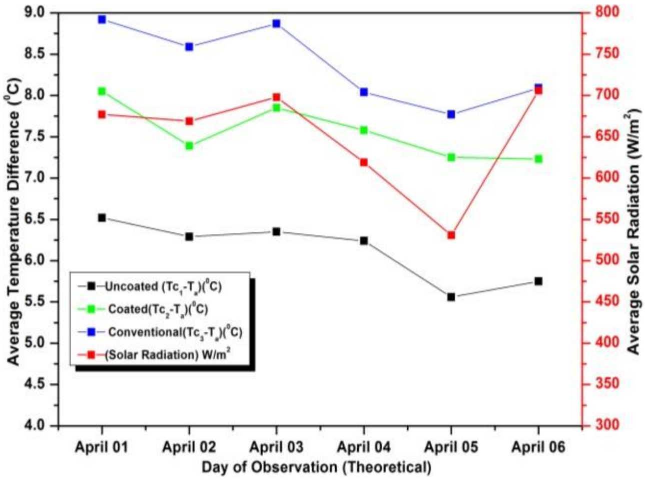

Figure 7: Variation of Day wise Tavg Difference (∆T) (Observed) for 0.01 kg/sec.

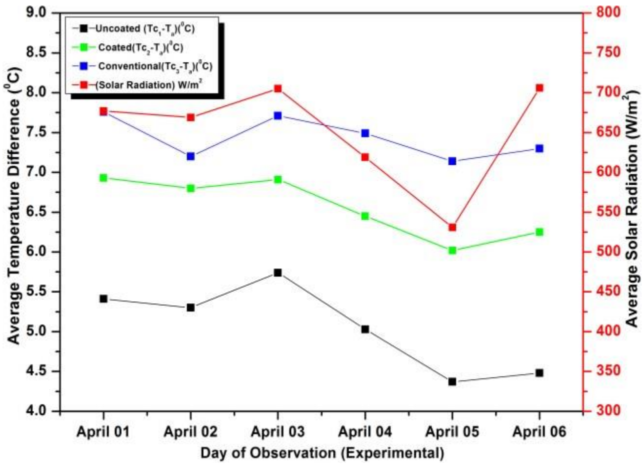

Figure 8: Variation of Day wise Tavg Difference (∆T) (Simulated) for 0.01 kg/sec.

The experimental observations were conducted over the course of six days, from April 1 to April 6, 2022. The experimental and theoretical results at a flow rate of 0.01 kg/sec are graphically displayed (Figure 7 and 8). Since the heat gain and collector efficiency exclusively depend onthe temperature difference, all graphs are produced with reference to the temperature difference (T). The marginal variance between the simulated and experimental temperature differences in figure 7 and 8 indicates that there is considerable agreement between the two. The little

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discrepancy suggests that the observed and simulated values are well compatible. For all three absorbers uncoated, coated, and conventional the day wise in temperature differential exhibit the same pattern in all of the plots.

5.1.2 For a flow rate of 0.013 kg/s

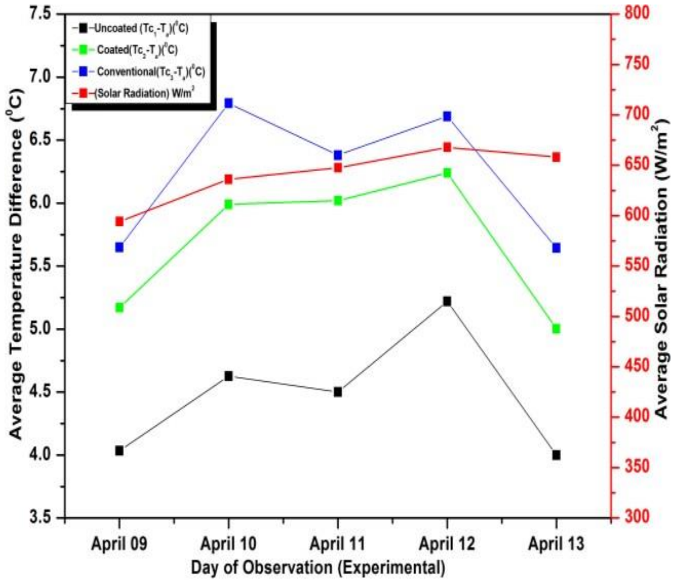

Figure 9: Variation of Day-wise Average Temperature Difference (∆T) (Observed) for 0.013 kg/sec.

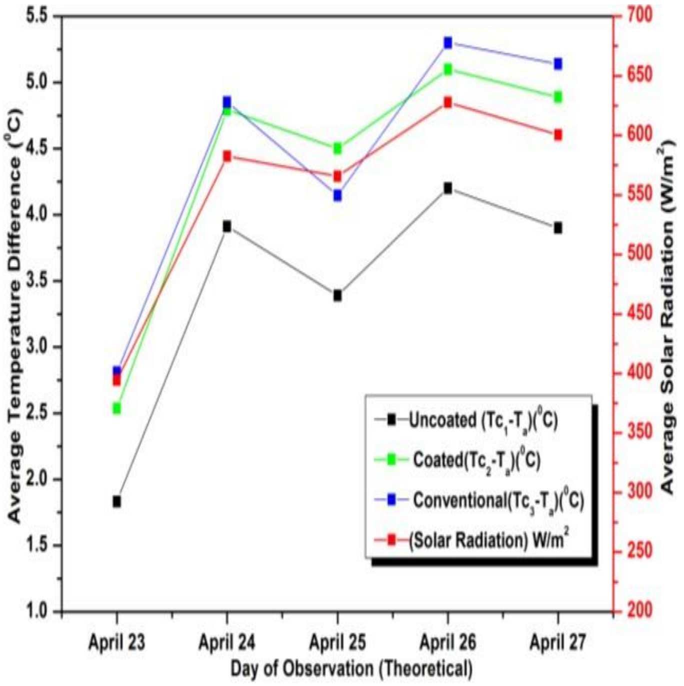

Figure 10: Variation of Day-wise Average Temperature Difference (∆T) (Simulated) for 0.013 kg/sec.

The study took place for five days, from April 9 to April 13, 2021, with a fluid flow rate of 0.013kg/sec. The simulated and experimental findings are shown visually (Figure 9 and 10). The highest incident solar radiation on that day, on April 12, 2021, was found to be the cause of the largest temperature difference, the highest temperature difference was discovered at 13 Hr, when the incident radiation was at its lowest 855 W/m^2 despite the fact that the highest incident radiation occurred at that time 924 W/m^2.

5.1.3 For a flow rate of 0.016 kg/s

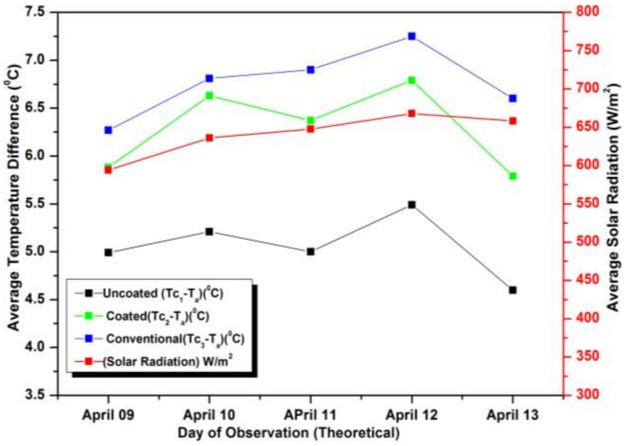

Figure 11: Variation of Day wise AverageTemperature Difference (∆T) (Observed) for 0.016 kg/sec.

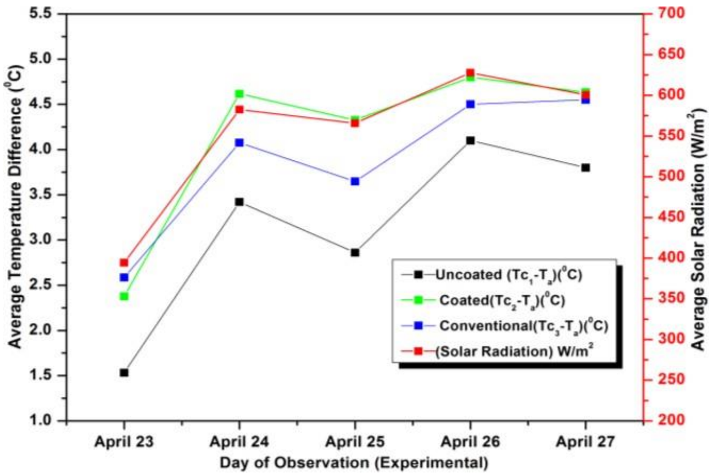

Figure 12: Variation of Day wise Average Temperature Difference (∆T) (Simulated) for 0.016 kg/sec.

The experiment conducted five days, from April 23 to April 27, 2021, with a fluid flow rate of 0.016 kg/sec. The incident radiation was found to be at its peak on April 26, 2021, and as a result, the temperature difference was also at its peak on that day. The greatest incomingradiation and maximum observed temperature difference were both recorded at 13 hours, which suggests no losses, according to the results of figure 13. As predicted, the measured efficiency was determined to be at its peak on April 26, 2021, with a little variation on April 27, 2021.

5.1.4 Results of proposed pebble solar thermal collector for varying Tilt angle (12° and 18°)

The surface is pointed toward the pole when is negative and the equator when is positive. The position and tilt of a solar collector in relation to the horizon affect its efficiency. The direction and tilt angle both influence how much solar energy reaches the collector's surface. The tilt angleand orientation of the collector are crucial in solar thermal collector systems. In addition to determining the collector's ability to reflect, transmit, and absorb radiation, it also establishes the radiation intensity on a collection. In this work, experimental results were used to calculate the collector tilt angle and orientation at SIT, Tumkur, Karnataka which is situated at 14° north latitude.

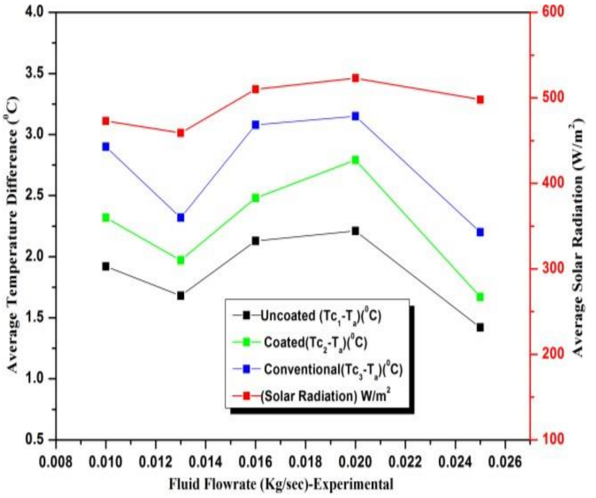

Figure 13: Variation of T_{avg} Difference (∆T) (Observed) for 12° Tilt angle at varying flow rates

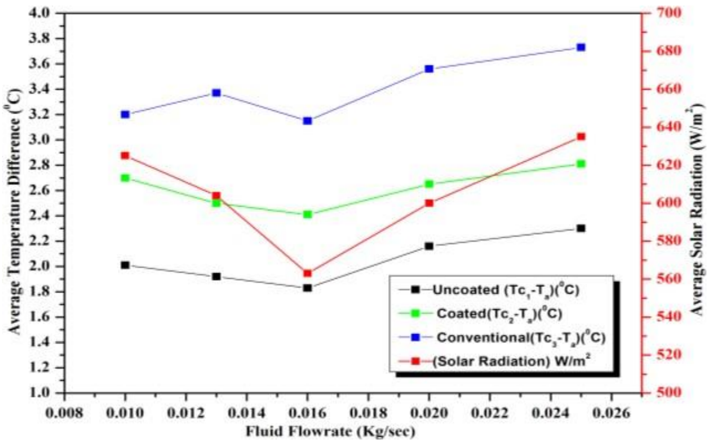

Figure 14: Variation of T_{avg} Difference (∆T) (Simulated) for 12° Tilt angleat varying flow rates

In order to determine the angle at which the incoming radiation was greatest, the solar radiation was measured using a solarimeter mounted on the plane of a hypothetical flat plate solar collector. The sun may be tracked by devices to make sure they are in the optimum possibleposition for incident solar radiation and absorbed solar energy. It was also shown that, given the same azimuth angle, the tilt angle of a stationary solar collector does not significantly alter the amount of solar radiation absorbed or the amount of usable energy gained.

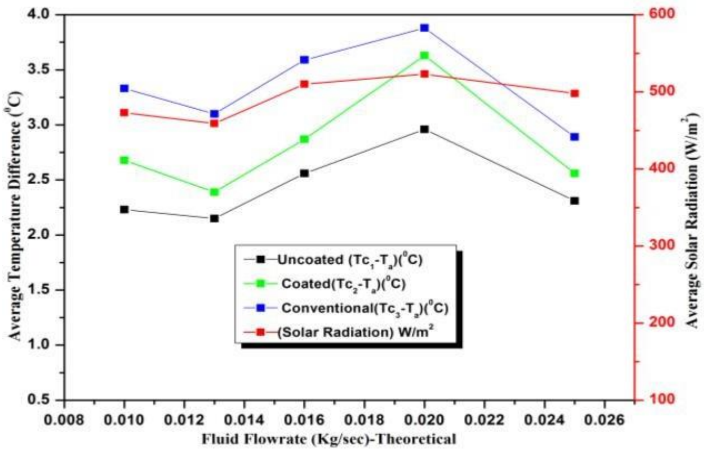

Figure 15: Variation of T_{avg} Difference (∆T) (Observed) for 18° Tilt angle at varying flow rates

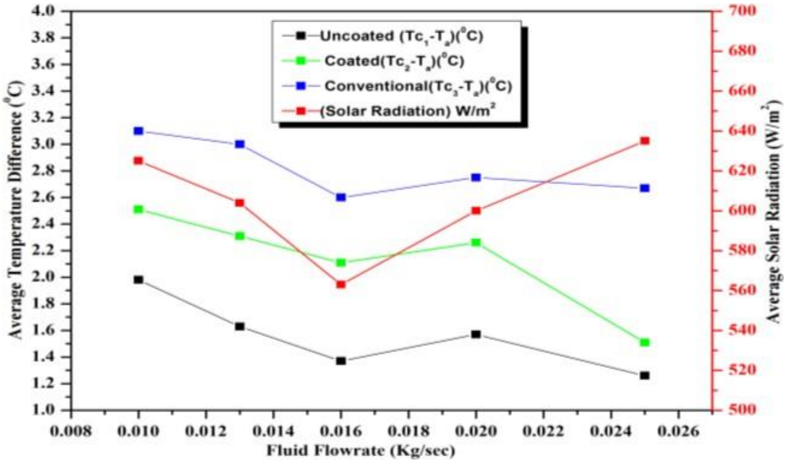

Figure 16: Variation of T_{avg} (ΔT) (Simulated)for 18° Tilt angle at varying flow rates

6. Conclusion

- The coated pebble absorber is more efficient than the uncoated pebble absorber and less efficient than the conventional metal absorber collector at all the flow rates. The total average efficiency of coated absorber collector was 67.036%, 51.35% for the uncoated absorber collector and 72.857% for the conventional copper absorber collector.
- As a result, the coated absorber collector performs 5.8215% more efficiently than the energy intense metal absorber collector whereas the uncoated absorber collector performs 15.686% less efficient.
- For fluid flow rate 0.016 kg/sec, the simulated and experimental findings are shown. The incident radiation was discovered to be at its peak on April 26, 2021, and as a result, the temperature differential was also at its peak on that day. Here, it is discovered that the rise in incoming radiation lowers efficiency for a given heat gain since efficiency is the ratio of heat gain to incident radiation.
- The tests were carried out at various flow rates of 0.01 kg/sec, 0.013 kg/sec, 0.015 kg/sec, 0.016 kg/sec, 0.02 kg/sec and 0.025 kg/sec to know the influence of flow rate on the performance. It was observed that for the fluid flowrate 0.016 kg/sec the PASTC performed well when compared to other flow rates.
- Although it is theoretically known that an FPC performs best when tilted at an angle corresponding to the location's latitude, experiments were conducted to see how well the FPC performed when tilted at two additional tilt angles, 12° and 18°, in accordance with the literature.
- The 14° tilt angle was used in the prior study to evaluate performance at different flow rates. The sun radiation was measured using a solarimeter installed on the plane of a proposed flat-plate solar collector, and the maximum incoming radiation angle was identified at 14° tilt angle

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