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Ameliorating Heat Transfer Performance of Absorber Tube for Single Axis Concentrators

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Abstract

Solar parabolic trough collectors are being widely used to exploit solar energy for both thermal and power generation applications. But, these systems require long arrays of reflective troughs with absorber tube running along the axis of parabolic dish. A successful attempt to reduce the length of arrays was accomplished by experimentally analysing the modifications done in absorber tube. Three out of four tubes were fabricated and they were employed to obtain the performance parameters through experimentation conducted at VIT University, Vellore, India. Distilled water was used as the working fluid. Maximum efficiency of 39.12\% was acquired at 451.6 W/m\textsuperscript{2} of direct normal irradiance (DNI) for absorber tube with internal pin-fins and without glass tube (AFWG\textsubscript{t}) compared to 8.15\% obtained at same value of DNI and other conditions for simple absorber tube without glass cover (AWG\textsubscript{t}). Cylindrical parabolic trough available at the university was utilized, providing the basis for designing and fabrication of the tubes. Plots for varying mass flow rate at interval of 10 minutes were made against instantaneous thermal efficiency and heat utilized, for direct normal irradiance vs. temperature difference across the tubes and instantaneous thermal efficiency. Through the experimentation conducted, better performance was procured compared to earlier works. Thus, the proposal infers that absorber tube with internal fins has good scope for its application, both domestically as well as industrially. It also calls for further research and development of proposed techniques so as to achieve better performance curves.

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1. Introduction

As by [1] the concentrating systems can be classified into three major categories, point focus concentration, line focus concentration and linear concentration. Concentrating paraboloid concentrators are types of point focus concentrations, whereas parabolic trough collectors lies in category of line focus concentrators and Fresnel collectors rests in the category of linear collectors. Solar parabolic trough collector (SPTC) provides an effective way to harness solar energy providing “one-axis concentration” such that fluid flowing through the absorber tube, gains the concentrated energy and accomplish useful work. Parabolic trough collectors, with water as fluid, are basically used for two major applications, industrial steam generation and water heating application. Former application requires heating of water up to a temperature of range 300-400 °C, while the later requires temperature range of around 100-250 °C.

| Abbreviations | Description |
|---------------|-------------|
| DNI           | direct normal irradiance |
| STPC          | solar parabolic trough collector |
| AGt           | absorber tube with glass cover |
| ABGt          | absorber tube with hinged blades and glass cover. |
| AWGt          | absorber tube without glass cover. |
| AFWGt         | absorber tube with internal fins and without glass cover. |

| Nomenclature | Description |
|--------------|-------------|
| I            | solar beam flux, W/m² |
| T_in         | inlet temperature of water, °C |
| T_out        | outlet temperature of water, °C |
| v            | volume flow rate, m³/hr |
| m            | mass flow rate, kg/s |
| Q_m          | energy absorbed by absorber tube surface, W |
| Q_o          | energy utilised by water, W |
| η            | instantaneous thermal efficiency, % |
| θ_r          | rim angle, degree |
| I_p          | solar flux from pyrheliometer, mV |
| f            | focal length of trough, 0.2626 m |

Since many years, researchers have been trying to optimize the working performance of SPTC so that rapid heat transfer can take place and overall length of the trough collector can be reduced. Supporting the above statement, the review paper on state of parabolic trough collectors by [2] conveys that intensive research and development is required in this field of SPTC to reduce cost and augment their operation. Work done by [3] introduces design method and working principle for new type of trough collector with efficient performance of SPTC by introducing widely opened concentrating collectors. However, increase in the width of concentrating apparatus may result to unbalanced design and higher probability of back reflection of the incident solar radiation. To avoid such hindrances, requirement of precise tracking and high cost engrossment will be needed, which add some more minuses to the proposed design. Effort on solar selective coatings by [4] and cobalt electrodeposition on absorber tubes by [5] enhances the efficiency for performance of solar devices. But radiation thermal losses may increase with increase in coating temperature, thus resulting to development of high thermal stresses in the collector tube.

[6] Showed the implementation and development of recirculating operation mode for SPTC, increasing the output temperature and performance of the apparatus. But, the system possesses minor drawbacks concerning the use of steam at high pressures, risk for steam leakage and higher stresses on tube. Experimental work with bimetallic tube by [7] is appreciable, posing a new field for further research. However, employment of bimetallic tube requires high investment and also the proposed tube has very large diameter (31.7 mm), which affect heat transfer rate.
Performance analysis of selectively coated solar collector tube with U-tube by [8] employing reticulation of working fluid presented results employing very less mass flow rate through the tube, while the tube had unexploited and considerable space to fit in another U-tube. Utilizing the available space, performance of the tube could have been optimized. An innovative numerical model evaluation of heat transfer characteristics for porous disc receiver by [9] presents an efficient design of absorber tube, but flow across the tube is very high and also the system will require only pure fluid to avoid accumulation of particles on the tube walls than can be caused by highly interrupted flow through the receiver tube with sequential porous discs.

Although there may be an extensive list of researches, developments and innovations for improving effectiveness of absorber tube, the authors of the paper present another innovative research to enhance efficiency nearly by two to three times compared to that of conventional absorber tubes. The fabrication procedure and experimental analysis for the modifications done in the absorber tube are presented. The proposed solar absorber tube can be employed for application in both line and linear focus concentration apparatuses with numerous advantages as well. With VIT University, Vellore (12.92°N, 79.13°E) as the experimentation site, the experiments were performed on August 23rd, 2015 with AGt and ABGt, and on August 25th, 2015 with AWGt and AFWGt. Because of unavailability of the glass tube, the experiment on August 25th was performed without evacuated glass cover on both the tubes. Nevertheless, the obtained results are very much accurate and can be compared with available studies as well.

2. Materials and Methods

Among the four tubes used for the experiments, three tubes were designed and fabricated, excluding AGt that was available from the university. The specifications of cylindrical axis trough collector and the absorber tubes are given in Table 1 and Table 2 respectively. All the tubes were made of copper. Although the total length of the three fabricated tubes was kept as 2 m, effective length of tubes receiving reflected radiations from parabolic trough was 1.5 m and arrangements were made such that the temperature differences for the fluid across the effective length of the tubes were measured accurately. Parabolic trough available at the university, with rim angle of 120° and focal length 26.26 cm, was used which has reflective surface of aluminium alloy and reflectivity of about 80%. Details for fabrication processes of the tubes and pictures taken during the experiments have been included.

Table 1. Specification of trough collector

| Component                  | Dimension |
|----------------------------|-----------|
| Length, L                  | 1.5 m     |
| Width, W                   | 0.91 m    |
| Concentration ratio, C     | 19        |
| Specific heat of fluid, Cp | 4182 J/kgK |
| Tilt factor for beam radiation, R | 1.00 |

Table 2. Specification of absorber tubes

| Component                  | Dimension |
|----------------------------|-----------|
| Inner diameter, d          | 0.013 m   |
| Outer diameter, D          | 0.015 m   |
| Inner diameter of glass tube | 0.030 m |
| Thickness of glass tube    | 0.005 m   |
| Vacuum pressure in glass tube | 0.8 bar |

AGt, was the conventional tube of specified dimension with glass cover. The enclosed volume in the glass tube was evacuated to develop a low pressure vacuum, thus reducing the heat transfer losses. For ABGt, 2 mm drill holes were made along a straight line with pitch distance of 50 mm and galvanized iron sheets of $7 \times 7$ mm$^2$ were made to hang along the axis of the absorber tube using the hinged supported from the drilled holes, such that the blades don’t make contact with tube’s inner surface. This ensured the continuous flow of distilled water. The drill holes were welded using gas welding to make the tube leak proof and also to make the blades swing naturally along with the flowing fluid, creating turbulence in the flow. Increase in turbulence increases the contact time between fluid and absorber tube’s inner surface, hence the heat transfer increases.
Due to unavailability of more number of glass tubes, the experiment on other two tubes was performed without evacuated glass cover. AWGt was similar to AGt with the only difference of the glass tube covering the absorber tube, and thus the tube was subjected to minor heat transfer losses. For AFWGt, drill holes were made in helical pattern all over the tube at pitch distance of 25 mm and extrusion using a solid copper wire, 1.5 mm diameter, was provided at each hole with gas welding on the surface. The length of the extruded wires, functioning as internal pin-fins for the tube, was kept constant at 5 mm. The 3D models for simple absorber tube is shown is Fig.1, absorber tube with hinged blades shown in Fig.2 and absorber tube with internal fins in Fig.3, are presented showing internal design. Feature ‘a’ presents the isometric view of a section of absorber tube while feature ‘b’ presents the front view.

Fig.1. Simple absorber tube (AGt / AWGt)

Fig.2. Absorber tube with hinged blades (ABGt)

Fig.3. Absorber tube with internal fins (AFWGt)
3. Theory and calculation

Although the experiments for two pair of absorber tubes were conducted on two different days, the results obtained can be compared because of availability of almost same radiation on both the days. Initially, absorber tube was fixed on SPTC’s axis and the trough was adjusted such that axis of focus and the absorber tube accords. Then the tube was connected to the pump through a hose and distilled water, used as working fluid, was collected in tank. The pump was switched on, leaving the system for 10 minutes with specified volume flow rate, controlled by valves. Parabolic trough collector was adjusted frequently to align the absorber tubes with focus of reflected radiations to maintain tilt factor with the value of 1.00 ± 2%. Pyrheliometer, with sensitivity of 4.95 mV/W/m², was used to measure the beam radiation. The required performance parameters were noted, such as DNI value from multimeter, temperature values for atmospheric condition, inlet and outlet, and volume flow rates. Then, flow rate was altered at an interval of 10 minutes and data for same parameters was collected at different flow rates. The experiment for each tube was conducted for a span of 50 minutes and total of 5 readings were obtained.

Pictures of the experimentation have also been included for authentication of the work done. The Fig. 4 presents experimental set-up for AGt, Fig. 5 for ABGt, Fig. 6 for AWGt and Fig.7 for AFWGt. Based on the available parameters, some more parameters for parabolic trough and performance analysis were calculated using the equations 1-6 made available by [10]

Rim angle for parabolic trough,
\[ \theta_r = 2 \times \tan^{-1} \left( \frac{W}{2f} \right) \]  
(1)

Concentration ratio for parabolic trough,
\[ C = \frac{W - D}{\pi D} \]  
(2)

Direct normal irradiance incident on absorber tubes,
\[ I = \left( \frac{I_b \times 3.1552 \times 221.4}{4.95} \right) \]  
(3)

Incident energy,
\[ Q_{in} = I \times W \times L \]  
(4)

Energy utilized,
\[ Q_u = \dot{m} C_p (T_{out} - T_{in}) \]  
(5)

Fig. 4. Experimental set-up for AGt  
Fig. 5. Experimental set-up for ABGt
Instantaneous thermal efficiency of absorber tubes,

$$\eta = \frac{Q_u}{Q_{in}} \times 100$$  \hspace{1cm} (6)

A tank of 15 liters capacity was employed to store distilled water that was pumped across the tubes through a valve and a rotameter. Thus, volume flow rates could be varied and experimentation was done with varying mass flow rates. Digital thermocouple was used to measure the temperature values and stop watch for measuring time required to fill a liters capacity collecting jar.

4. Results and Discussion

Based on the experimental results and observations, plots were obtained for mass flow rate vs. energy utilized in Fig. 8, mass flow rate vs. instantaneous efficiency in Fig.9, DNI vs. temperature difference Fig. 10 and DNI vs. instantaneous efficiency in Fig. 11.

The Fig. 8 shows that for almost same mass flow rates, the simple tubes, both with and without glass tube, could utilize very less amount of energy ranging from about 50-75 W, while AFWGt utilized nearly four-fold of their utilization ranging from 200-250 W and ABGt could utilize about double of that energy ranging from 100-150 W. The extrusions or pin-fins provided turbulence in flow with extended surface area for heat transfer and thus higher energy was used. However, the hinged blades provided mainly turbulence in the flow that contributed to increased but less energy utilization. The simple tubes neither provided turbulence nor additional heat transfer resulting to their lowest transfer rates. Hence, in Fig. 9, the instantaneous efficiencies follow the same increasing trend with AWGt having the lowest performance efficiency, almost equal to that obtained by AGt. ABGt performed with efficiency almost twice that of AGt while AFWGt resulted to highest performance efficiency of range 35-40 %, about three times increment from AWGt.

It can be inferred that both efficiency and energy utilized increases with decrease in mass flow rate of the working fluid. The procured results can be very well compared to the results presented by[8]. The authors maintained very low mass flow rates of 0.001 kg/s, 0.002 kg/s and 0.003 kg/s and obtained efficiency of about 35-40% with higher radiation densities of about 950 W/m². In the present work, it should be noticed that AGt and AWGt utilizes amount same amount of energy and delivering almost same thermal instantaneous efficiencies. But, as per the theory, energy utilized by AGt must be higher than that of AWGt with availability of glass cover. This shift can be explained by the fact that performance test for AWGt was done on August 25th, when higher radiation intensity was available.
Fig. 8. Mass flow rate vs. energy utilized by absorber tubes

Fig. 9. Mass flow rate vs. instantaneous efficiencies of the tubes
Fig. 10. DNI vs. temp. difference of working fluid across absorber tubes

Fig. 11. DNI vs. instantaneous efficiencies of absorber tubes
Variation of temperature difference across the absorber tubes with varying DNI in Fig. 10 presents the direct proportionality relation amongst the two parameters i.e. with increase in DNI, temperature difference for the working fluid also increments. Again because of difference in incident radiation intensities, the difference of temperatures for both AGt and AWGt is almost constant. But, this difference of temperature almost gets doubled in case of ABGt and augments to four times for AFWGt. The higher temperature verifies the better efficiency of AFWGt compared to other absorber tubes, as presented in Fig. 11. It should be noted that this temperature difference was obtained only for 1.5 m long SPTC and at low DNI values.

The experimental data provided by Dudley et al. (1994) [11] for SEGS LS-2 collector, about 4 m long, used DNI values varying from 900 W/m² to 930 W/m² with very high inlet temperature of working fluid ranging from 100 °C to 350 °C and achieved temperature increment of about 20 °C in all cases. Whereas, the experimental values provided by the authors for AFWGt have DNI values ranging from about 400 W/m² to 450 W/m² and almost constant inlet temperature of 31.5 °C, achieving temperature rise of 3.5 °C within the absorber tube length of only 1.5 m. For direct steam generation using parabolic troughs with collector length of 600 m and inlet temperature of 190 °C, Odeh et al. (1998) [12] presented analyzed and developed model achieving maximum efficiency of about 70%, whereas efficiency close to 40% was achieved for AFWGt, without evacuated glass cover.

The proposed design appears to have substantial application in the developing fields as well. It can be used for thermal applications, involving heat transfer, organic rankine cycles and even in absorption power and cooling cycles, making performance of system efficient. Works presented by co-authors of the presented work, Shankar and Srinivas (2012, 2012),[13,14] can also be optimized with use of internally finned absorber tube for minimising the length of solar thermal parabolic trough collector, increasing heat input load to the generator and making cycle more efficient, both in cost and performance. Also the experimental investigation of a natural circulation heat pipe for steam generation by Zhang et al. (2012) [15] uses high pressure of 7.5 bar for steam generation securing nearly 38.52 % thermal efficiency which can be optimized to a great extent, if the proposed internally finned absorber tube are used.

5. Conclusion

Vellore is 216 m above sea level and receives two periods of monsoons mostly during June – August and October – December. As the experiments were conducted during the second phase of monsoon, intensified solar flux was not available compared to that obtained in summer season, affecting the performance curves of the proposed absorber tubes. Also the arrangement of aluminium alloy sheet over the parabolic trough had minor irregularities, resulting to lessened reflective and optical efficiency compared to mirror reflectors. The unavailability of glass tube for AFWGt also contributed to the procured less efficient results. Reduction of overall length of arrays required for harnessing of solar energy, especially for application of direct steam generation in solar thermal power plants, was the prime aim of this project. With the obtained results, it can be concluded that the modifications of introducing hinged blades and internal fins in the absorber tubes of solar parabolic concentrating collector can deliver highly efficient performance compared to that of traditional tubes. Average instantaneous thermal efficiencies of 36.89 % and 28.17 % were obtained for internally finned tube and tube with hinged blades respectively. Such modifications can be revolutionary in the field of solar energy, hence cutting off the overall cost of the projects to a great extent. On concluding, it can be inferred that absorber tube with internal pin-fins proves to be most efficient, although there was a con for the experimentation that use of evacuated glass cover was avoided due to lack of sufficient funding. If evacuated glass cover was used, better and more efficient results could have been obtained compared to the various referred works.

References
[1] Fernandez-Garcia, A., Zarza, E., Valenzuela, L., Perez, M., 2010, Parabolic-trough solar collectors and their applications. Renew. and Sustain. Energy Rev. 14, 1695–1721.
[2] Price, H., Lupfert, E., Kearney, D., Zarza, E., Cohen, G., Gee, R., Mahoney, R., 2012, Advances in Parabolic Trough Solar Power Technology. J. of Sol. Energy Eng. 124, 109-125.
[3] Tao, T., Hongfei, Z., Kaiyan, H., Mayere, A., 2011, A new trough solar concentrator and its performance analysis. Sol. Energy 85, 198–207.
[4] Farooq, M., Raja, I.A., 2008, Optimisation of metal sputtered and electroplated substrates for solar selective coatings. Renew. Energy 33, 1275–1285.

[5] Barrera, E., Gonzalez, I., Viveros, T., 1998, A new cobalt oxide electrodeposits bath for solar absorbers. Sol. Energy Mater. and Sol. Cells 51, 69-82.

[6] Valenzuela, L., Zarza, E., Berenguel, M., Camacho, E.F., 2006, Control scheme for direct steam generation in parabolic troughs under recirculation operation mode. Sol. Energy 80, 1–17.

[7] Flores, V., Almanza, R., 2004, Direct steam generation in parabolic trough concentrators with bimetallic receivers. Energy 29, 645–651.

[8] Ma, L., Lu, Z., Zhang, J., Liang, R., 2010, Thermal performance analysis of the glass evacuated tube solar collector with U-tube. Build. and Environ. 45, 1959-1967.

[9] Ravi Kumar, K., Reddy, K.S., 2009, Thermal analysis of solar parabolic trough with porous disc receiver. Appl. Energy 86, 1804–1812.

[10] Sukhatme, S. P., 2005, Solar Energy Principles of Thermal Collection and Storage, Second ed. Tata McGraw-Hill Education, New Delhi.

[11] Dudley, V.E., Koib, G.J., Sloan, M., Kearney, D., 1994, Test results SEGS LS-2 solar collector, Sandia National Laboratories, National Technical Information Service, United States.

[12] Odeh, S.D., Morrison, G.L., Behnia, M., 1998, Modelling of parabolic trough direct steam generation solar collectors. Sol Energy 62, No. 6, 395–406.

[13] Shankar, R., Srinivas, T., 2012, Modelling of energy extraction in vapor absorption refrigeration system. Procedia Eng. 38, 98-104.

[14] Shankar, R., Srinivas, T., 2012, Solar thermal based power and vapor refrigeration absorption system. Procedia Eng. 38, 730-736.

[15] Zhang, L., Wang, W., Yu, Z., Fan, L., Hu, Y., Ni, Y., Fan, J., Cen, K., 2012, An experimental investigation of a natural circulation heat pipe system applied to a parabolic trough solar collector steam generation system. Sol. Energy 86, 911–919.