PERFORMANCE ENHANCEMENT OF PEBBLE ABSORBER SOLAR THERMAL COLLECTOR (PASTC) USING MULTIPLE REFLECTORS

Submitted by:

ABDUL VAKEEL 1AY15ME001
ADITYA 1AY15ME005
AJAY SHETTY 1AY15ME008
K VISHAL KUMAR 1AY15ME054

Under the guidance of
Mr. CHANNA KESHAVA NAIK N  M.Tech.,(Ph.D)
Assistant Professor
Department of Mechanical Engineering
Acharya Institute of Technology,
Bangalore-560107

ACHARYA INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MECHNICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING
ACHARYA INSTITUTE OF TECHNOLOGY
(Affiliated to Visvesvaraya Technological University, Belagavi)
SOLDEVANAHALLI, BANGALORE-56007
1. INTRODUCTION

1.1 PREFACE

In today’s scenario utilization of energy in an effective manner is must and that is the need of the time. In order to develop a poverty free world, energy security for all sectors must be ensured. As the conventional sources of energy are limited and cannot meet the increasing need of the common people, wide dissemination of renewable energy technologies is the only way out [1]. After industrial revolution we are using the classical energy sources which are dependent on fossil fuels. The rate of exploration of these resources are much higher along with the higher rate of pollution. With the advancement in technology more efficient alternative energy sources have been recognized for environmental protection and are now available for various applications. The solar energy which is coming from the sun in the form of solar radiation can be an alternative source of energy. The greatest advantage of solar energy as compared with conventional energy source is that it is clean and can be supplied without any environmental pollution. One of the simplest and most direct applications of this energy is the conversion of solar radiation into heat, which can be used in water heating systems [2].

1.2 SOLAR POWER IN INDIA

India being a tropical country receives good sunshine over most parts of the country, and the number of clear sunny days in a year is also quite high. Solar power in India is a fast developing industry. The country’s solar installed capacity reached 23 GW as of 30 June 2018 [3]. India expanded its solar-generation capacity 8 times from 2,650 MW on 26 May 2014 to over 20 GW as on 31 January 2018 [4]. The 20 GW capacity was initially targeted for 2022 but the government achieved the target four years ahead of schedule [5]. The country added 3 GW of solar capacity in 2015-2016, 5 GW in 2016-2017 and over 10 GW in 2017-2018, with the average current price of solar electricity dropping to 18% below the average price of its coal-fired counterpart [6]. The improvements in solar thermal storage power technology in recent years has made this task achievable as the cheaper solar power need not depend on costly and polluting coal/gas/nuclear based power generation for ensuring stable grid operation [7]. With about 300 clear and sunny days in a year, the calculated solar energy incidence on India’s land area is about 5000 trillion kilowatt-hours (kWh) per year (or 5 EWh/yr) [8].
PERFORMANCE ENHANCEMENT OF PEBBLE ABSORBER SOLAR THERMAL COLLECTOR (PASTC) USING MULTIPLE REFLECTORS

India’s Year-on-Year Targets to Reach 100 GW Solar Goal

![Chart showing India’s Year-on-Year Targets to Reach 100 GW Solar Goal.](chart_image)

**Figure 1:** India’s Year-on-Year Targets to Reach 100 GW Solar Goal.

1.3 SOLAR COLLECTORS

Thermal applications are drawing increasing attention in the solar energy research field, due to their high performance in energy storage density and energy conversion efficiency. In these applications, solar collectors and thermal energy storage systems are the two core components. Solar collectors need to have good optical performance (absorbing as much heat as possible) [9], whilst the thermal storage subsystems require high thermal storage density (small volume and low construction cost), excellent heat transfer rate (absorb and release heat at the required speed) and good long-term durability [10]. A solar collector, the special energy exchanger, converts solar irradiation energy either to the thermal energy of the working fluid in solar thermal applications, or to the electric energy directly in PV (Photovoltaic) applications. For solar thermal applications, solar irradiation is absorbed by a solar collector as heat which is then transferred to its working fluid (air, water or oil). The heat carried by the working fluid can be used to either provide domestic hot water/heating, or to charge a thermal energy storage tank from which the heat can be drawn for use later (at night or cloudy days) [11].

1.4 SOLAR FLAT PLATE COLLECTORS

Flat-plate collectors are the most widely used kind of collectors in the world for domestic water-heating systems and solar space heating/cooling. The first accurate model of flat plate solar collectors was developed by Hottel and Whillier in the 1950's. A typical flat plate solar collector usually consists of glazing covers, absorber plates, insulation layers, recuperating tubes (filled with heat transfer fluids) and other auxiliaries. Glazing is made of single or
multiple sheets of glass or other materials with high transmissivity of short-wave radiation and low transmissivity of long-wave radiation. It not only reduces convection losses from the absorber plate, but also reduces irradiation losses from the collector due to the greenhouse effect. Low-iron glass [12] is regarded as a desirable glazing material due to its relatively high transmittance for solar radiation (approximately 0.85–0.87) [13] and an essentially zero transmittance for the long-wave thermal radiation (5.0 µm – 50 µm).

**Figure 2:** Schematic diagram of Flat Plate Solar Collector.

The absorber plate is usually coated with blackened surface in order to absorb as much heat as possible; however various colour coatings have also been proposed in the literatures [14, 15]. Desirable selective surfaces usually consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to long-wave thermal radiation, and a thin lower layer that has a high reflectance and a low emittance for long-wave radiation. Such selective surfaces with a desirable optical performance usually have a high manufacturing cost, but several low-cost manufacturing ideas have also been proposed [16, 17].

### 1.7 SOLAR FLAT PLATE COLLECTOR WITH REFLECTOR

The reflector is introduced here to concentrate both the direct and diffuse radiation of the sun on the collector, which will increase the temperature difference between the inlet and outlet water flow through the collector. A reflector focuses direct radiation onto a first or movable collector, as in Figure 4 and reflects a substantial portion of the diffused radiation onto the flat plate collector positioned near the focus of the reflector. The flat plate collector was oriented in such a way that it received both direct and diffuse radiation during the daytime. To observe the improvement of performance, the collector efficiency for two conditions, with or without using reflector is obtained in this analysis. The collector was faced toward the sun and changed its position with time or the position of sun. A solar energy
Performance enhancement of pebble absorber solar thermal collector (PASTC) using multiple reflectors

The conventional flat plate collector has expensive black coated copper fin tubes. This expensive copper fin tubes will replace the cheap pebbles. A pebble is porous and has high heat absorbing properties, so it has highest temperature in comparison with normal flat plate collector. A pebble is a clast of rock with a particle size of 2 to 64 millimetres based on the Krumbein phi scale of sedimentology. Pebbles are generally considered larger than granules (2 to 4 millimetres diameter) and smaller than cobbles (64 to 256 millimetres diameter). A rock made predominantly of pebbles is termed a conglomerate. Pebble tools are among the earliest known man-made artifacts, dating from the Palaeolithic period of human history. These are naturally found on beaches of sea and ocean. They can also be found in lakes, ponds and on the banks of rivers.

1.8 Pebbles

The conventional flat plate collector has expensive black coated copper fin tubes. This expensive copper fin tubes will replace the cheap pebbles. A pebble is porous and has high heat absorbing properties, so it has highest temperature in comparison with normal flat plate collector. A pebble is a clast of rock with a particle size of 2 to 64 millimetres based on the Krumbein phi scale of sedimentology. Pebbles are generally considered larger than granules (2 to 4 millimetres diameter) and smaller than cobbles (64 to 256 millimetres diameter). A rock made predominantly of pebbles is termed a conglomerate. Pebble tools are among the earliest known man-made artifacts, dating from the Palaeolithic period of human history. These are naturally found on beaches of sea and ocean. They can also be found in lakes, ponds and on the banks of rivers.
Pebbles are naturally formed by combination of quartz, feldspar and biotite. Quartz is a shiny crystal of refractive index varying from 1.44 to 1.5. This property makes pebble to trap heat radiation inside it. In the modified part of collector, the copper fin tubes are replaced by pebbles as it has high specific heat and also the pebbles act as heat storage. The pebbles are employed in the collector in the form of array.
## 2. LITERATURE REVIEW

<table>
<thead>
<tr>
<th>Sl no.</th>
<th>Author and YOP</th>
<th>Title</th>
<th>Remarks</th>
</tr>
</thead>
</table>
2. Use of insulating baffle plate improves the performance of the system during day time as well as night time.  
3. The system with baffle plate supply hot water up to 55°C in the early morning hours. |
| 19.   | K. A. Joudi et al., (1984) | An experimental investigation into the performance of a domestic forced circulation solar water heater under varying operating conditions | 1. Here the system was operated with and without thermostat control.  
2. Collector efficiency improved with system loading and operated with a differential thermostat to regulate positive operation of the pump and to prevent reversing the function of the collectors. |
2. It is also observed that the annual SF is improved by about 4%-7% and the CF are improved by about 12%-19% when a steel absorber plate is replaced by an Al plate, whereas, the SF and the CF are increased only about 1% and 3%, respectively, when a Cu plate is used instead of an Al. |
2. In the development of latent heat storage systems, two important factors considered i.e phase change materials and of heat exchangers. PCM, such as salt hydrates, paraffins, non-paraffins, eutectics and solid state PCMs, have good potential for low temperature thermal energy storage applications. |
<table>
<thead>
<tr>
<th>Page</th>
<th>Authors</th>
<th>Title</th>
<th>Details</th>
</tr>
</thead>
</table>
| 22   | Mikio Enoeda et al., (1998) | Effective Thermal conductivity measurements of the binary pebble beds by hot wire method for the breeding blanket | 1. In this work Hot Wire Method is used to measure thermal conductivity of Li$_2$O and Be pebble beds.  
2. Measured value of Li$_2$O 1 mm pebble bed resulted the value of contact area fraction, $4.9 \times 10^{-3}$  
3. Measured value of Be 0.6 and 1 mm pebble bed showed good agreement with the correlation by $1 \times 10^{-4}$ of contact area fraction. |
2. Here coatings used are black nickel, a NiS-ZnS complex on a nickel plated substrate, and black chrome, a Cr-CrO$_x$ complex on a nickel plated substrate. |
| 24   | Ali Abou-Sena et al., (2007) | Experimental measurements of the effective thermal conductivity of a lithium titanate (Li$_2$TiO$_3$) pebbles-packed bed | 1. The experimental results showed that $k_{eff}$ of (Li$_2$TiO$_3$) decreased from 1.40 to 0.94 W/mK with the increase of temperature from 50 to 500°C. |
2. A measure of a flat plate collector performance is the collector efficiency. |
| 26   | S. Abdallah et al., (2008)   | Sun tracking system for productivity enhancement of solar still       | 1. Introducing the sun tracking system to a fixed solar still has improved the performance of the traditional fixed single slope solar system by 22%.  
2. By using the sun tracker the water temperature increases, and the thermal capacity of the water decreases, by which the evaporation rate increases, hence the production will be increased. |
**PERFORMANCE ENHANCEMENT OF PEBBLE ABSORBER SOLAR THERMAL COLLECTOR (PASTC) USING MULTIPLE REFLECTORS**

<table>
<thead>
<tr>
<th>28</th>
<th>A. Mawire et al., (2012)</th>
<th>Simulated performance of storage materials for pebble bed thermal energy storage (TES) systems</th>
<th>1. A validated simplified single phase model for an oil pebble TES system has been used to examine the thermal performance of three solid sensible heat pebble materials (fused silica, alumina and stainless steel). 2. It is concluded that fused silica possesses the best thermal stratification performance whilst stainless steel achieves the highest total energy stored at the expense of a greater drop from the peak value as charging progresses.</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>Ljiljana T. Kostic et al., (2012)</td>
<td>Optimal position of flat plate reflectors of solar thermal collector</td>
<td>1. These results show the positive effect of reflectors made of Al sheet and there is an energy gain in the range 35–44% in the summer period for thermal collector with reflectors, which is expected to reduce the cost payback time.</td>
</tr>
<tr>
<td>30</td>
<td>Hicham Mastouri et al., (2013)</td>
<td>Pebbles Bed Thermal Storage for Heating and Cooling of Buildings</td>
<td>1. Here pebbles are used as thermal storage system to provide a thermal comfort inside residential buildings. 2. The most important factor is that the size of pebbles must be as uniform as possible to avoid significant pressure losses.</td>
</tr>
<tr>
<td>31</td>
<td>D. Aquaro and R. L Frano (2014)</td>
<td>Preliminary experimental evaluation of thermal conductivity of ceramic pebble beds</td>
<td>1. Pulsed Hot Wire Method (HWM) and Hot Plate with guard rings method is used to measure K of ceramic pebble beds. 2. K increases along with the bed temperature. 3. In the absence of compression load, the K seems to be less. 4. Void fraction of pebbles mainly influences on K of bed.</td>
</tr>
<tr>
<td>Page</td>
<td>Authors</td>
<td>Title</td>
<td>Summary</td>
</tr>
<tr>
<td>------</td>
<td>--------------------</td>
<td>----------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>32</td>
<td>Bhagyashree P. Dabhane, S. P. Adhau (2014)</td>
<td>Experimental Analysis of Flat Plate Collector Solar Water Heater</td>
<td>1. Experiments were performed at different input parameters i.e. by varying radiation level and wind velocity. It can be said that with the decrease in radiation level overall heat loss coefficient increase. 2. Heat removal factor at low radiation is less as compared to higher radiation level. Hence at higher radiation level we get high efficiency whereas at lower radiation level we get somewhat less efficiency.</td>
</tr>
<tr>
<td>33</td>
<td>Mahesh.V. Kulkarni (2016)</td>
<td>Investigation of a New Flat Plate Collector Performance for Solar Water Heating System</td>
<td>1. Here Cu tubes are replaced by Al tubes in addition to rectangular aluminium pocket. Owing to this development total cost of solar water heater with Al pocket is reduced to that of solar water heater with Cu tubes. 2. Temperature of water obtained at outlet of a new collector is about 69°C and efficiency of the collector is 35.47% as compared to that of conventional collector efficiency is around 40.05%.</td>
</tr>
<tr>
<td>34</td>
<td>M. De Beer et al., (2017)</td>
<td>A methodology to investigate the contribution of conduction and radiation heat transfer to the effective thermal conductivity of packed graphite pebble beds, including the wall effect.</td>
<td>1. This paper introduces Computational Fluid Dynamics (CFD) simulations to separate the contributions of radiation and conduction heat transfer, including the wall effects. 2. The conduction is reduced due to the higher porosity of pebbles. 3. The radiation is also reduced due to the reduction in pebble surface area exposed to radiation at higher porosity. 4. The conduction increases at lower temperatures due to the characteristic increase in the graphite thermal conductivity.</td>
</tr>
<tr>
<td>35</td>
<td>Cheng Ren et al., (2017)</td>
<td>Theoretical Analysis of Effective Thermal Conductivity for the Chinese HTR-PM Heat Transfer Test Facility</td>
<td>1. Results show that heat transfer by radiation plays a dominant role in the high temperature region, while heat transfer through gas conduction and...</td>
</tr>
</tbody>
</table>
### PERFORMANCE ENHANCEMENT OF PEBBLE ABSORBER SOLAR THERMAL COLLECTOR (PASTC) USING MULTIPLE REFLECTORS

<table>
<thead>
<tr>
<th>Page</th>
<th>Reference</th>
<th>Title</th>
<th>Summary</th>
</tr>
</thead>
</table>
| 36   | T. Hatano et al., (2017) | Effective Thermal Conductivity of a Li2TiO3 Pebble Bed | 1. The effective thermal conductivity of the Li2TiO3 pebble bed was measured by the hot wire method with compressive loads at high temperature.  
2. It was found that the effective thermal conductivity increases with the increase of the strain of the pebble bed. |
| 37   | Himangshu Bhowmik et al., (2017) | Efficiency improvement of flat plate solar collector using reflector | 1. The collector efficiency is obtained here, without reflector as 51%, and with reflector as 61%.  
2. Overall efficiency of the flat plate solar collector is increased approximately 10% by using the reflector with the collector. |
| 38   | Hapazari et al., (2017) | Construction and Performance Evaluation of a Low-Cost Flat-Plate Solar Energy Collector | 1. System is capable of sustaining water temperatures above 40°C against ambient temperature of as low as 10°C, which is acceptable for bathing and other household chores. |
| 39   | Ruth M. Saint et al., (2018) | Thermal Performance through Heat Retention in Integrated Collector-Storage Solar Water Heaters: A Review | ICSSWH systems have a number of benefits over other solar thermal systems, namely that they do not require an additional water storage tank, are simple to construct and install and with fewer associated costs. Baffles and fins promote the convection and conduction transfer of heat from the absorber to the water store while the glazing and insulation prevent convective and radiative heat losses. |
3. OBJECTIVE OF THE PROPOSED RESEARCH WORK

1. Designing a collector depending on the required temperature (°C) and a magnitude of heat (W).

2. To substitute pebbles in place of conventional metal collector which eliminates the corrosion problem and reduces the cost.

3. To theoretically analyse the performance of the pebble collector.

4. To fabricate the designed collector.

5. To test and analyse the performance of designed and fabricated Pebble absorber solar thermal collector.
4. METHODOLOGY

- Literature Survey
- Design and Development of PASTC
- Evaluating the Design
- Development of PASTC
- Fabrication of PASTC
- Testing of PASTC model

With Reflector
- Varying Shape of Pebbles
- Varying colour of Pebbles
- Varying size of Pebbles

Without Reflector
- Varying Shape of Pebbles
- Varying colour of Pebbles
- Varying size of Pebbles

Forced Convection Test
Natural Convention Test
Comparing results of the pebble absorber solar collector with conventional absorber solar collector
5. EXPECTED OUTCOME OF THE PROPOSED STUDY

1. Naturally available material (pebble) for collector.

2. Net performance of the proposed collector is definitely more than a conventional collector since pebble is a natural collector material while the conventional materials like Al or Cu need energy for their mining and refining.

3. Environmental friendly (Compared to energy intensive Al/Cu collectors).

4. Less production cost.

5. Fewer maintenance cost.

6. Solar thermal collector with enhanced performance compared to a conventional solar thermal collector.
6. REFERENCES


